Real-Time Radio Imaging with the E-Field Parallel Imaging Correlator (EPIC)

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EPIC Collaboration

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- Greg Taylor - University of New Mexico
- Adam Beardsley - Arizona State University
- Judd Bowman - Arizona State University
- Nithyanandan Thyagarajan - National Radio Astronomy Observatory

Overview

- Radio Interferometry and Direct Imaging
- First Light on the Long Wavelength Array
- Calibration
- Wide Field Imaging

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Interferometric Imaging Primer

- Radio source on the sky causes a complex wavefront incident on two antennas.
- Fourier transform of the voltage antenna, then multiply together.
- Gives measure of the spatial coherence function by cross-correlation. This is a “Visibility”.
- Each pair of antennas is a baseline.
- A fourier relationship between the spatial coherence measurement and the sky intensity exists: “Van Cittert-Zernike Theorem”.

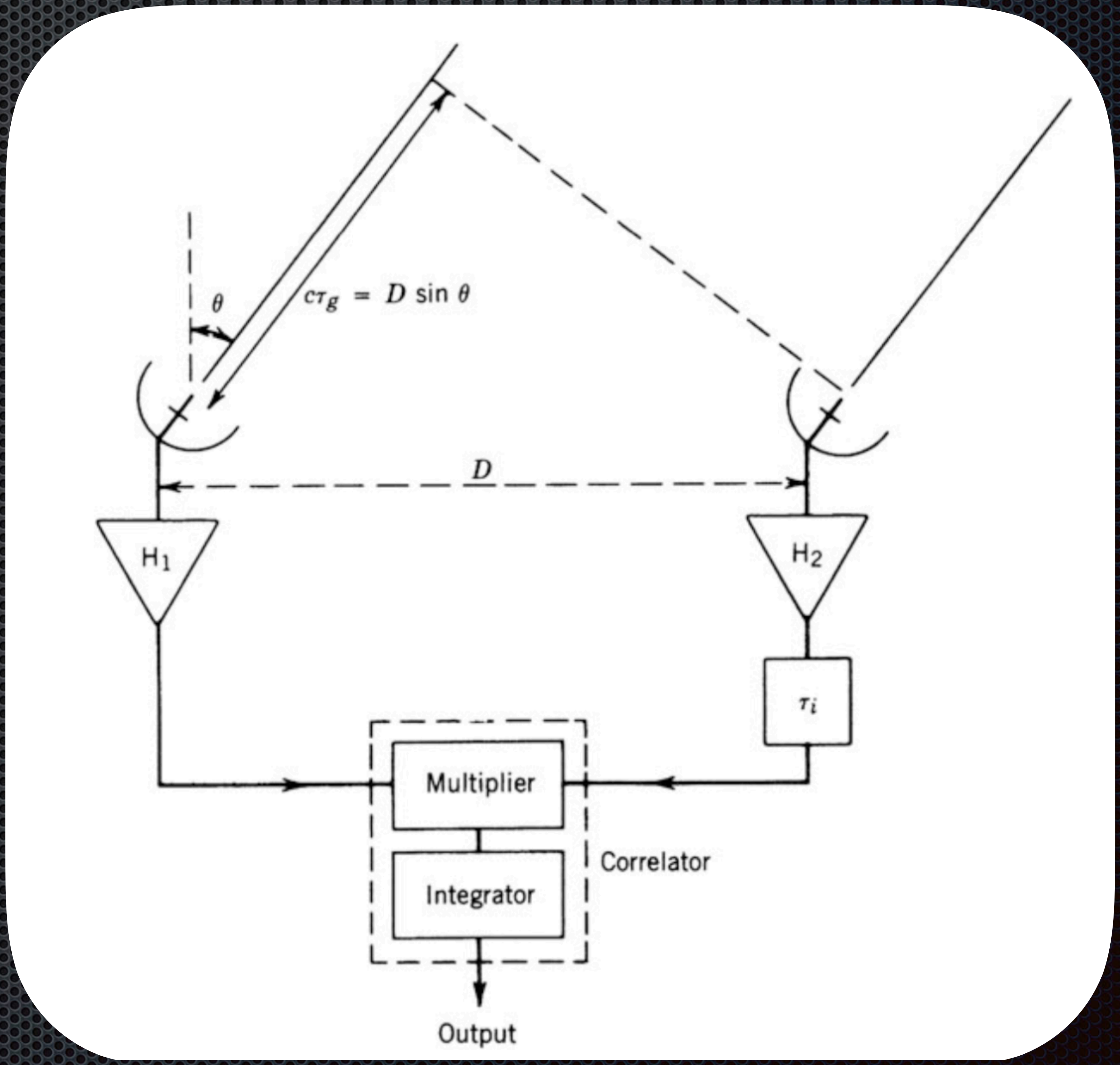


Image: Thompson, Moran, Swenson

Direct Imaging

- Doesn't cross-correlate through multiplication.
- Directly images by fourier transforming the electric fields measured by each antenna.
- Closely related to beamforming.

