Wide-field Wide-band Full-Mueller Imaging

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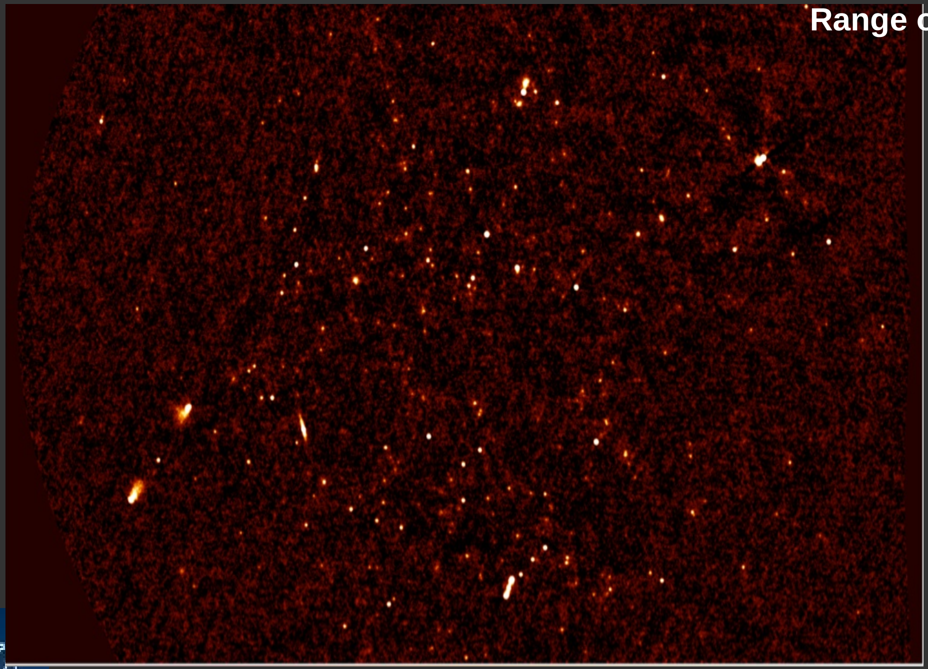
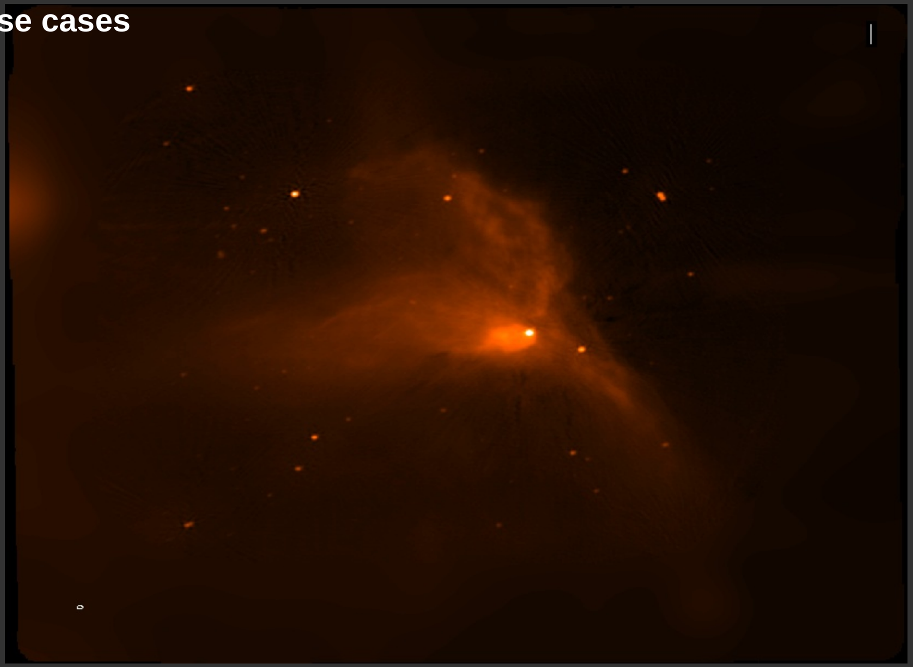
NRAO, Socorro

The Scientific Motivation

- Most projects with current telescopes require precise reconstruction of the sky brightness distribution.
  - Continuum science; High DR imaging
  - Polarimetry; High fidelity
  - Wide-band data: spectral index, RM mapping
  - All of the above for mosaic imaging

Range of use cases





WB AW-Projection + MT-MFS

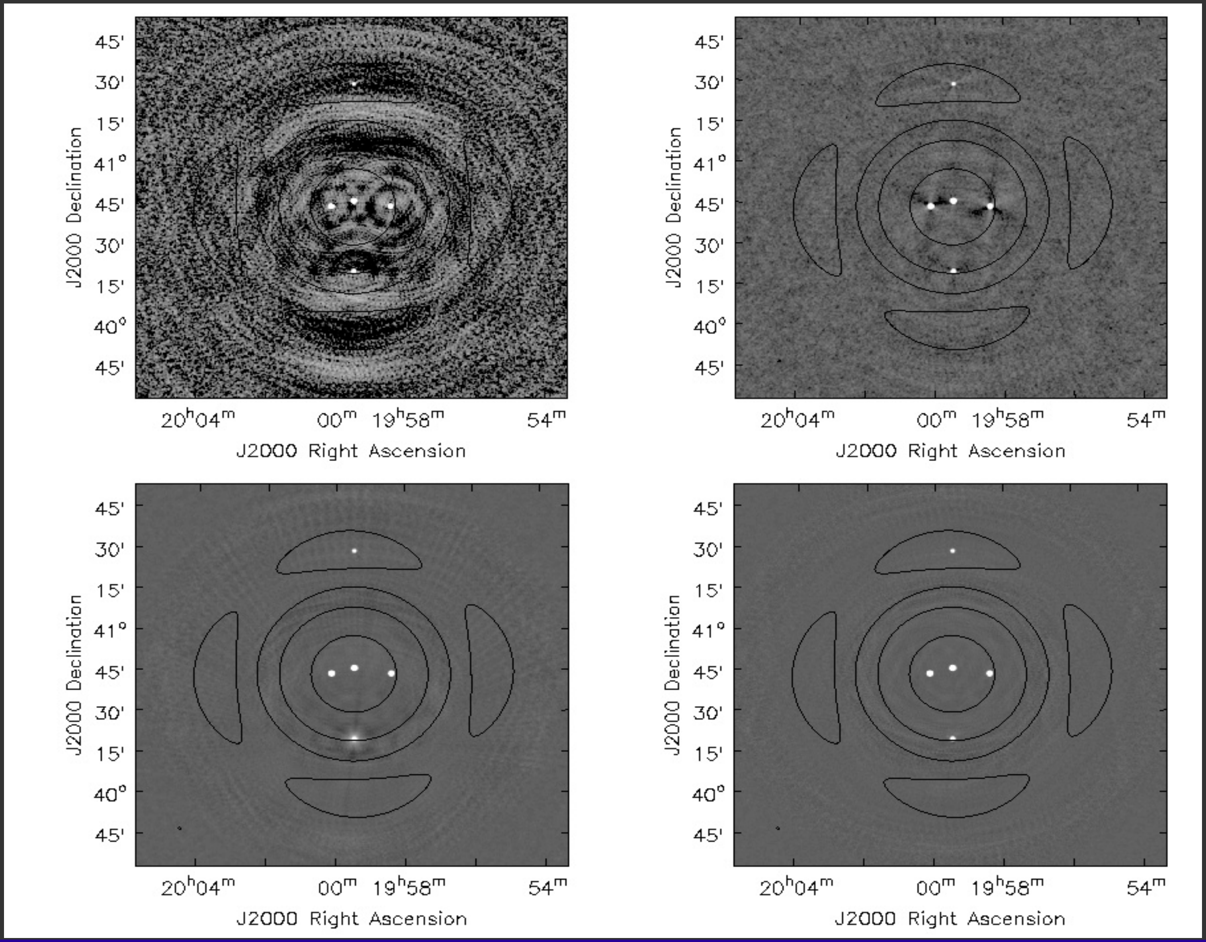
- Simultaneously account for the PB effects and frequency dependence of the sky

