Wide-band Mosaic Imaging

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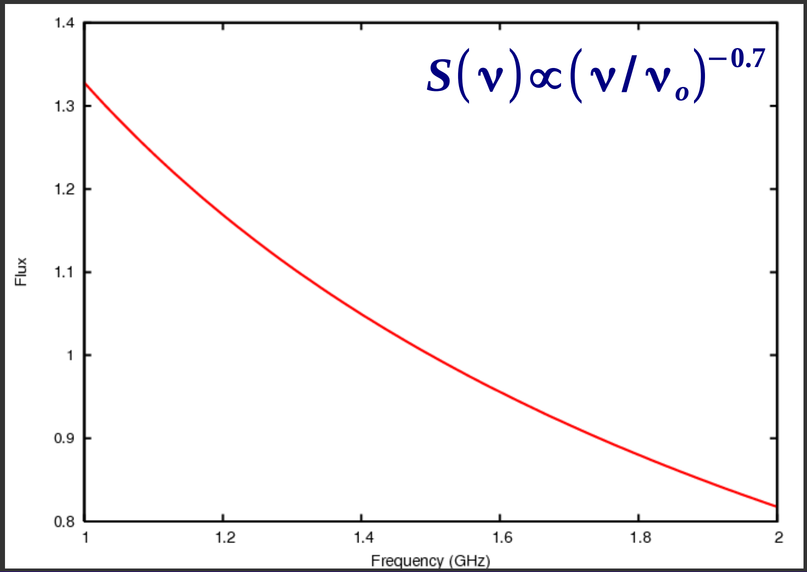
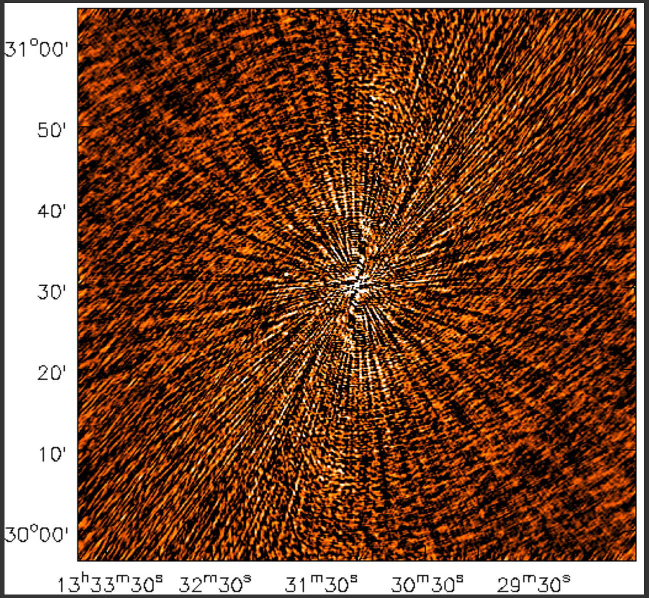
When are wide-band effects important?

- Fractional signal bandwidth used for imaging > ~20%
  - Plus source spectral index >= -1.0
  - Plus target dynamic range > 1000

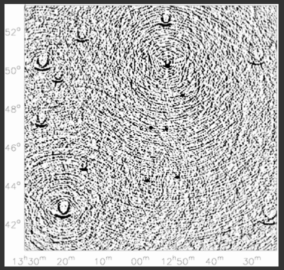
- Spectral effects for higher source spectral index will become significant at lower bandwidth ratios
  - Empirical Dynamic range : $\frac{I\alpha}{100}$
  - Spectral line imaging, by definition, does not require wide-band imaging algorithms





What is wide-field?

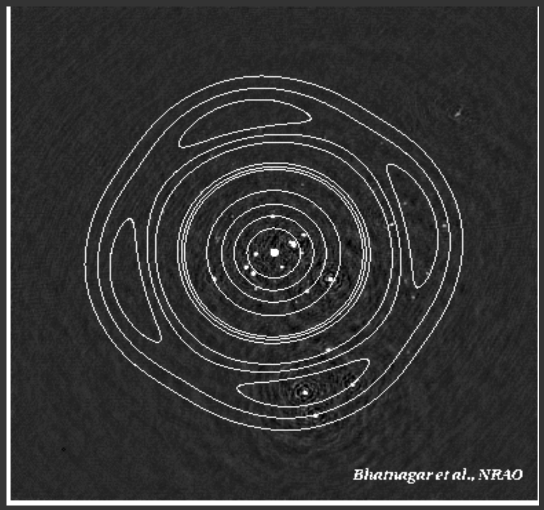
- Imaging that requires invoking any of the following:



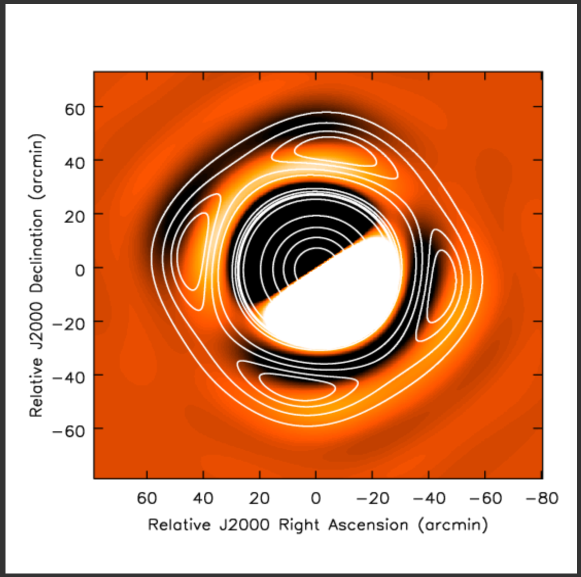
  - Corrections for non co-planar baseline effects $\frac{\lambda}{B_{max}} \leq \theta_f^2$
  - Corrections for the effects of the anntea PB
    - Full FoV imaging, mosaicking
    - Full-pol imaging (Jagannathan's talk next)
  - Corrections for the frequency or polarization dependent effects away from the pointing/image center

- Noise limited imaging of structure comparable to the PB beam-width
- Mosaicking: imaging on scales larger than the PB beam-width