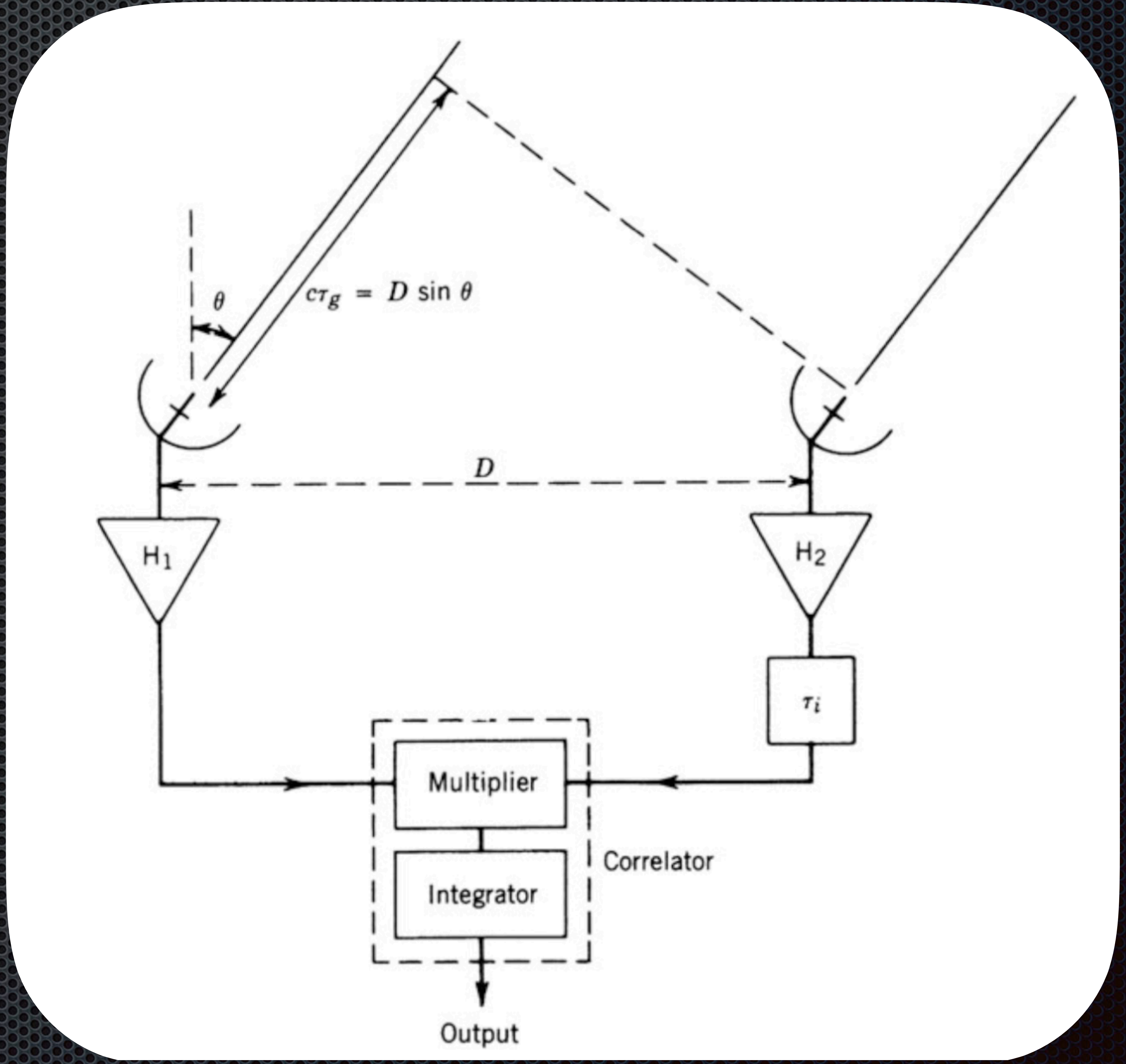


Image: Thompson, Moran, Swenson

History of Direct Imaging

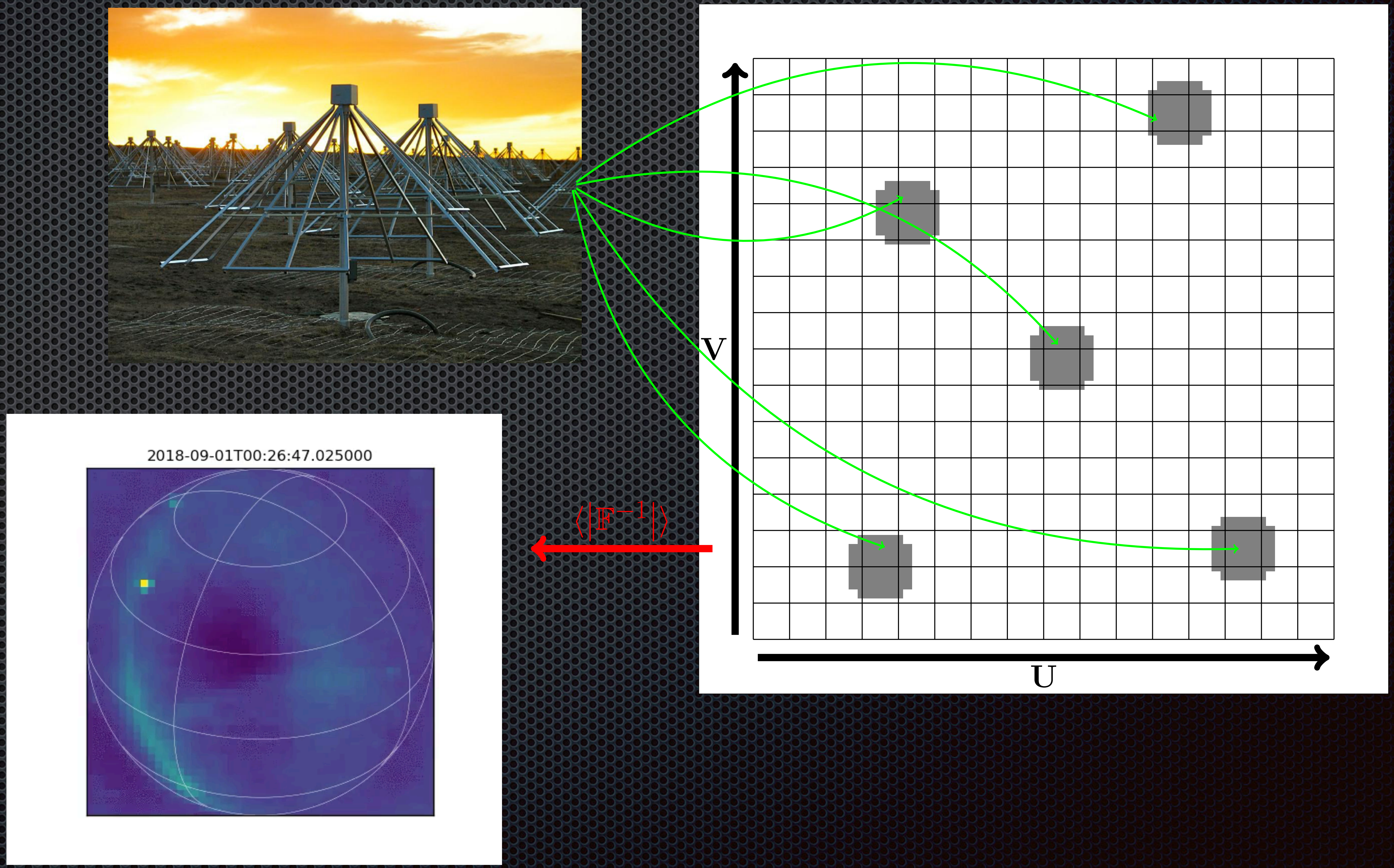
- Daishido et al. (1991) noted that a regularly spaced array could be imaged directly using the FFT algorithm.
- Morales et al (2009) noted that the van Cittert-Zernike theorem allowed generic direct imaging through an FFT correlator, with no constraints on array geometry.
- Foster et al (2014) demonstrated a direct imaging correlation on the redundantly spaced BEST-2 array.
- Thyagarajan et al (2017) built a generic simulation of EPIC to demonstrate technique and applicability to next generation telescopes.
- Beardsley et al (2017) demonstrated a calibration scheme for this generic FFT direct imaging.
- Kent et al (2019) demonstrated first working generic direct imager on the Long Wavelength Array.