  <u>Separation of instrumental calibration and sky brightness terms:</u>

  - 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

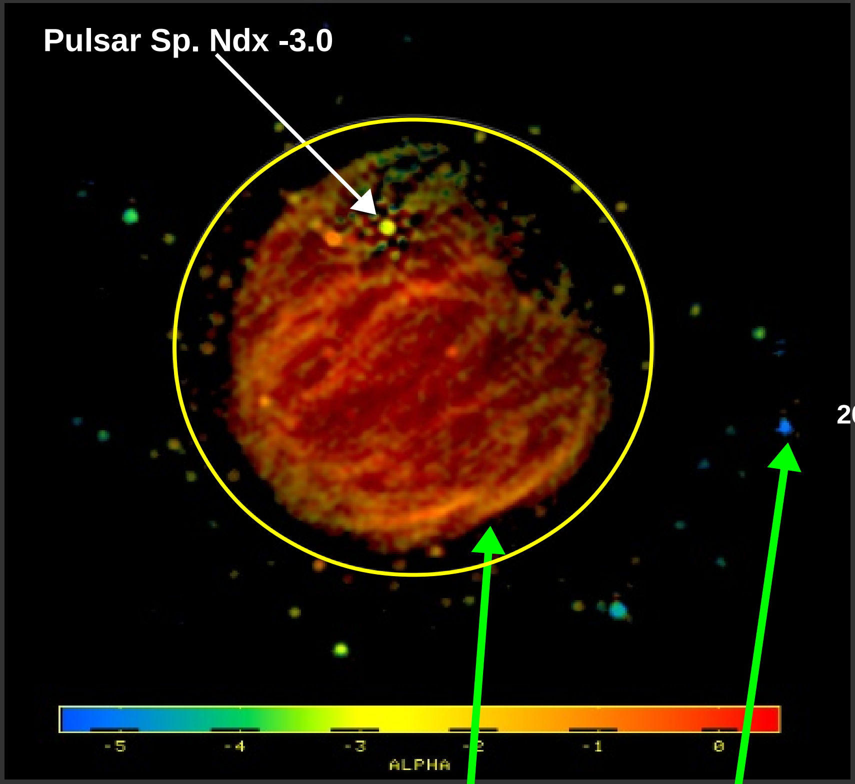
MT-MFS+ WB A-Projection

Ap.J., 2013; AJ, 2016

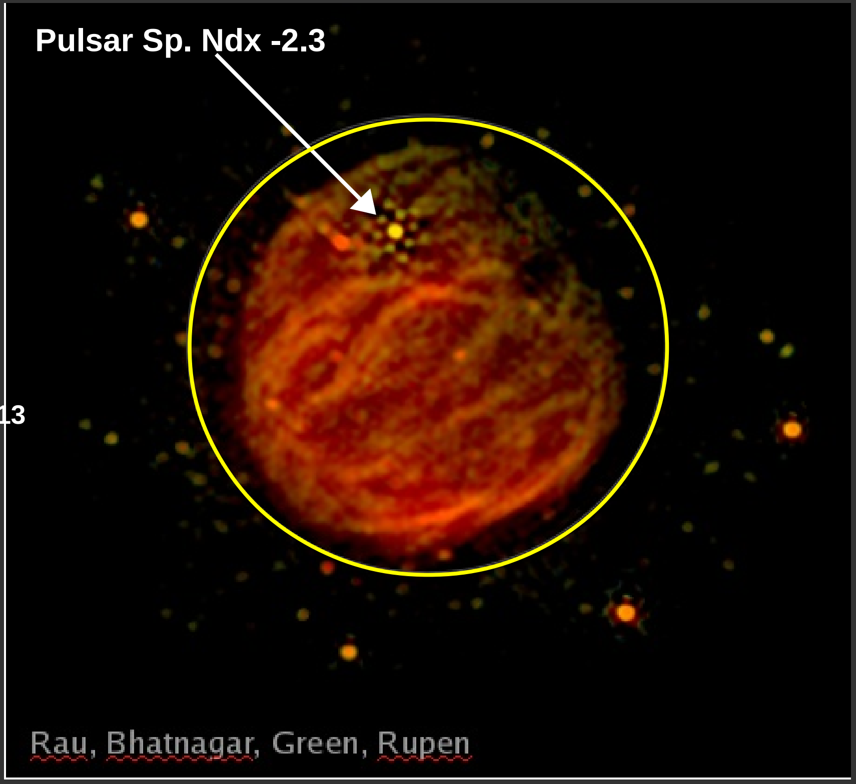
WB AW-Projection + MT-MFS

- **Results consistent with other independent measurements**

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



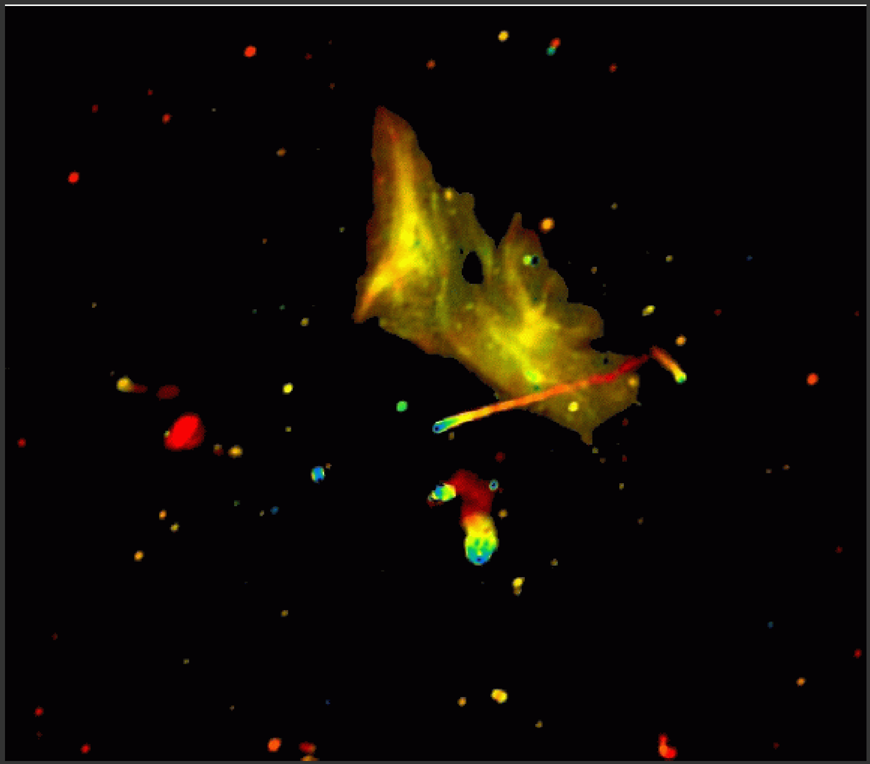
2011 → 2013



Artificially steep (due to PB)

ApJ, 2011, 2013

Imaging with the EVLA @ L-, S-Band

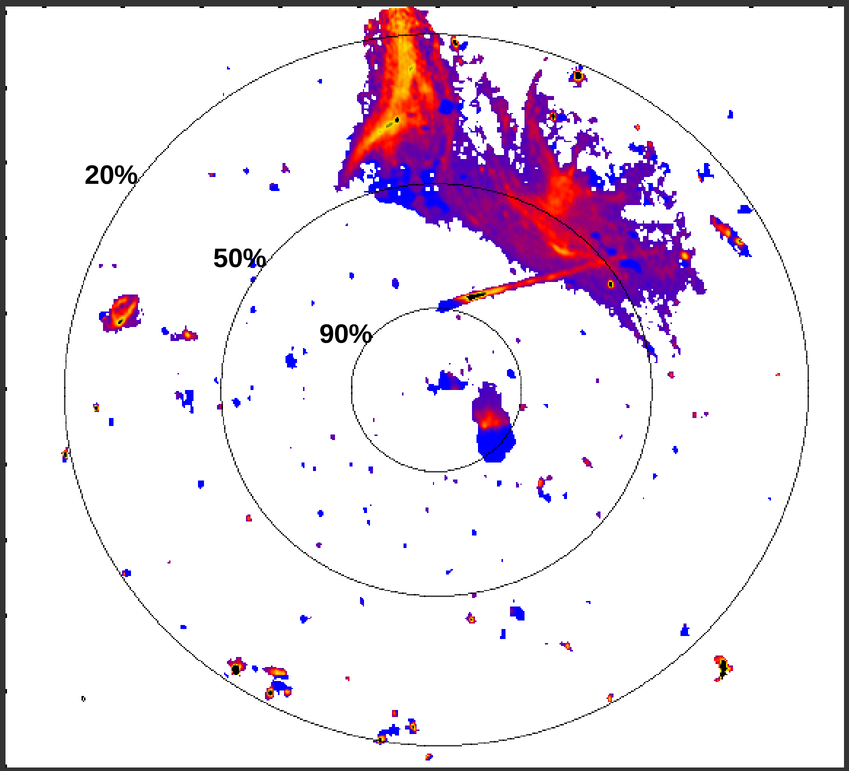


L-Band, MS-MFS

Intensity-weighted Sp. Ndx. Map

Single pointing, wide-field wide-band image

S-Band, WB AWP + MS-MFS



Spectral Index colour coding
- Red: < -3.0
- Blue: ~ -0.7

DD effects in full-pol imaging

- Measurement Equation in the image domain including DD terms:

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

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

- ***M*** is the DD Mueller Matrix
- Encodes the precise DD mixing of the elements of the input flux vector