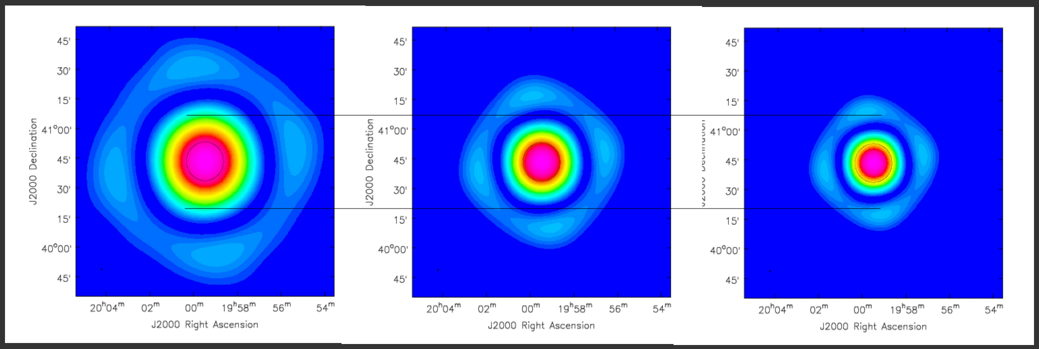
Wide-field Imaging and PB Effects



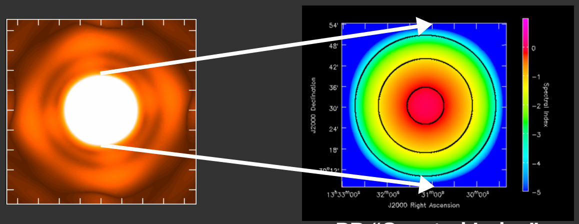
Time dependence



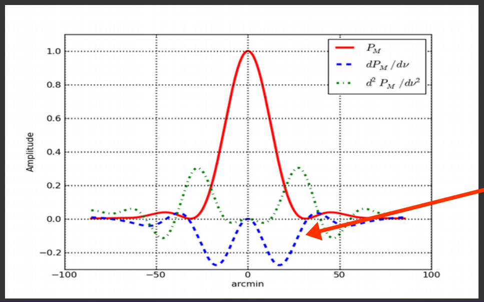
Polarization dependence



Frequency dependence

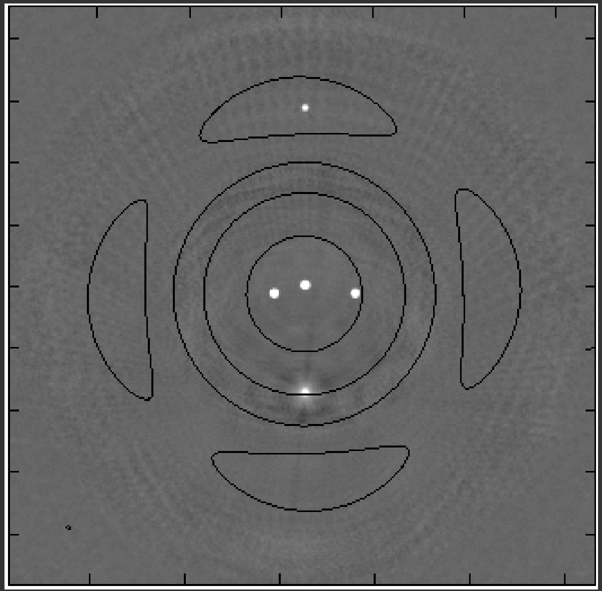


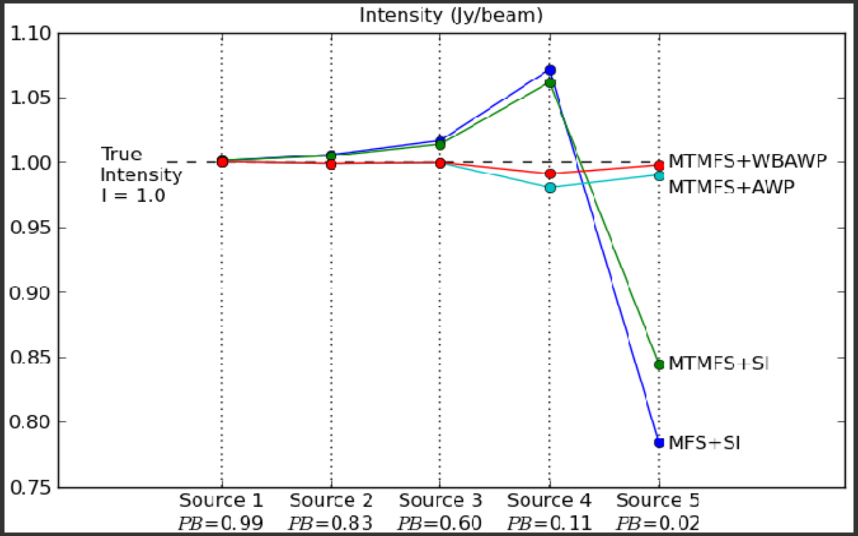
PB “Spectral Index”

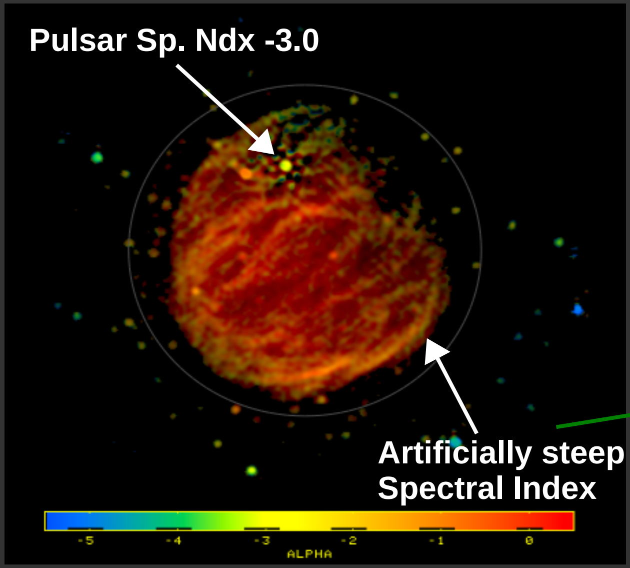


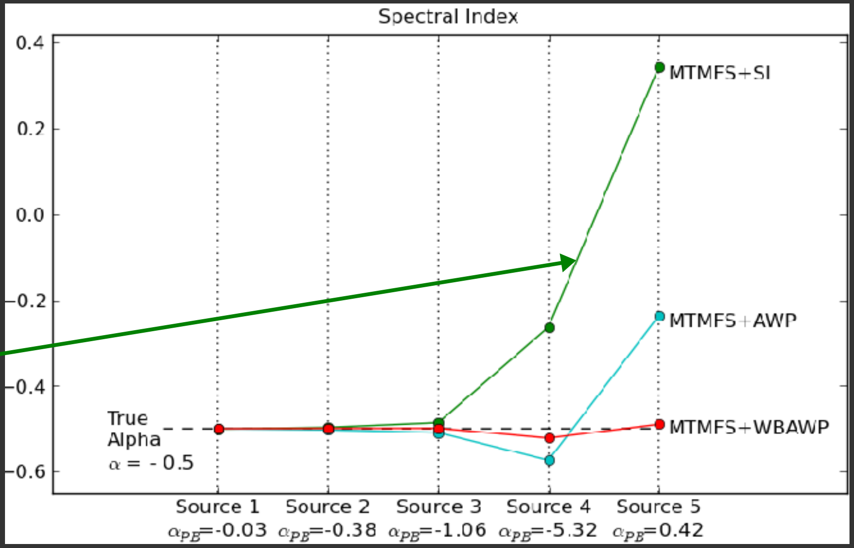
PB Frequency dependence (blue curve)