Direct Imaging: Mathematical Reference

- Van Cittert-Zernike Theorem:
  - $$I(l,m,w) = \iint V(u,v,w)\exp\left[2\pi i\left(ul + vm + w\left(\sqrt{1-l^2-m^2}-1\right)\right)\right]du\,dv$$
- A visibility matrix can be represented as an outer product between a vector of electric fields and its conjugate transpose (equivalent to a convolution):
  - $$V(u,v,w) = E(x,y,z) \otimes E(x,y,z)^H$$
- Re-arrange using multiplication-convolution theorem:
  - $$I(l,m,w) = \left\langle \left| \iint E(u,v,w) \times \exp\left[2\pi i\left(ul + vm + w\left(\sqrt{1-l^2-m^2}-1\right)\right)\right]du\,dv \right|^2 \right\rangle$$
- Have now defined a relationship between the sky brightness distribution and the electric fields measured at each antenna.

Direct Imaging: Visual Reference

1. Convolve Electric Fields onto regular grid.
2. Inverse FFT
3. Square and cross-multiply.
4. Accumulate



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E-Field Parallel Imaging Correlator (EPIC)

- General purpose direct imaging correlator:
  - No restrictions on heterogeneity of array.
  - No restrictions on array geometry
- Described in detail by Thyagarajan et al. (2017)