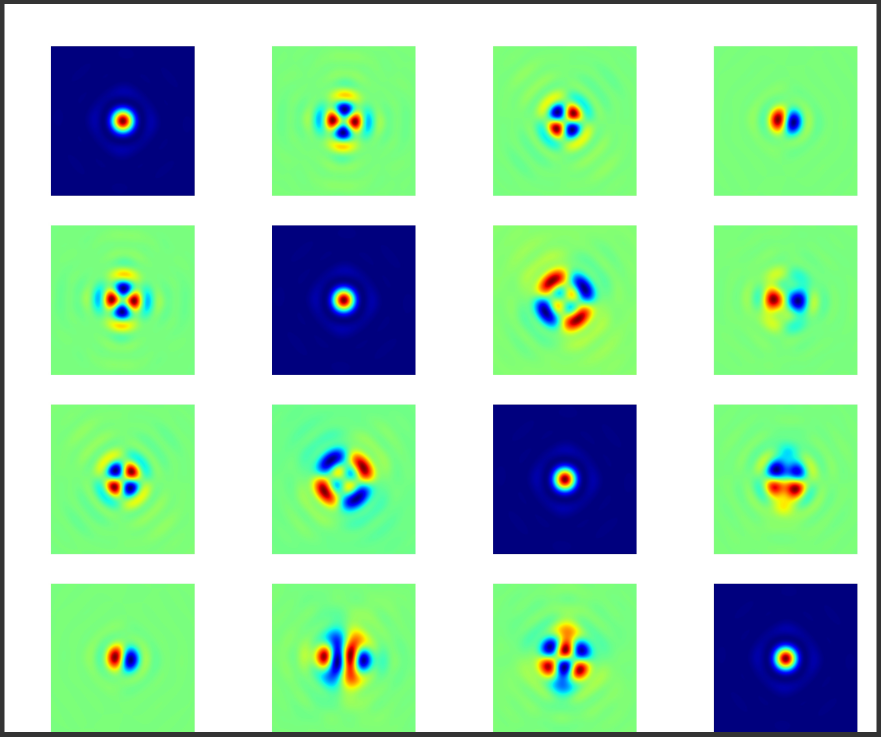
- WB A-Projection corrects for diagonal terms
- Ideally, full-Mueller imaging required
  - Significant increase in compute load and memory footprint

•Including the dominant off-diagonal terms necessary for full-Stokes imaging

NRAO

DD effects in full-pol imaging

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



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 leakage is few% of Stokes-I

[Jagannathan, Bhatnagar, Rau & Taylor]

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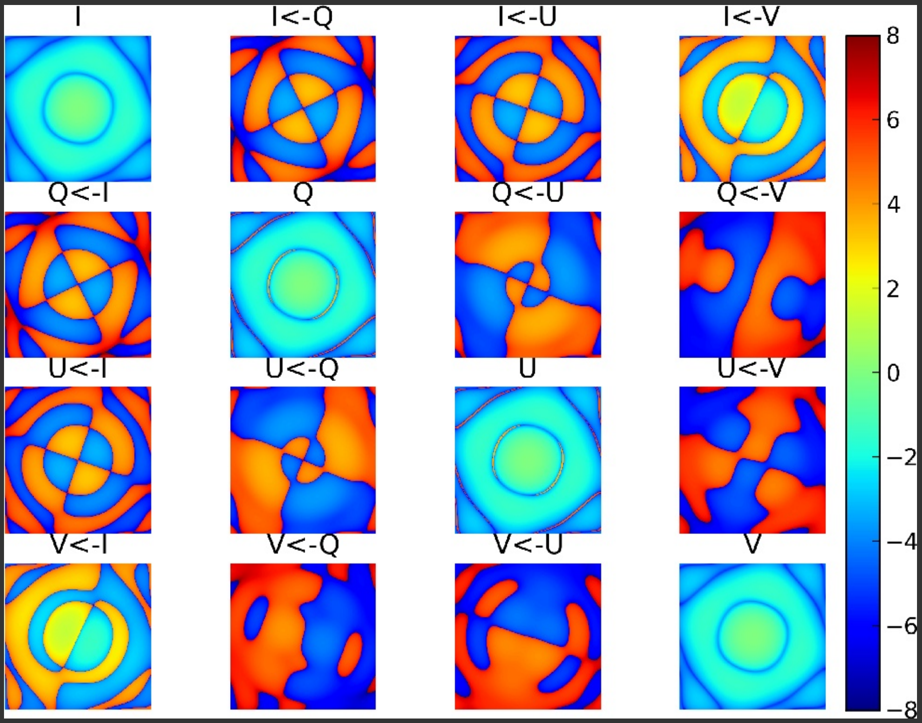

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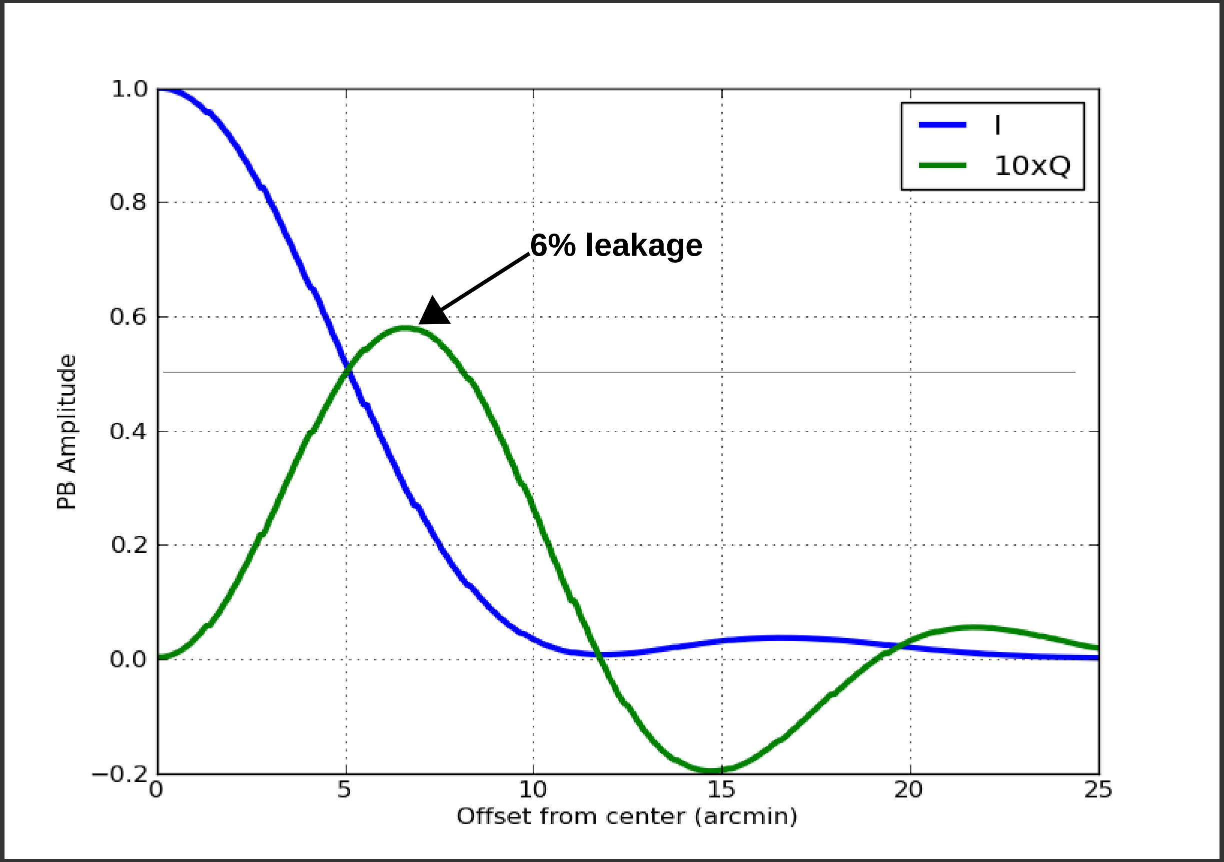
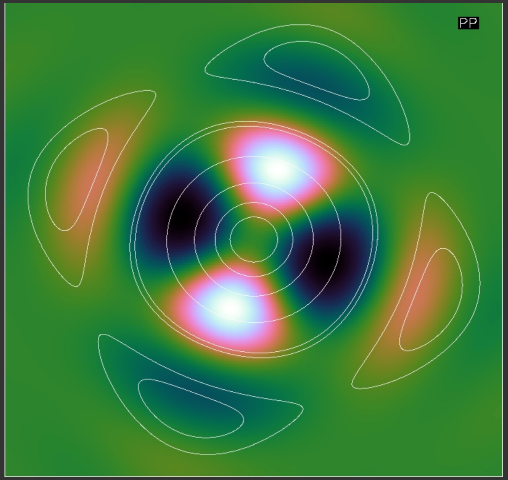
[Jagannathan, Bhatnagar, Rau & Taylor]