Instrumental frequency dependence





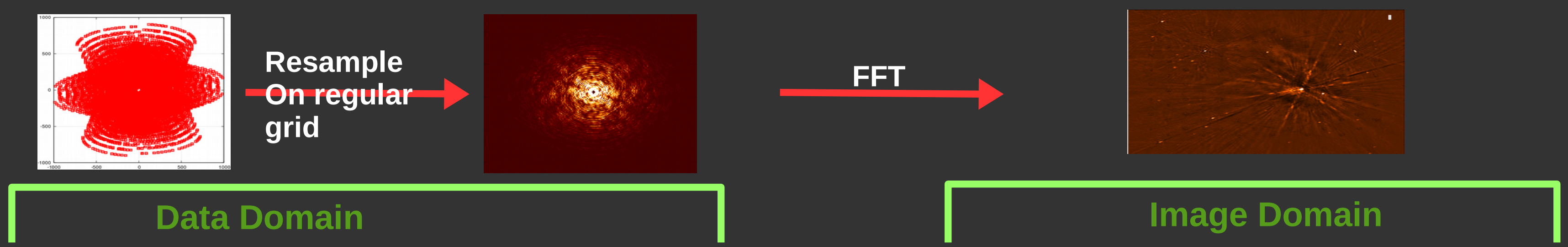




NRAO

Imaging & Deconvolution: A recap

- Imaging: Transform data to image domain



- *Imaging* is linear

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

  - Removing the effects of the PB cannot be separated from imaging
  - DD corrections are simpler in this linear part of the processing
  - Fastest varying term on the RHS determins the averaging scales in time and frequency

Mosaic Imaging Equation

- Image *reconstruction* is non-linear
  - a.k.a. “Image Deconvolution”
- Properly account for the Sky and Instrumental Frequency dependence, DD instrumental time and polarization dependencies.

Data transformed to image (a linear operation)

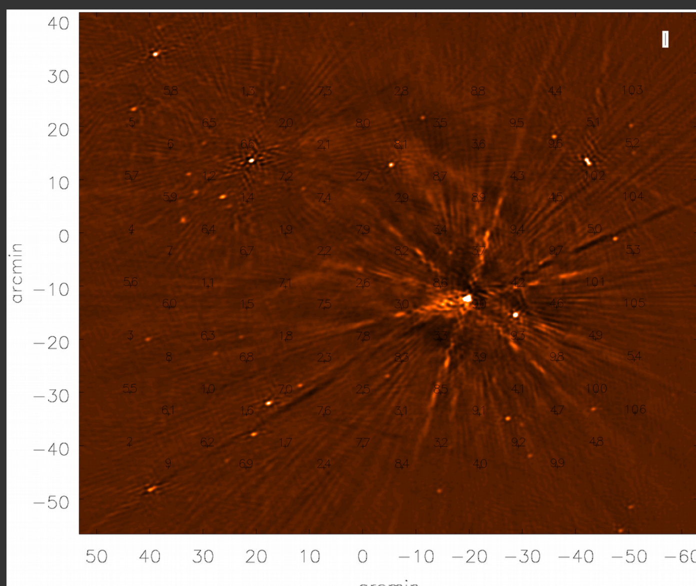
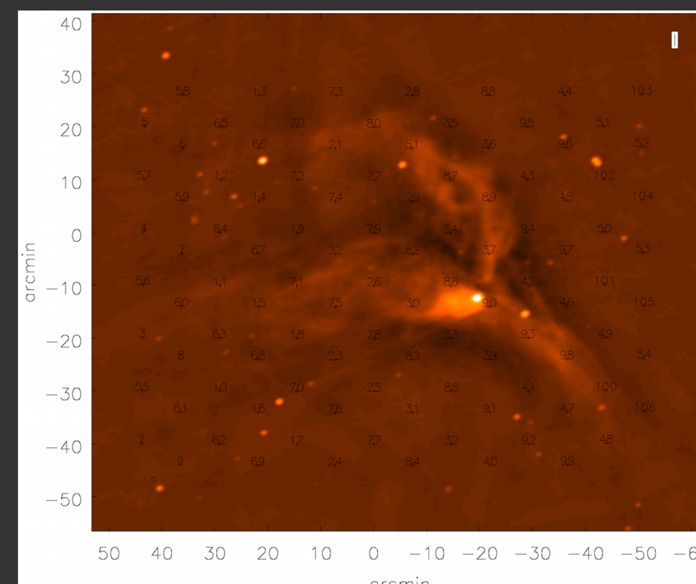
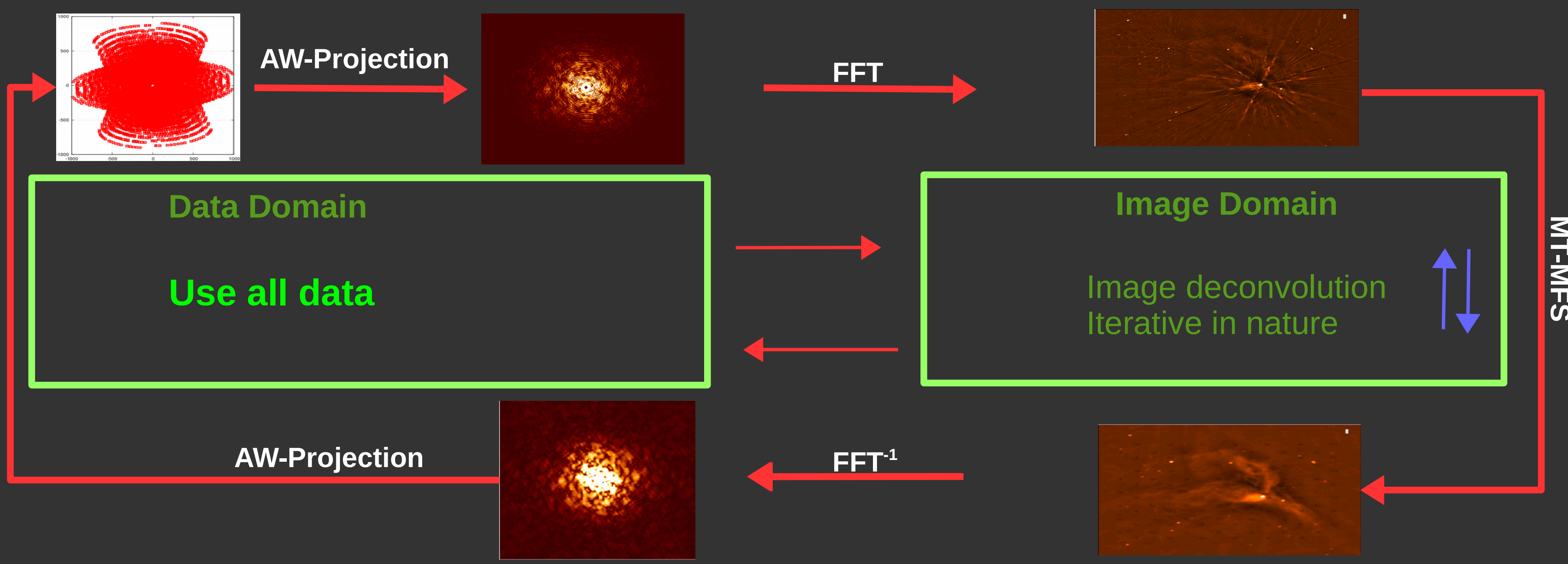