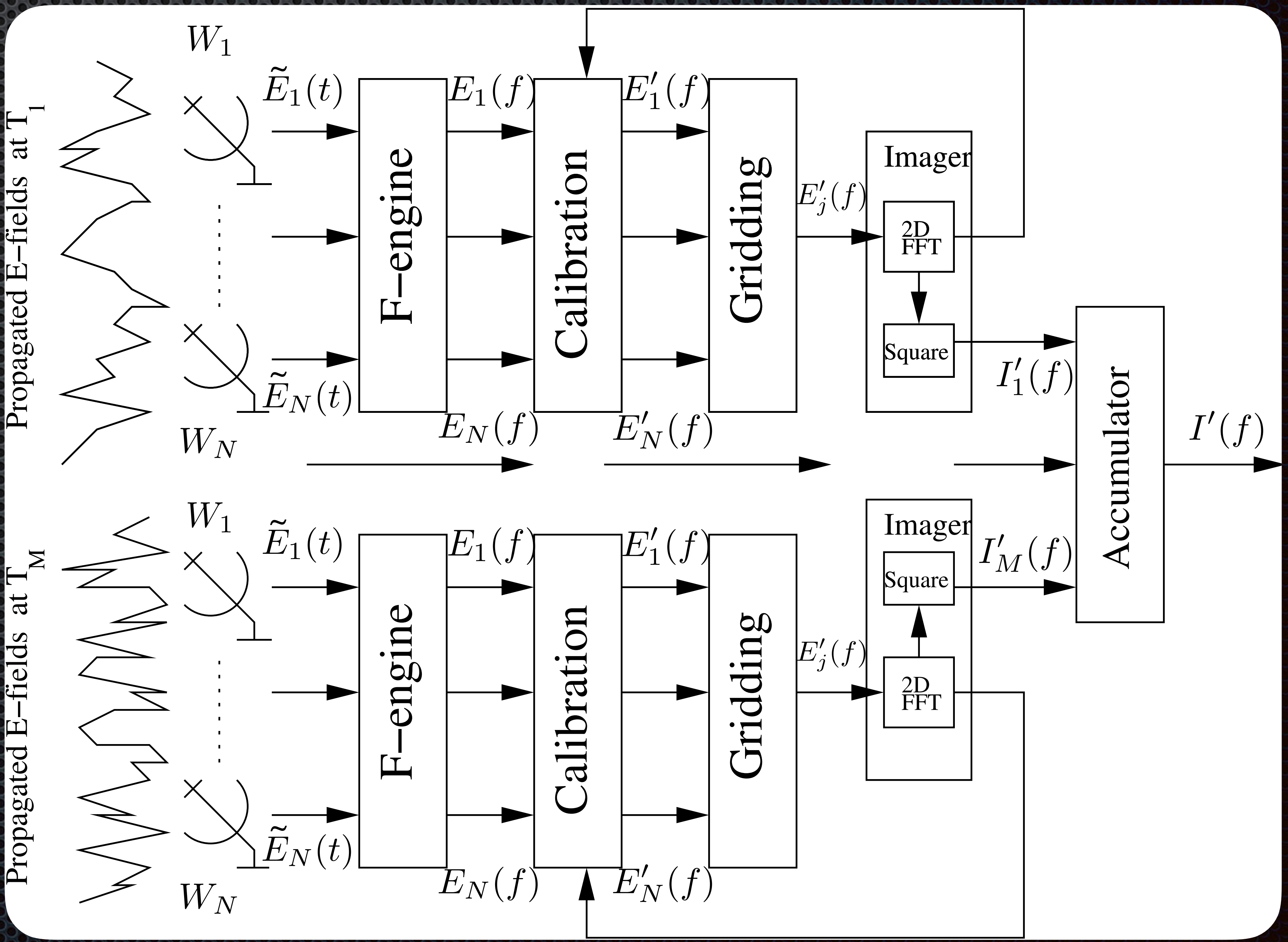

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Image: Thyagarajan et al. (2017)

Benefits

- Compute scaling of an FX correlation is $\mathcal{O}(n_a^2)$. n_a is number of antennas.
- Compute scaling of a direct imaging correlation using FFT is $\mathcal{O}(n_g \log n_g)$. n_g is grid size.
- In certain regime, MOFF formalism cheaper to implement than FX correlation.
- Data rate reduction.
- Time Domain Astronomy.