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



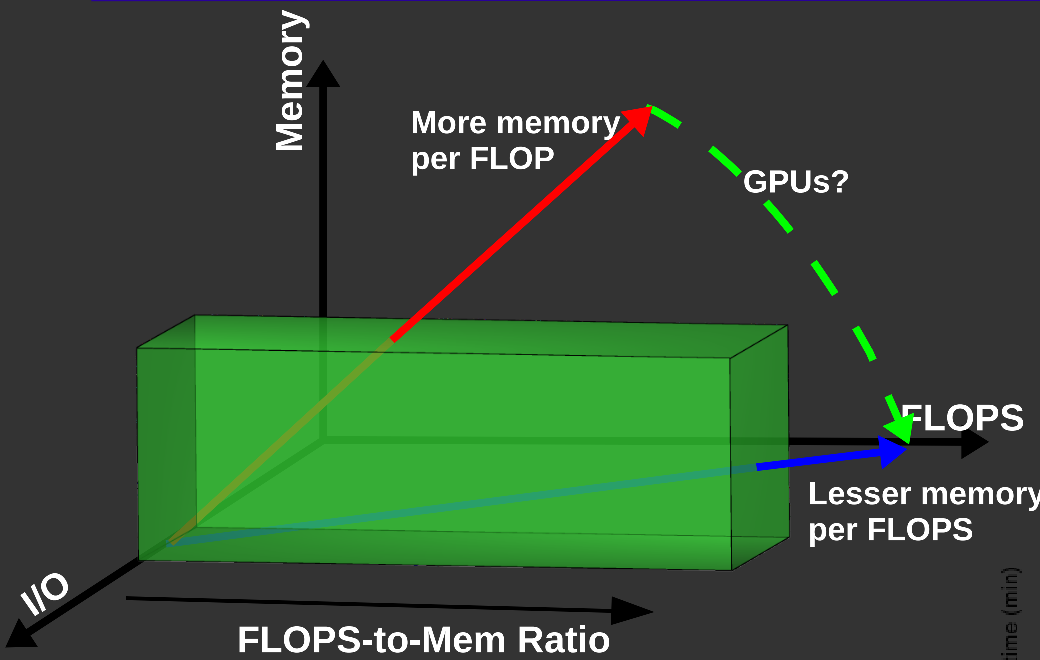


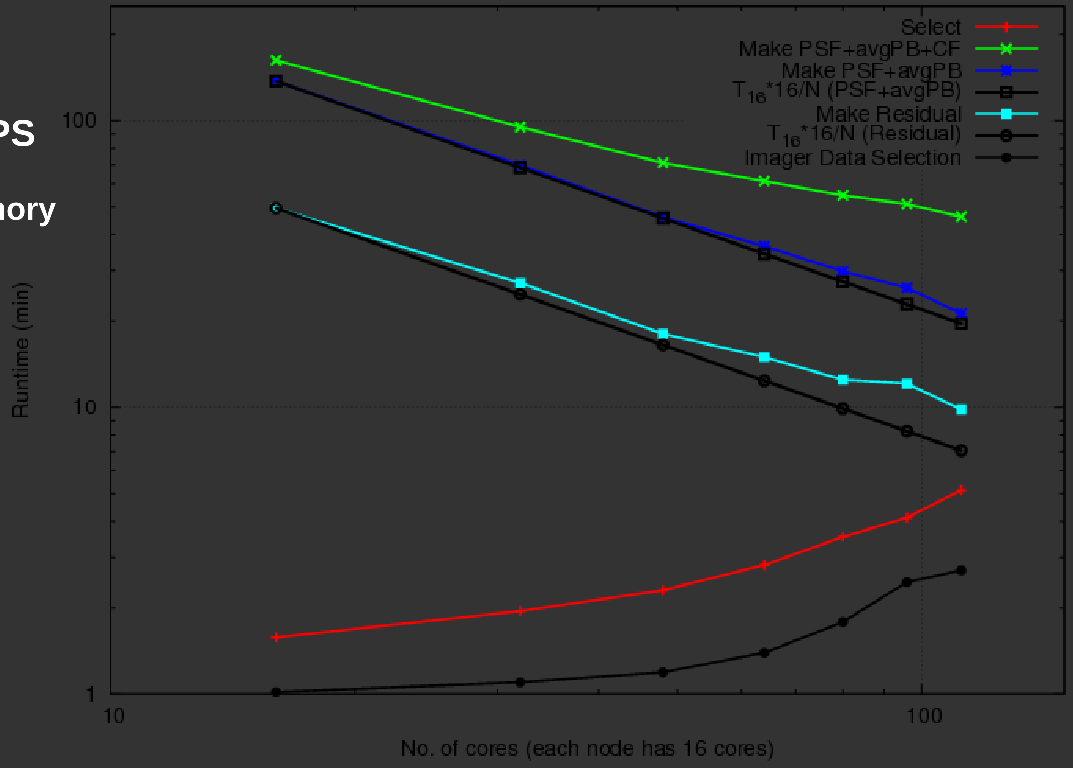
[Jagannathan, Bhatnagar, Rau & Taylor]

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**
  - **More expensive**: Fundamentally need more CF pixels for wide-field imaging
  - **Larger memory footprint**: Fundamentally, any which way you cut it

Computing/Algorithm architecture



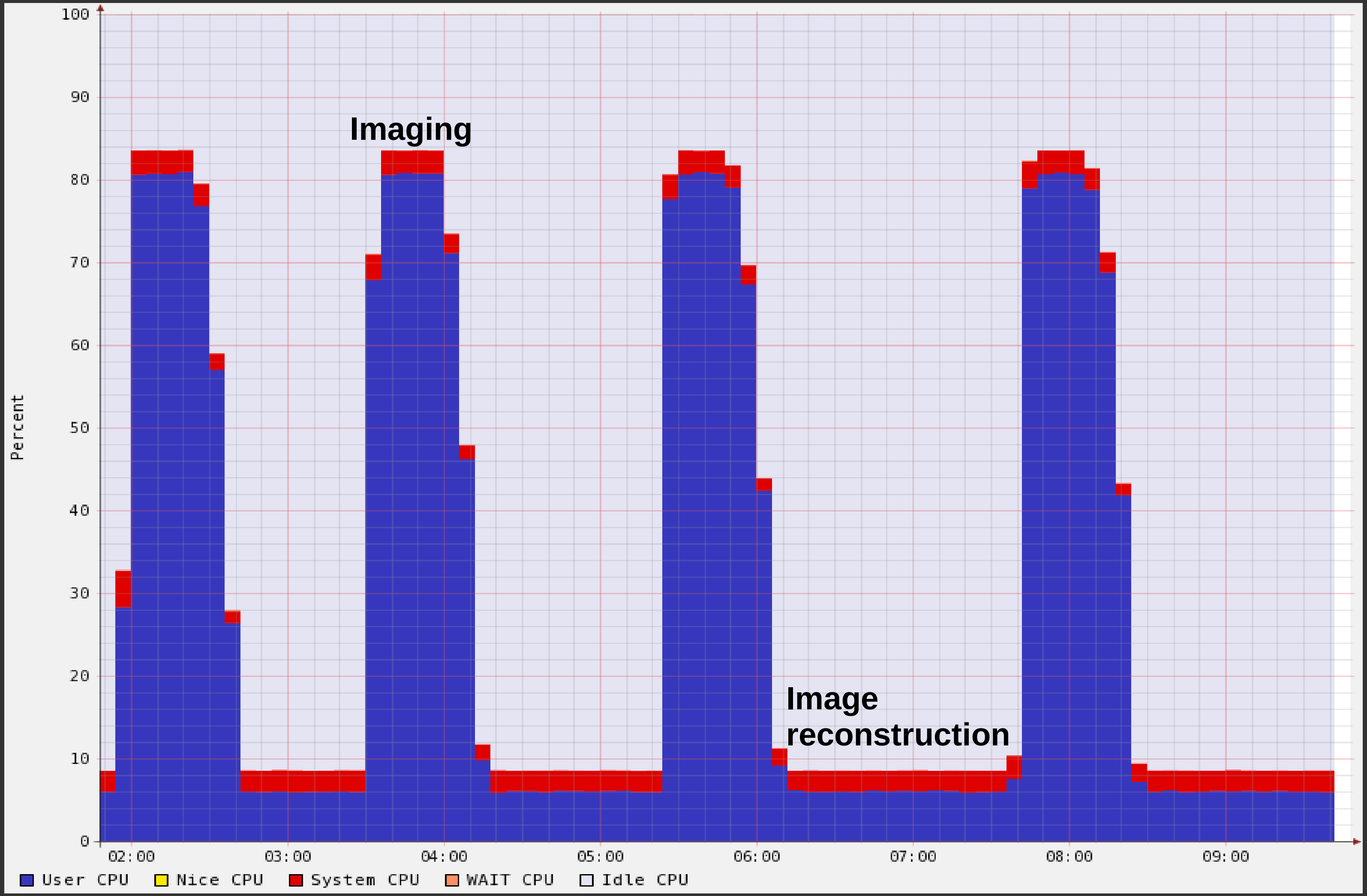


Algorithm design

- 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)