Image reconstrction (a non-linear operation)



Imaging & Deconvolution: A recap

- Reconstruction WB sky image: a.k.a. “Deconvolution’ in RA.

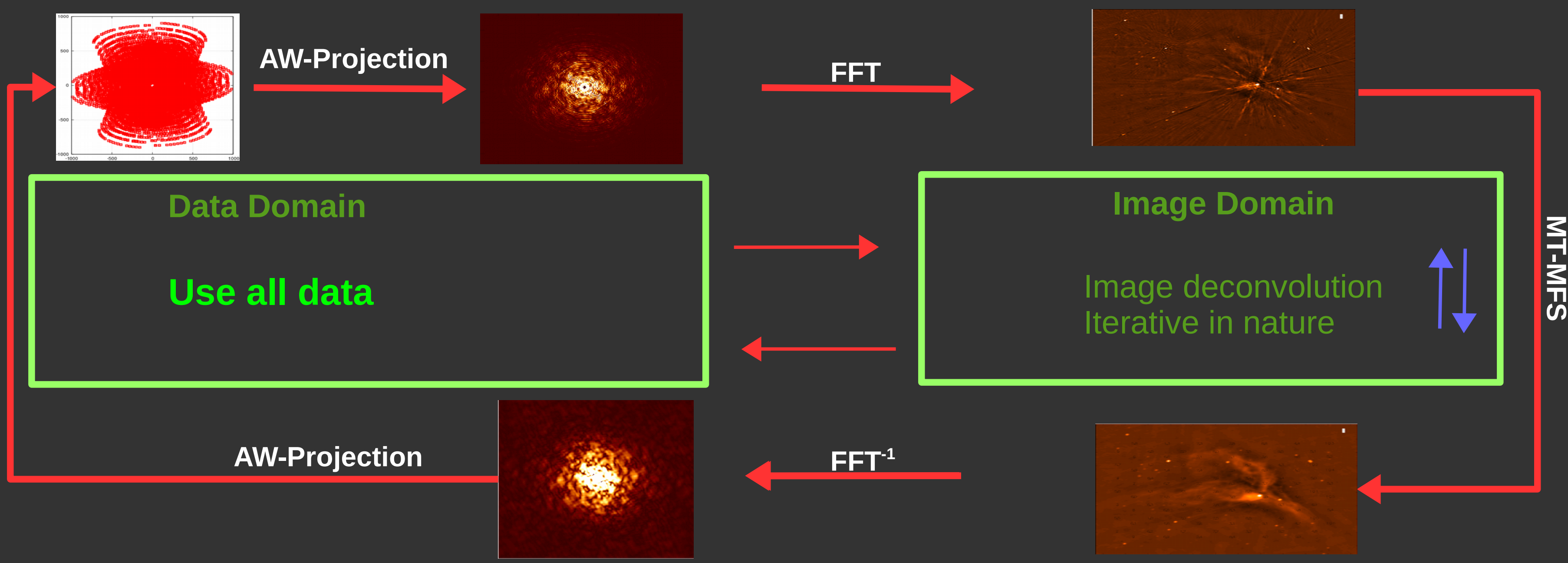


WB AW-Projection:
Make image free of PB- W-term effects

MT-MFS:
Images corrected for instrumental effects
Reconstruct WB sky model

Imaging & Deconvolution: A recap

- Reconstruction WB sky image: a.k.a. “Deconvolution’ in RA.



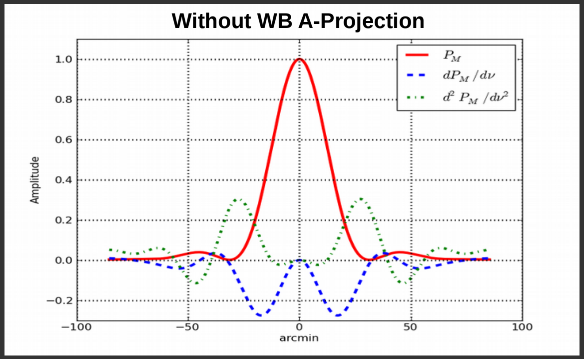
WB AW-Projection:
Make image free of PB- W-term effects

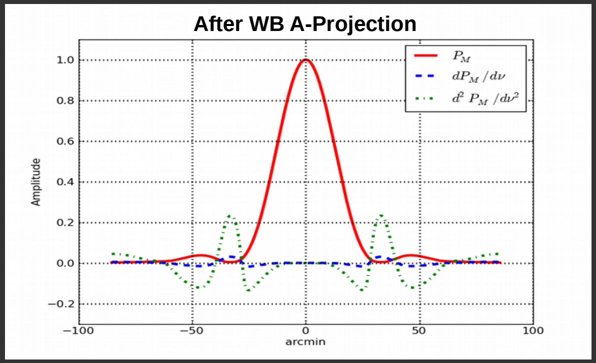
MT-MFS:
Images corrected for instrumental effects
Reconstruct WB sky model

- **Project-out PB effects before transforming to the image domain**
- **Image domain algorithms then need to model only the (WB) sky emission**