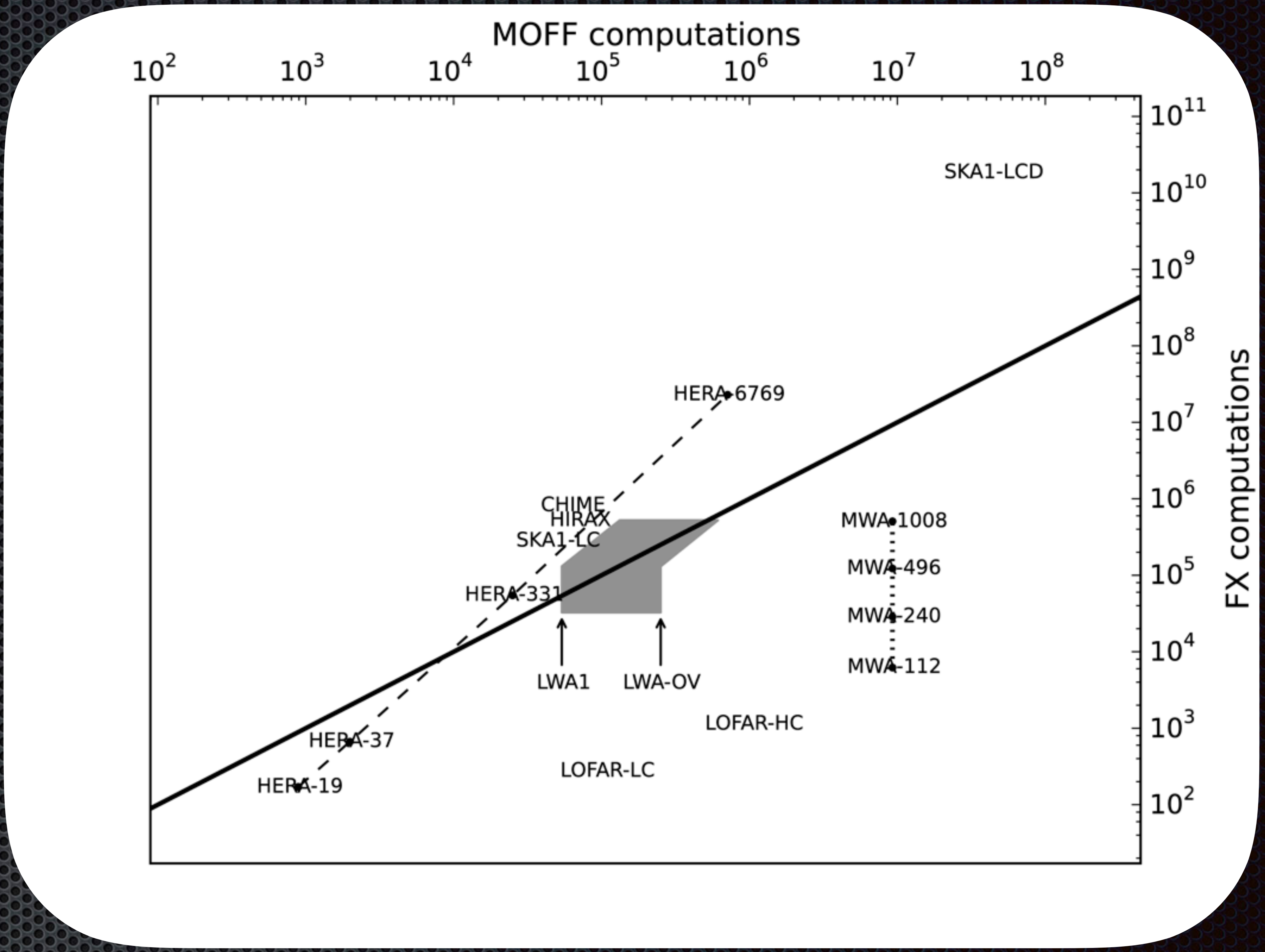

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Image: Thyagarajan et al. (2017)