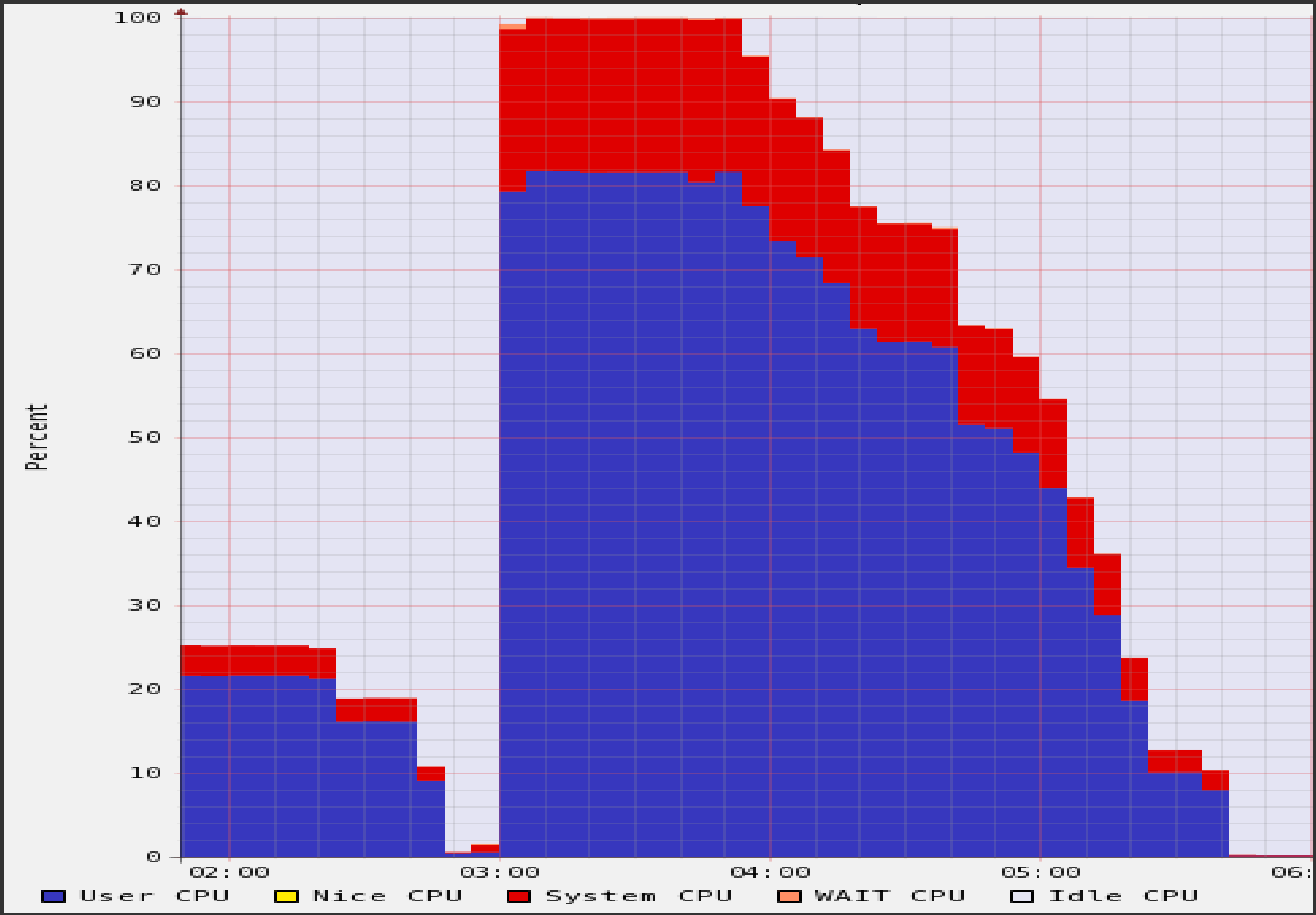
Load balance, memory footprint,...

- Imaging parallel, minor cycle algorithms serial
- 10x speed-up on a typical (modern) w/s within reach



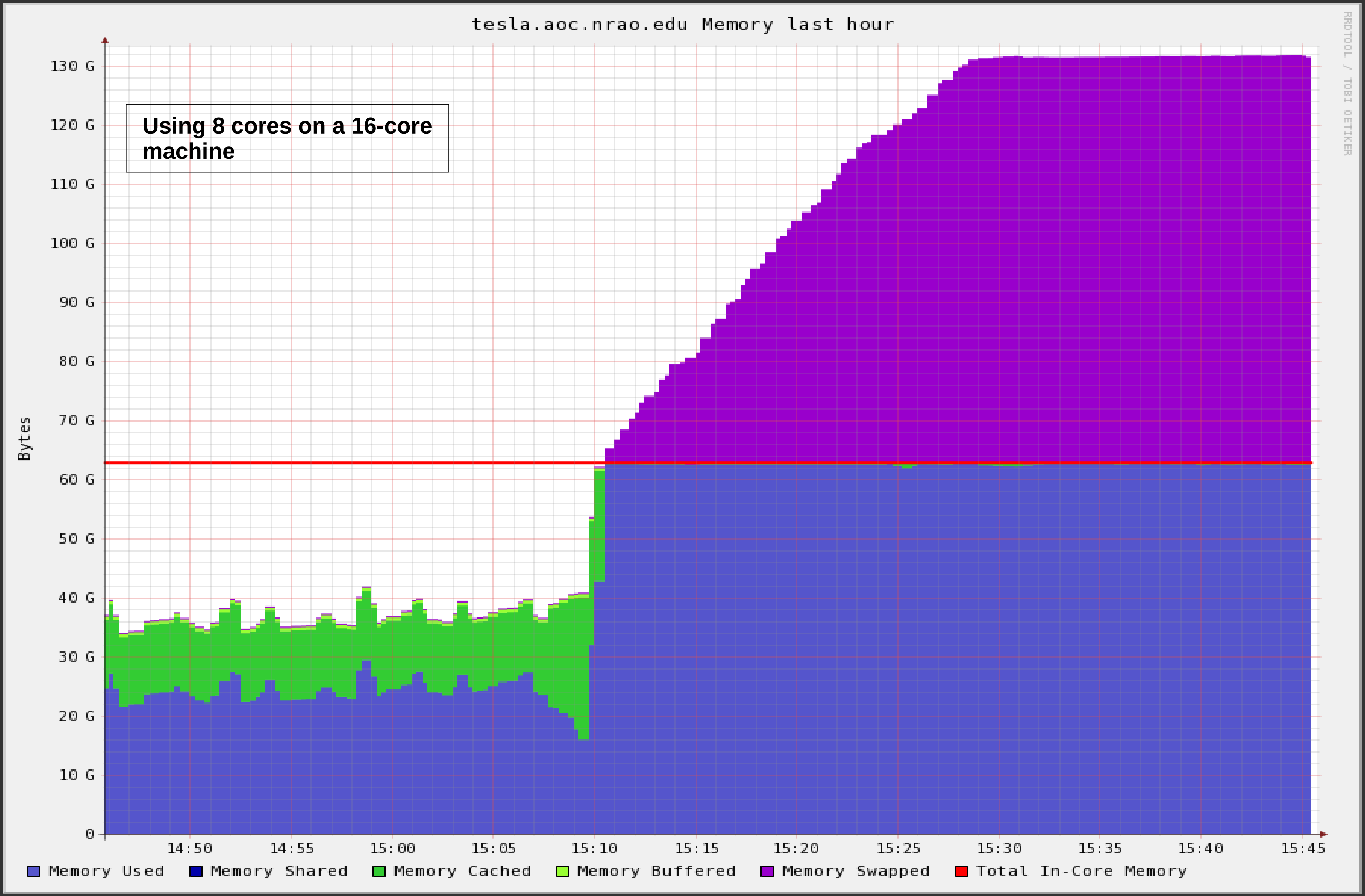
Load balance, memory footprint,...

- Load balancing necessary



Load balance, memory footprint,...