Wide-band Wide-field Imaging

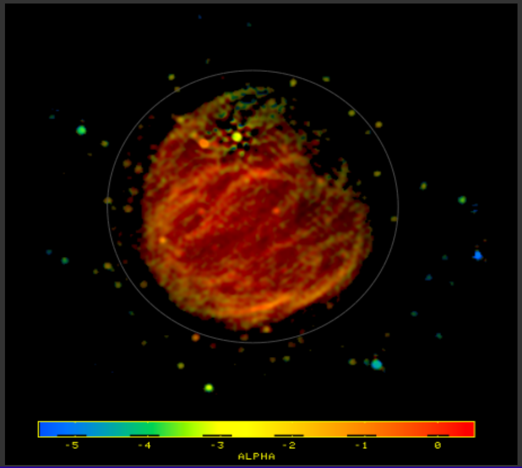
- WB A-Projection + MT-MFS
  - WB A-Projection for PB



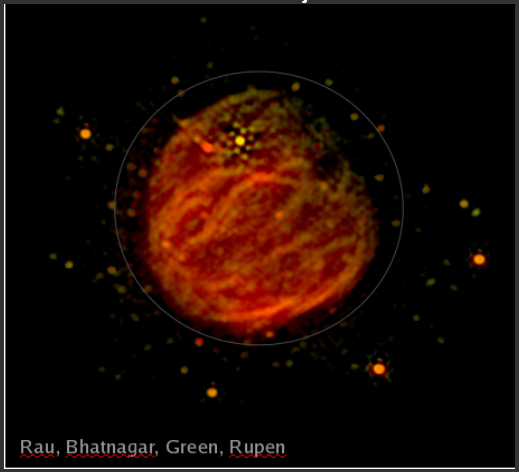


  - MT-MFS for sky
    - **Without PB correction the reconstructed spectral index increases with distance from the center**

Without WB PB Correction



With WB A-Projection



Wide-band Mosaic Imaging

- Instrumental effects
  - Observing mode: On-the-fly vs Point-n-shoot
  - Pointing Errors
  - Effects of w-term per pointing
  - Parametric Aperture Illumination model (Holographic measurements not sufficient)
  - In-beam effects : DD Leakage (Next talk)
- Variations with frequency
  - Frequency dependence due to PB
  - Frequency dependence of intrinsic Q and U (Next talk)
- Computing load: Easily parallelized, but…
  - Fundamentally more expensive
  - Larger memory footprint, any which way you cut it

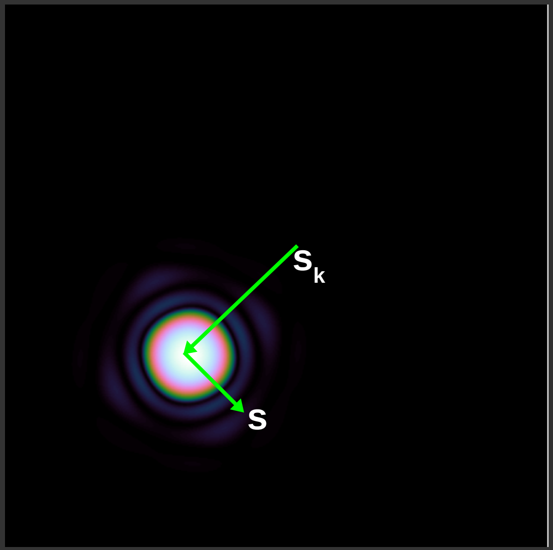
Mosaic Imaging Equation

- *Imaging* is linear

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

- *Mosaic imaging* is also linear

$$I^{Mos}(s)=\sum_k I(s+s_k,\nu,t)$$

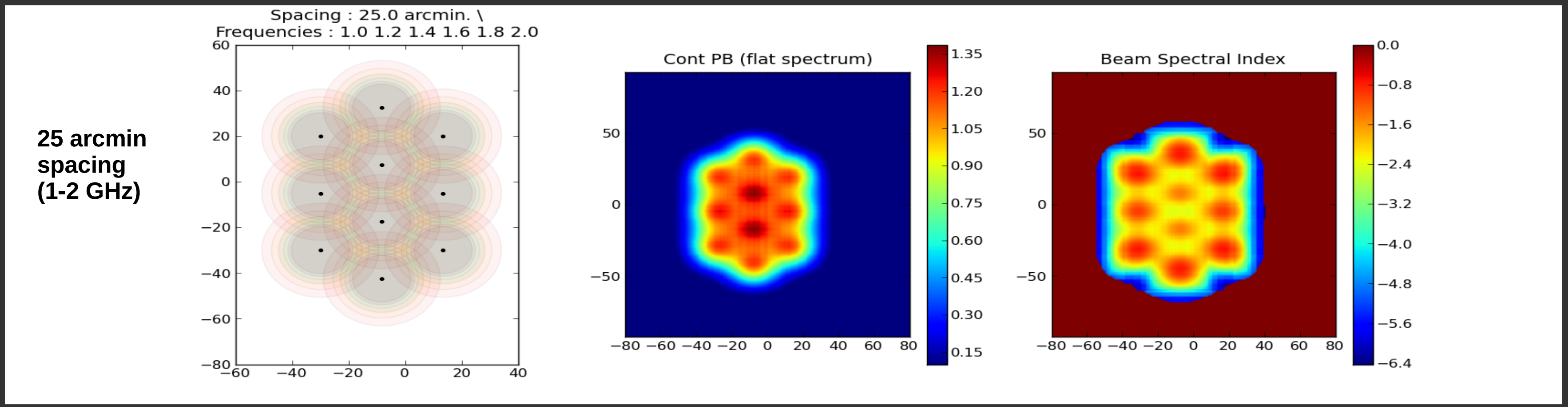


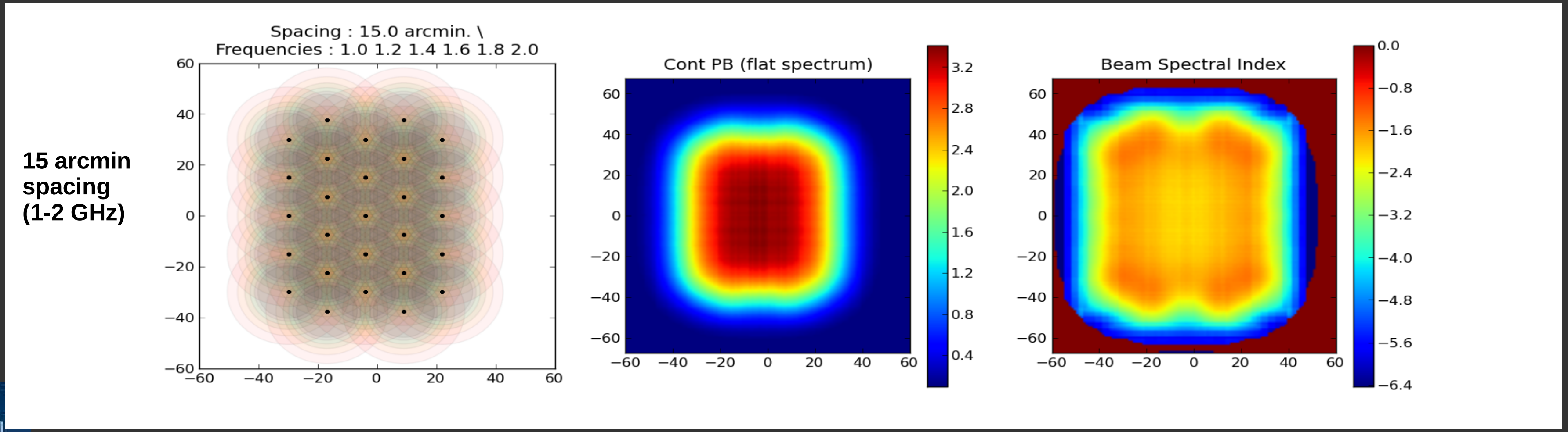
- Joint mosaic imaging
  - Linear addition of data from multiple pointings/phase centers, followed by Fourier Transform
  - Mosaic imaging is just the Shift Theoram of FT!