- Memory footprint for imaging limits the number of cores used



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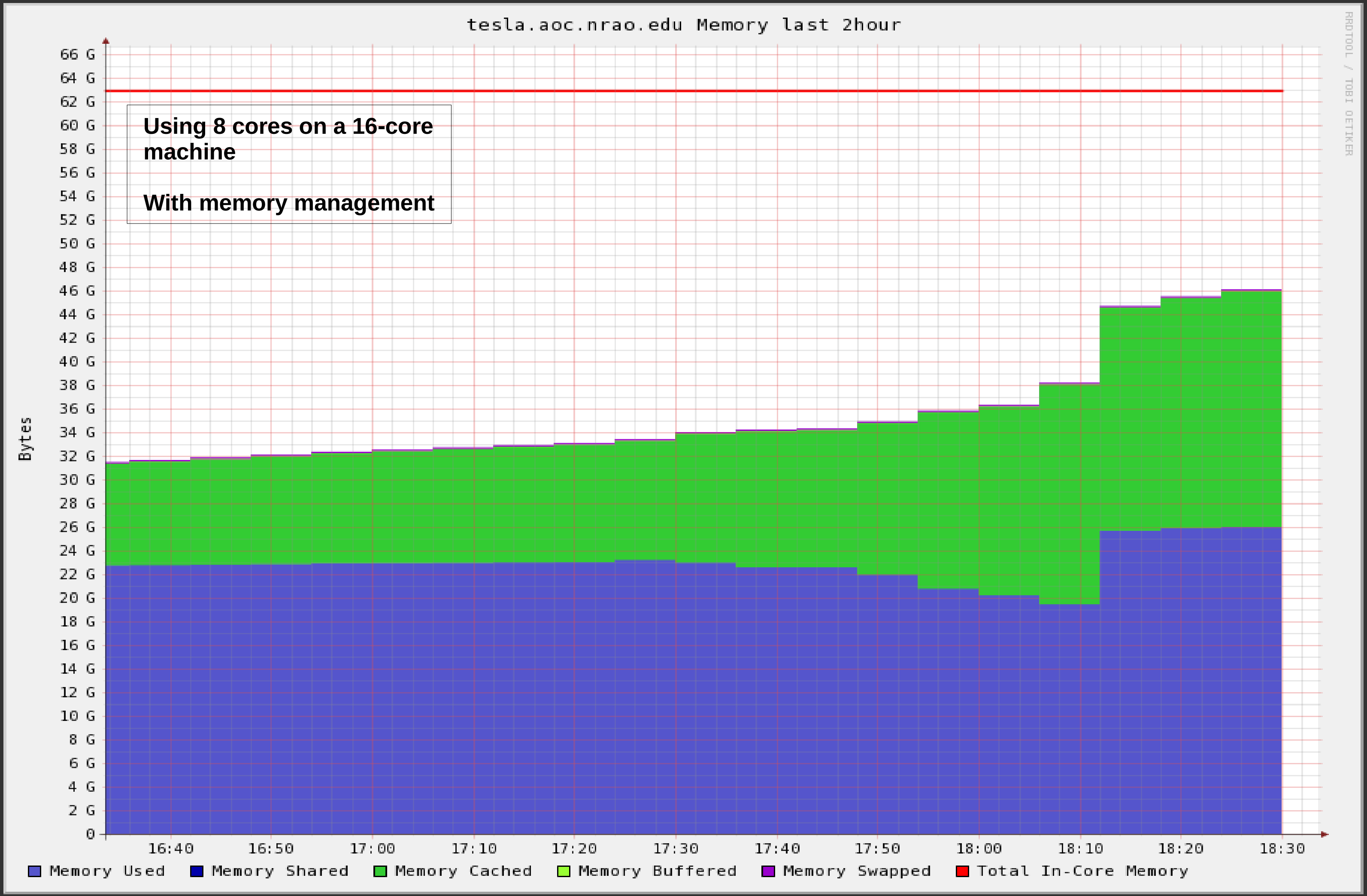
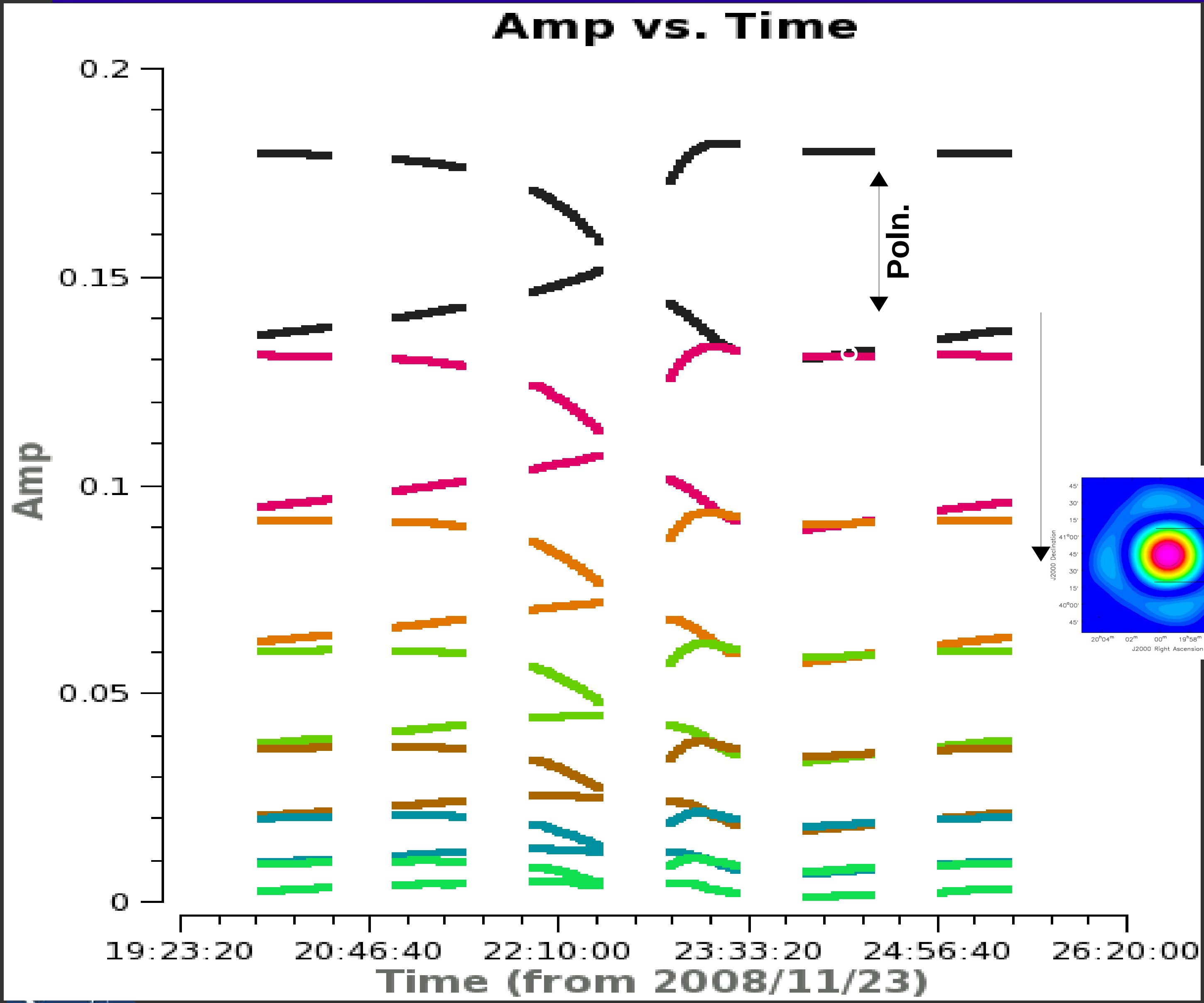
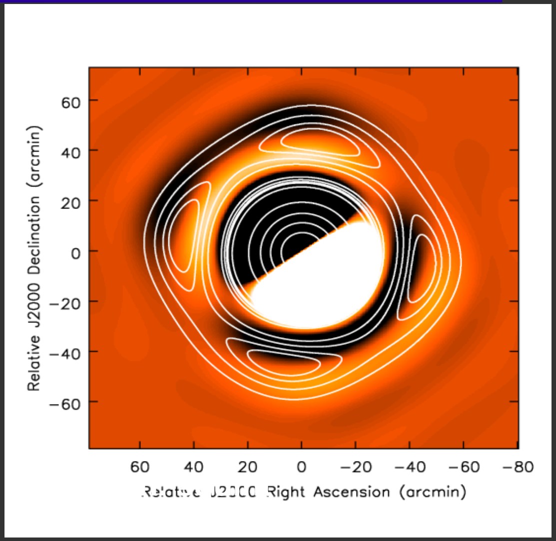
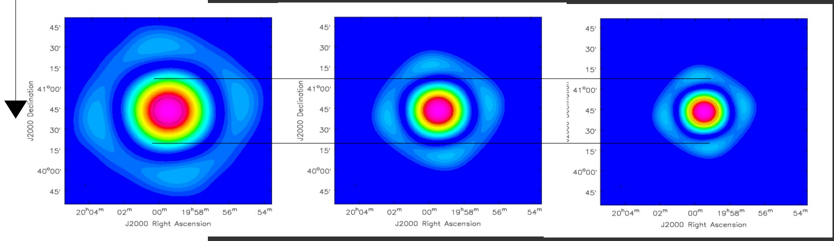


All PB effects together







Freq. scaling

DD Calibration

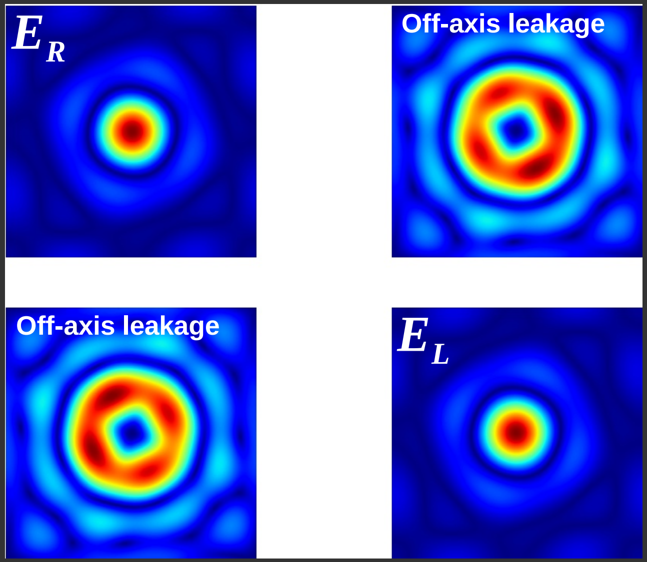
- Wide-band Full-Pol. A(W)-Projection

$$V_{ij}^{Obs} = \left[A_i \otimes A_j^T\right] * \left[V_{ij}^o\right] = \left[A_{ij}\right] * \left[V_{ij}^o\right]$$

$$V_{ij}^{Corr} = \left[A_{ij}^{M^T} * A_{ij}\right] * \left[V_{ij}^{Obs}\right]$$

- DD Jones Matrix: Each term is a complex gain pattern (a 2D function)
  - Antenna off-axis gains and polarization leakages

$$FT\left(A_i\right) =$$

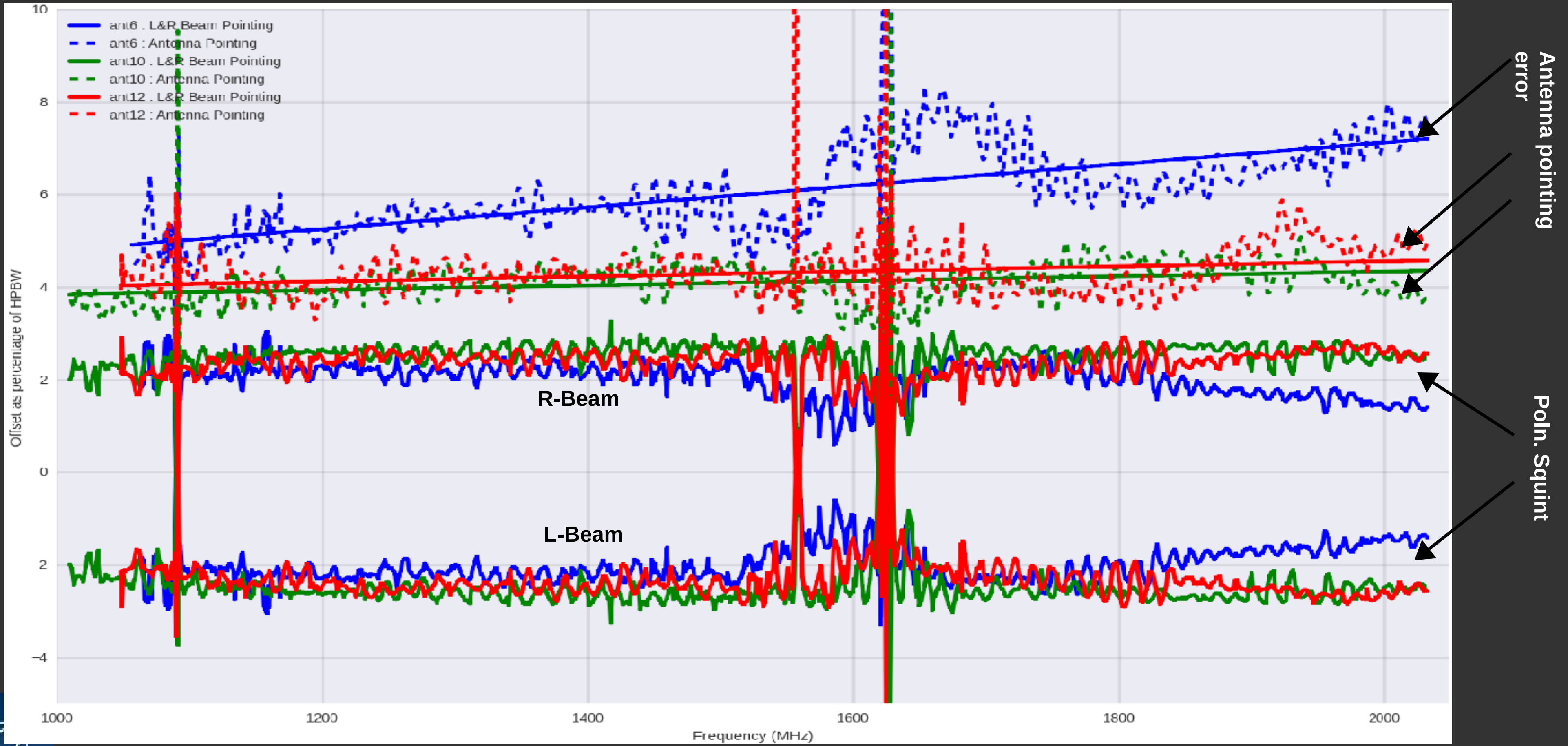


- Requires a model for the antenna aperture illumination
- Wide-band and up-to at least first sidelobe

Full-pol. Imaging: PB Effects

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

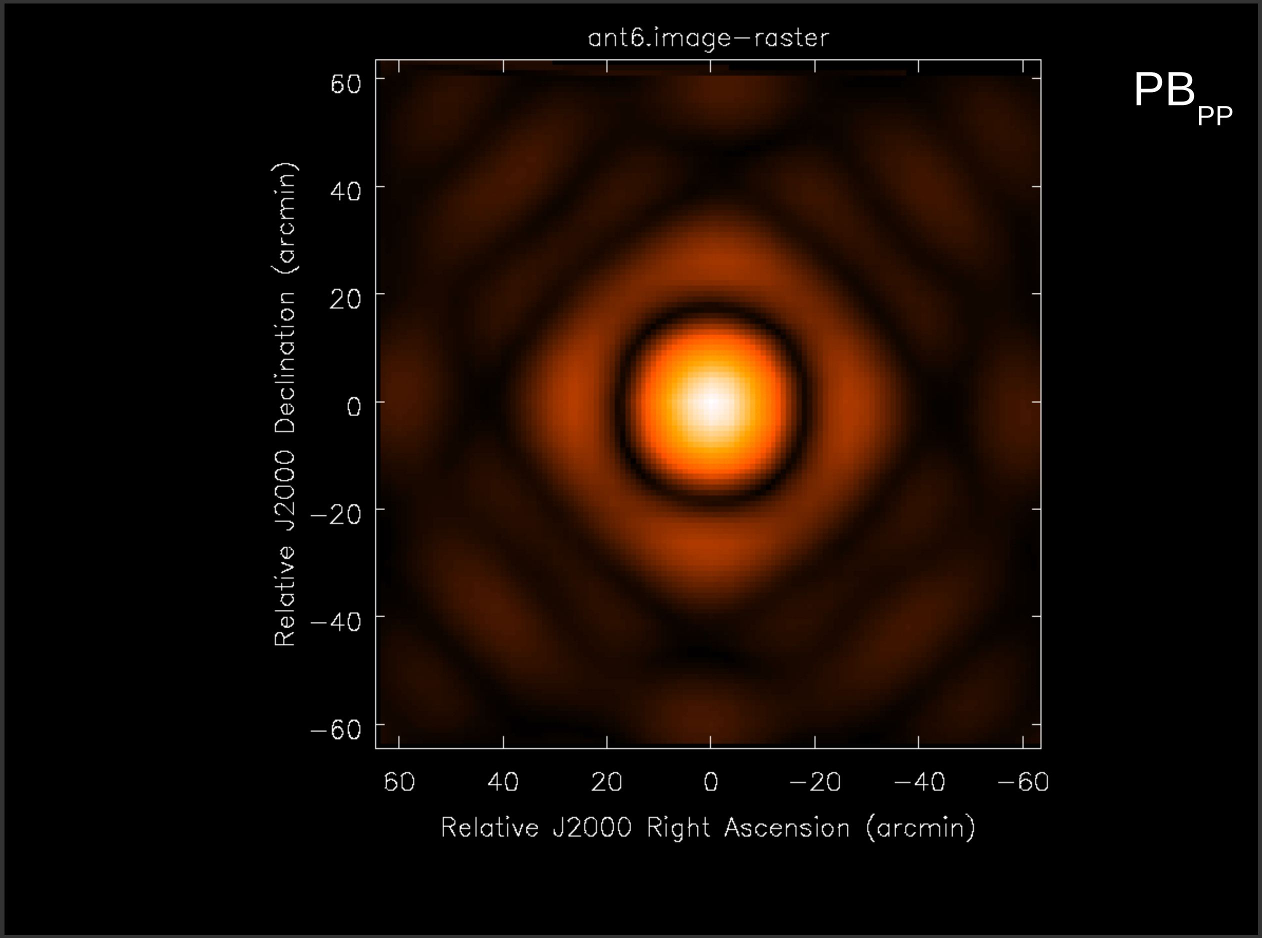
In the graph below: Optical effects should be independent of frequency (e.g. Poln. Squint)
Mechanical effects should show linear trends (e.g. Antenna pointing errors)



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

Full-pol. Imaging: PB Effects

- Needs better understanding of the aperture illumination in full pol.
  - EVLA Squint: **Expected: Lateral shift**
    Measured: Shift + Rotation