Mosaic Imaging and PB Effects

For single pointings, the wideband PB spectrum is relevant only away from the pointing center.

For mosaics, the wideband PB spectrum must be accounted-for <u>all over the mosaic field of view</u>





Rau & Bhatnagar (in prep.)

WB Mosaicking with the EVLA

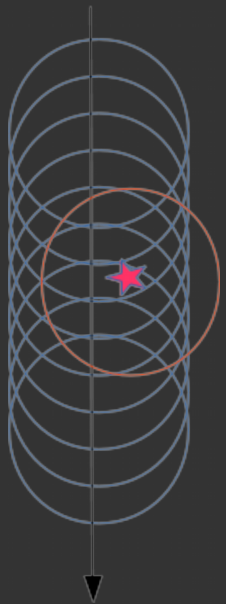
- VLASS as an example of OTF (Kimball's more detailed talk later)
  - Continuum imaging in the 2 – 4 GHz band (fractional BW ~67%)
  - Imaging 1 x 1 sq deg at a time using 40 pointings
  - OTF: Continuous antenna motion: 3.31 arcmin/sec, 0.45 sec integration per pointing
  - Quantized correlator phase-center change
  - ~100 uJy/b noise limit
  - Resolution: ~2 arcsec

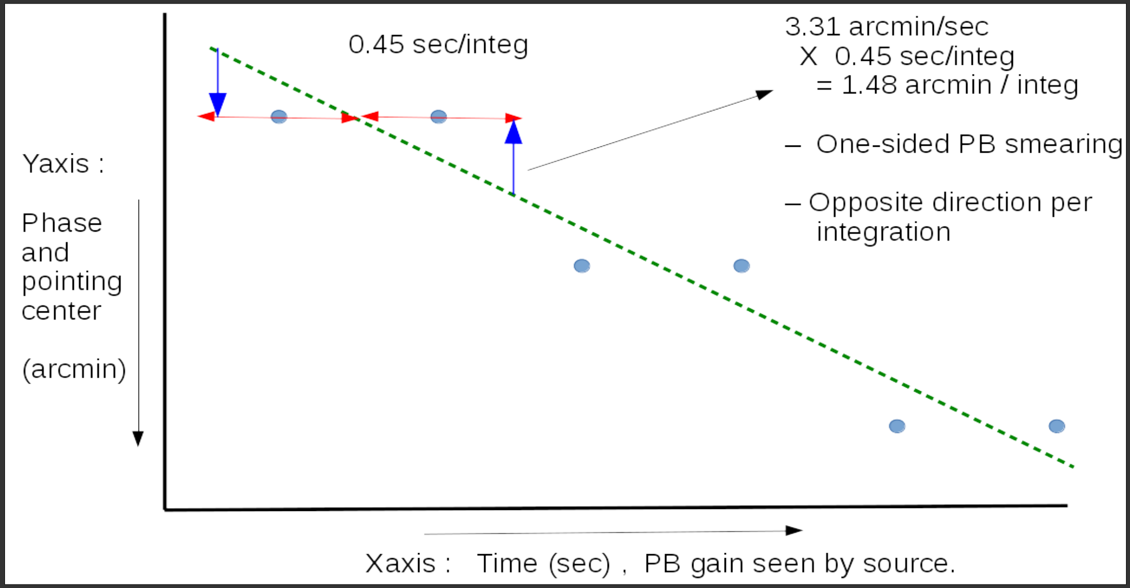
- Primary continuum scientific products
  - Source positions, flux, spectral indices, images

- Image size:
  - Wide-band sensitivity pattern about 2x2 sq deg.
  - 5400 pixels on a side (desired: 12K pixels on a side)

- Imaging
  - MT-MFS for image reconstruction
  - Algorithms for imaging still being evaluted
    - » Attempt to match-up actual computing cost with the original estimates