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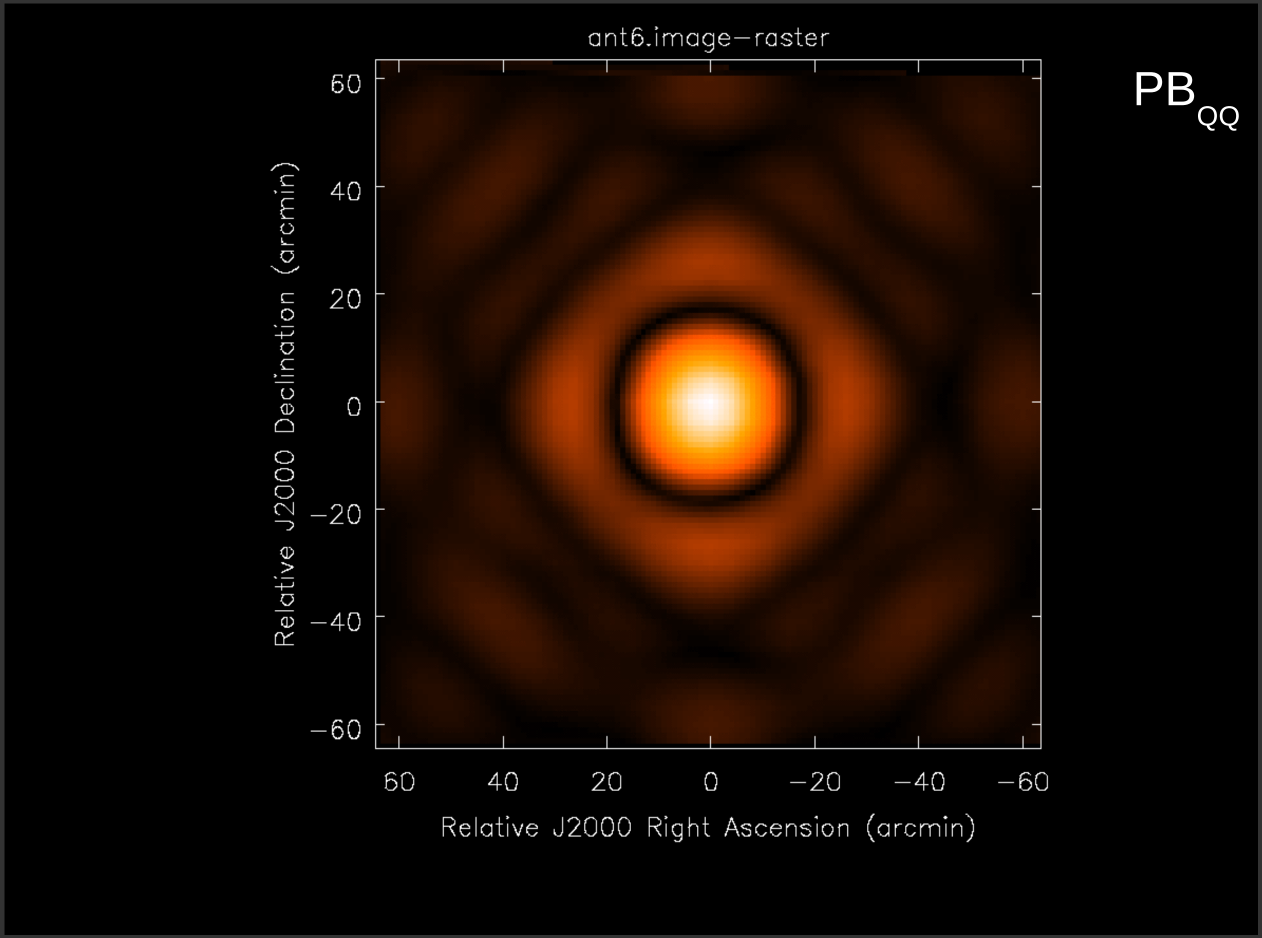
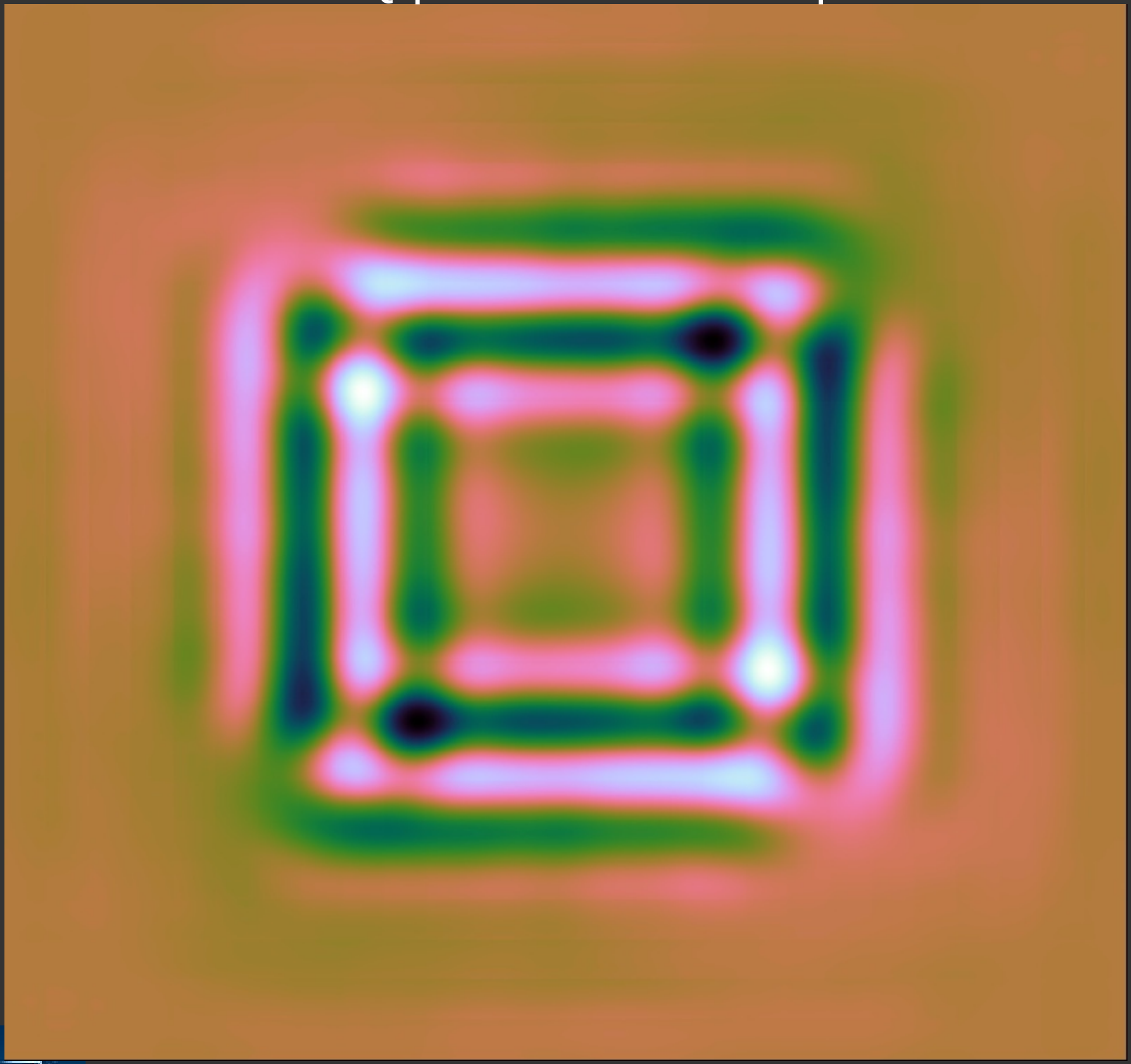


Full-pol. Imaging: Mosaic Sensitivity Pattern

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



- In-beam DD leakage spreads all across the mosaicked region.
- Rotation due to PA change ignored
- The resulting pattern is combination of overlapping Clover-leaf pattern of each pointing

[Jagannathan, Bhatnagar, Rau & Taylor]

Take away-1

- Projection algorithms are true DD generalization of DI algorithms
  - Need good models for the antenna aperture illumination patterns
  - Holographic measurements
- Computing architecture
  - Scale-able: Harder than appears in paper designs; Domain expertise crucial
  - Extensible : Needed functionality will be spread over time and people
  - Configurable: Watch out for the curse of Amdahl’s Law; resource balancing
  - Capable of utilizing heterogeneous platforms
- Develop human resource: People with multidisciplinary skills, without mental-block for simple math., rigor, tenacity
  - Capable of enjoying all of the above!

Take away-2

- WB A(W)-Projection + MT-MFS in CASA under commissioning
- Architecture allows use of beam models, full/partial-Mueller matrix, heterogeneous arrays (not tested yet), mosaic imaging and correction for pointing errors (not tested).

- Errors due to DD leakage can be 100% for Q- and U-images
- Work in advanced stage for testing Mueller imaging with WB EVLA data (Preshanth's thesis)

- HPC completely integrated with all of the above
  - Parallel CF computation, imaging, memory management
  - Measured to be close to linear scaling

- Full-pol corrections even more important for mosaic imaging