WB Mosaicking with the EVLA

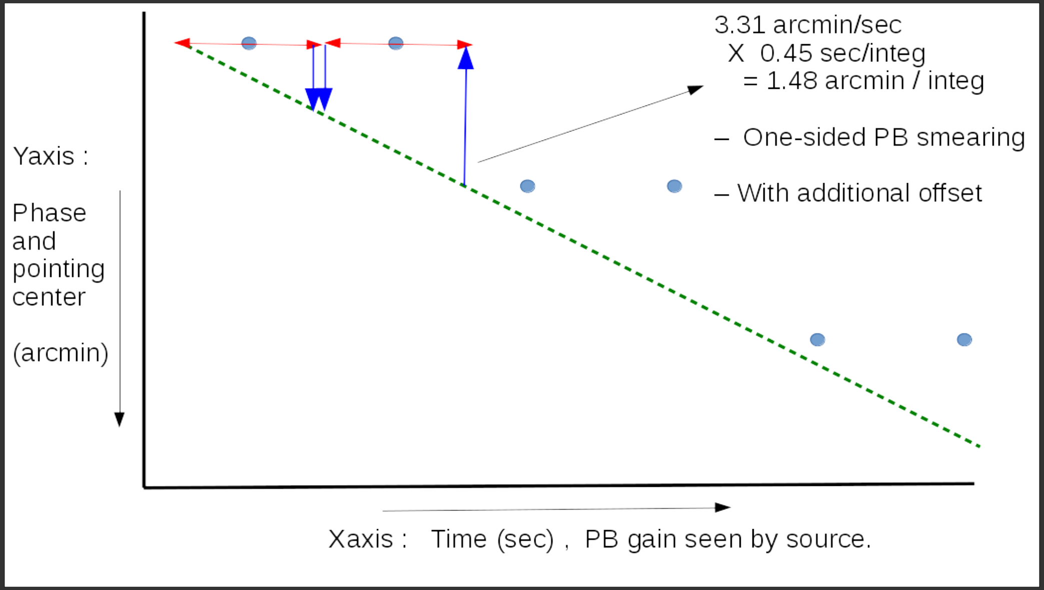


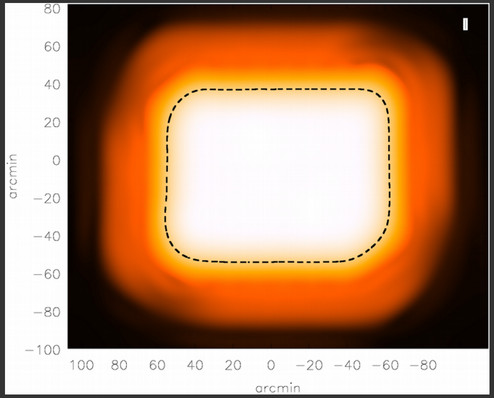


- Error in fluxes, positions and spectral indices were larger than the specification with the imaging setup used:
  - No W-correction: To reduce computing load, memory footprint
  - Narrow-band A-Projection: Minimize computing load and s/w complexity
  - Ignore the effects of WB PB sidelobe(s) : Use standard setup
  - Ignore pointing offsets : No s/w support/was expected to “average out”

WB Mosaicking with the EVLA

- Error in the reconstructed flux was dominated by errors in source positioning in the PB (pointing errors) and on the sky (W-term)
  - Pointing errors due to OTF mode + a software bug
  - Gain errors: PB sidelobe span ~2x antenna FoV



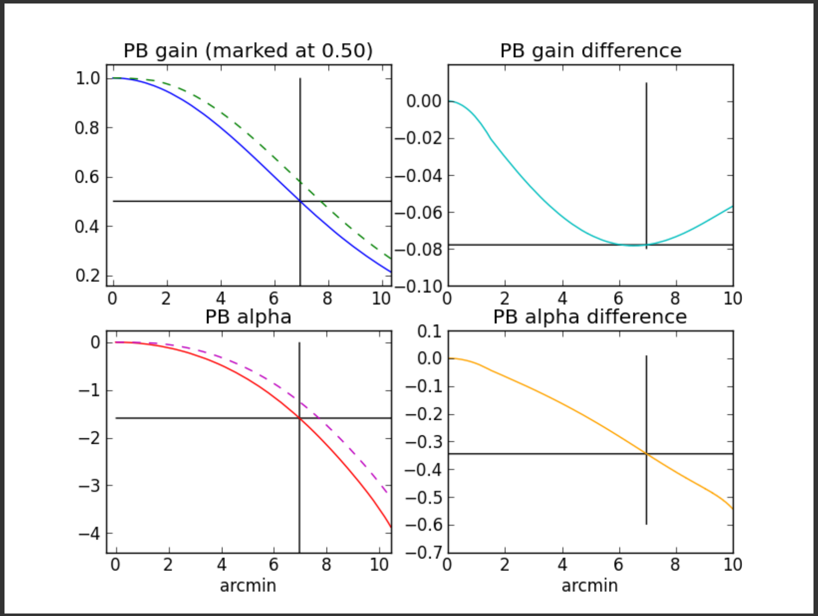


- Each pointing is a snapshot observation. W-term leads to radially-dependent source position offsets.
  - Actual position offset in a joint mosaic image is more complicated

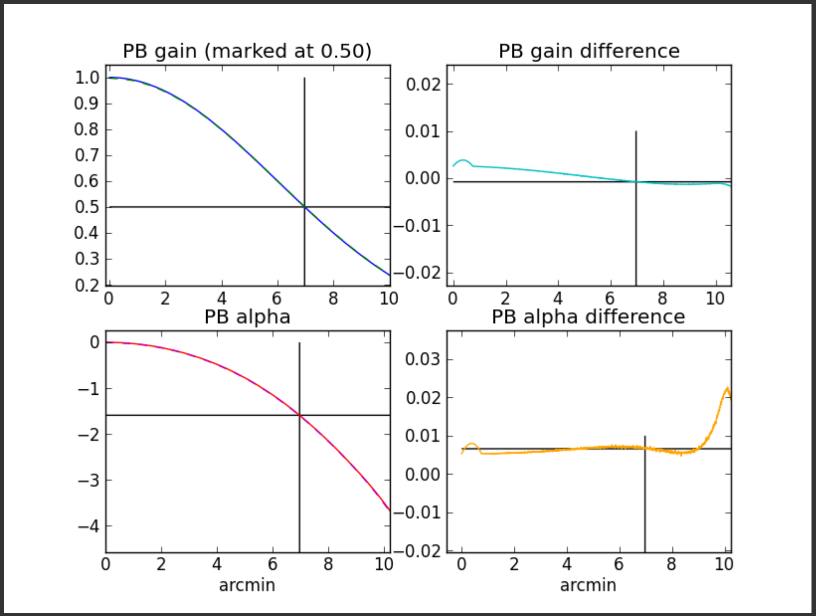
WB Mosaicking with the EVLA

- Effects of pointing errors and w-term do not in general "average out"
  - Source positioned in different parts of the PB of overlapping pointings
- Spectral index is extra sensitive to pointing and source position offsets
  - Systematic error of >100% or large error bars

Actual data



Intended data



- Computing load *10-100x* larger

Lessons learned for now

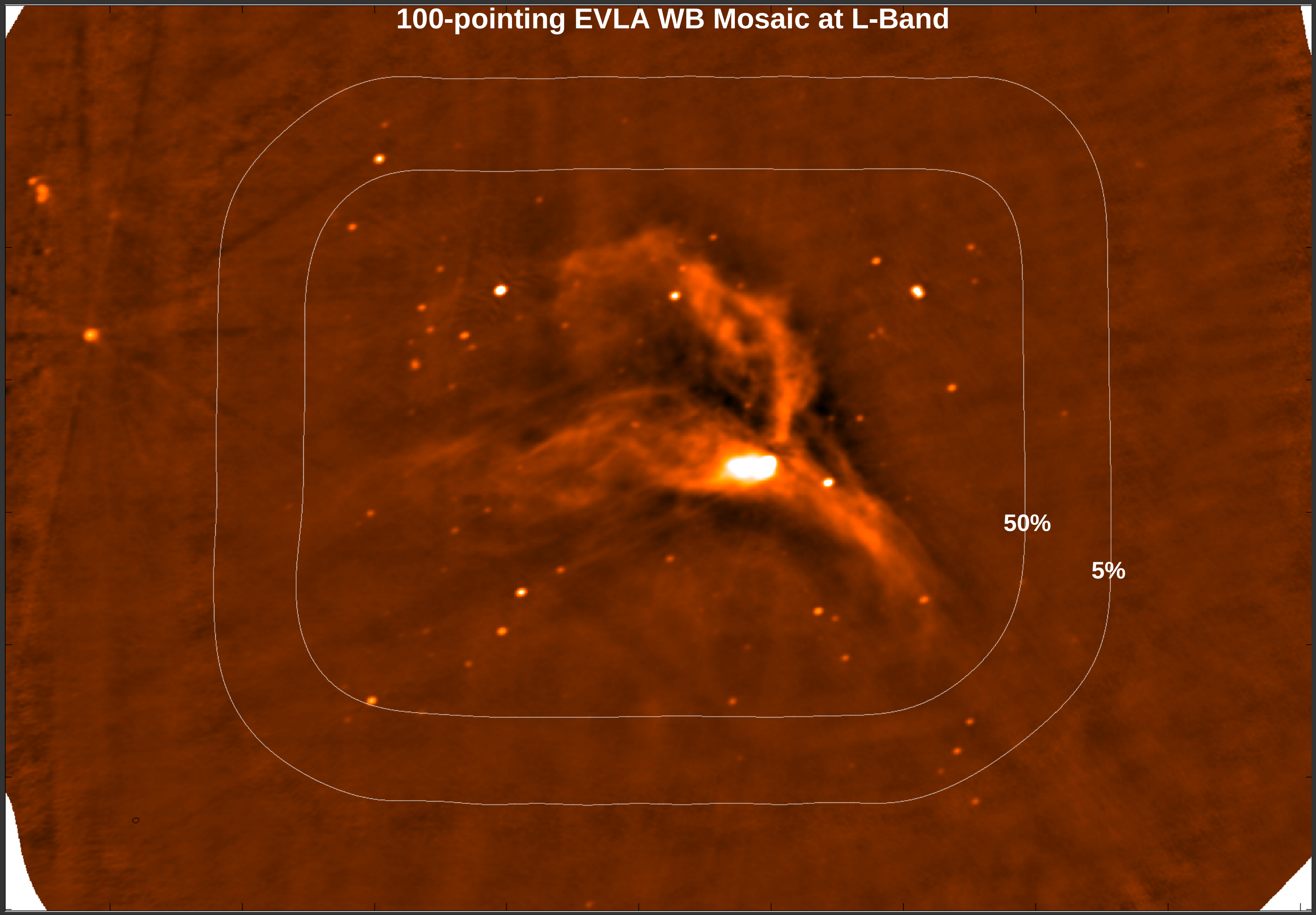
- Projecting-out DD effects in the linear parts of the processing is important
  - E.g. WB A-Projection to remove PB effects
- Not everything undesirable "averages-out"
  - Systematic effects do not average-out (WB-effects, W-term, pointing offsets,...)
- Computing load for pointing corrections during imaging is significant
  - Fractional pointing offsets of ~10% lead to significant error in imaging at 100 uJy/b noise limit.
  - Noise limit of ngVLA with a similar observing setup would be 10x lower.
  - Significant impact on computing budget to reach science goals
- WB imaging needs up to 2x larger image sizes
  - Significant impact on memory footprint
  - Can impact parallelization breath, increase computing costs

Lessons learned for the future

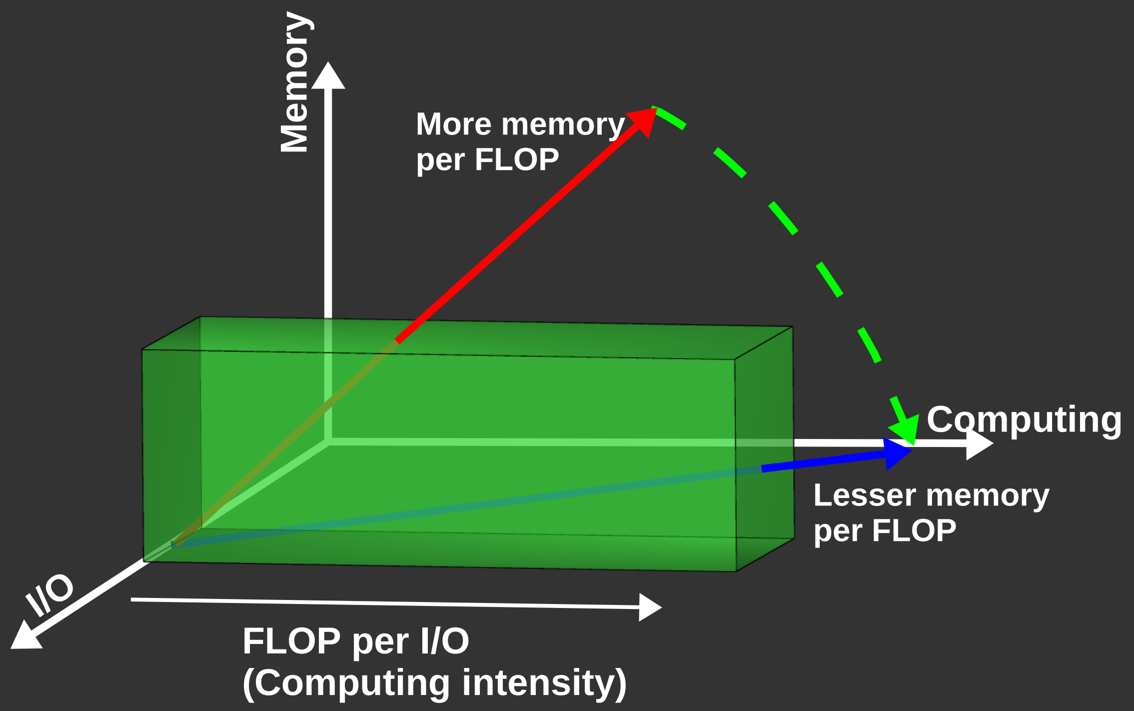
- Re-evaluate Point-n-shoot vs OTF in an End-to-end sense
  - Accurate knowledge of antenna pointing is critical
  - Beam smearing can limit scientific goals or make them unaffordable
  - Faster antenna positioning (slew + settle-down)
  - More agile real-time correlator system
- There is no “sampling theorem” dictating pointing separation <HPBW/2
  - Target SNR goals dictates pointing pattern
- Ignoring known effects in the data can lead to unexpected errors
  - E.g. w-terrm affects spectral index in WB imaging!
- Corrections in post-processing can have unexpectedly high cost
  - W-correction can be up to 50x more expensive
  - Pointing corrections can lead to 2x extra cost!
- Fractional pointing errors of a few% may be very significant for ngTelescopes
- Finally, when in doubt, follow the Physics of observations and Math of the algorithms!

Point-n-shoot mosaic

- WB sensitivity pattern 4x larger than the target area
- Parallel imaging: near linear scaling up to 200 cores



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