E-Field vs Visibility Imaging

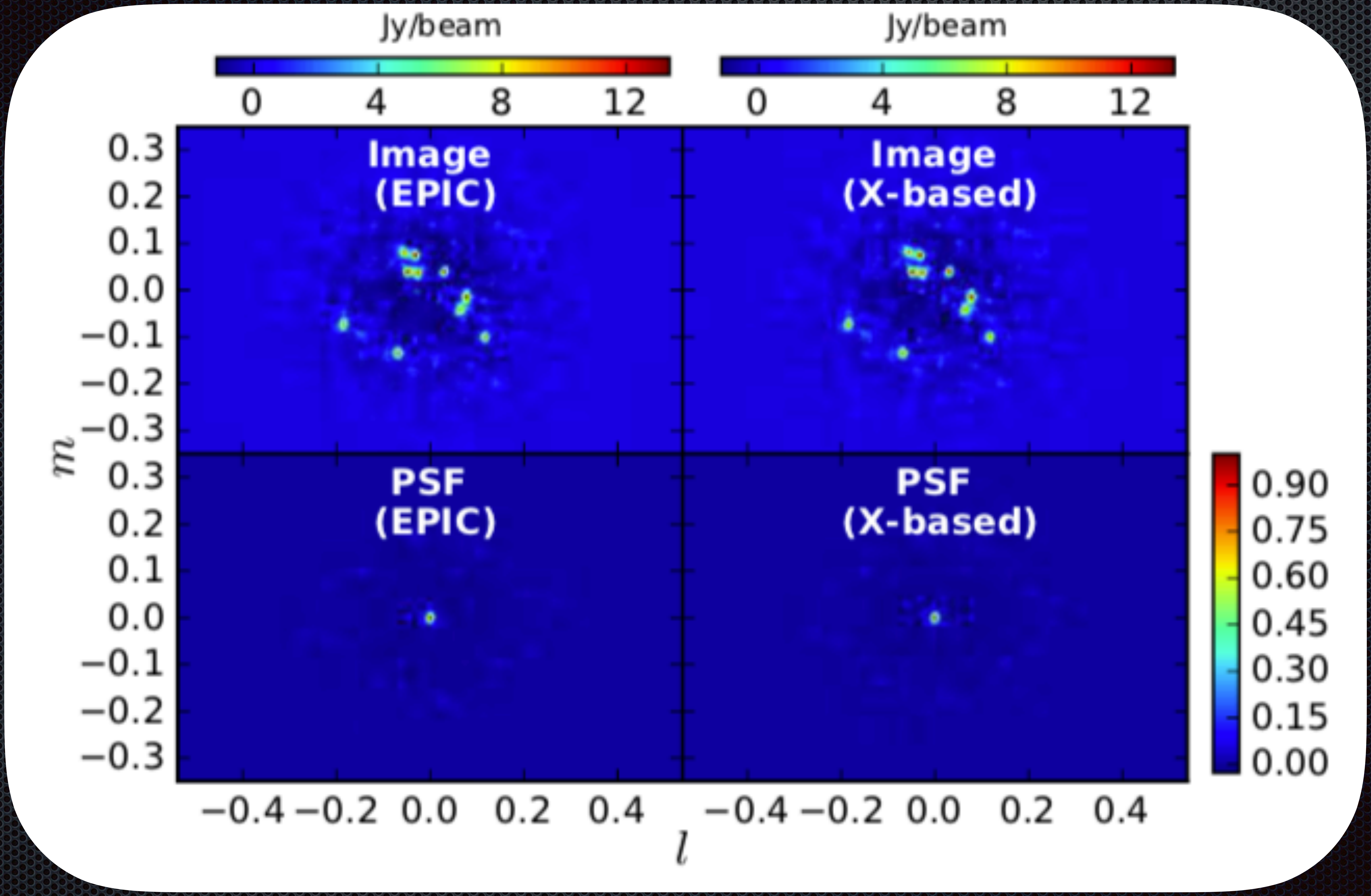

 Image: Thyagarajan et al. (2017)

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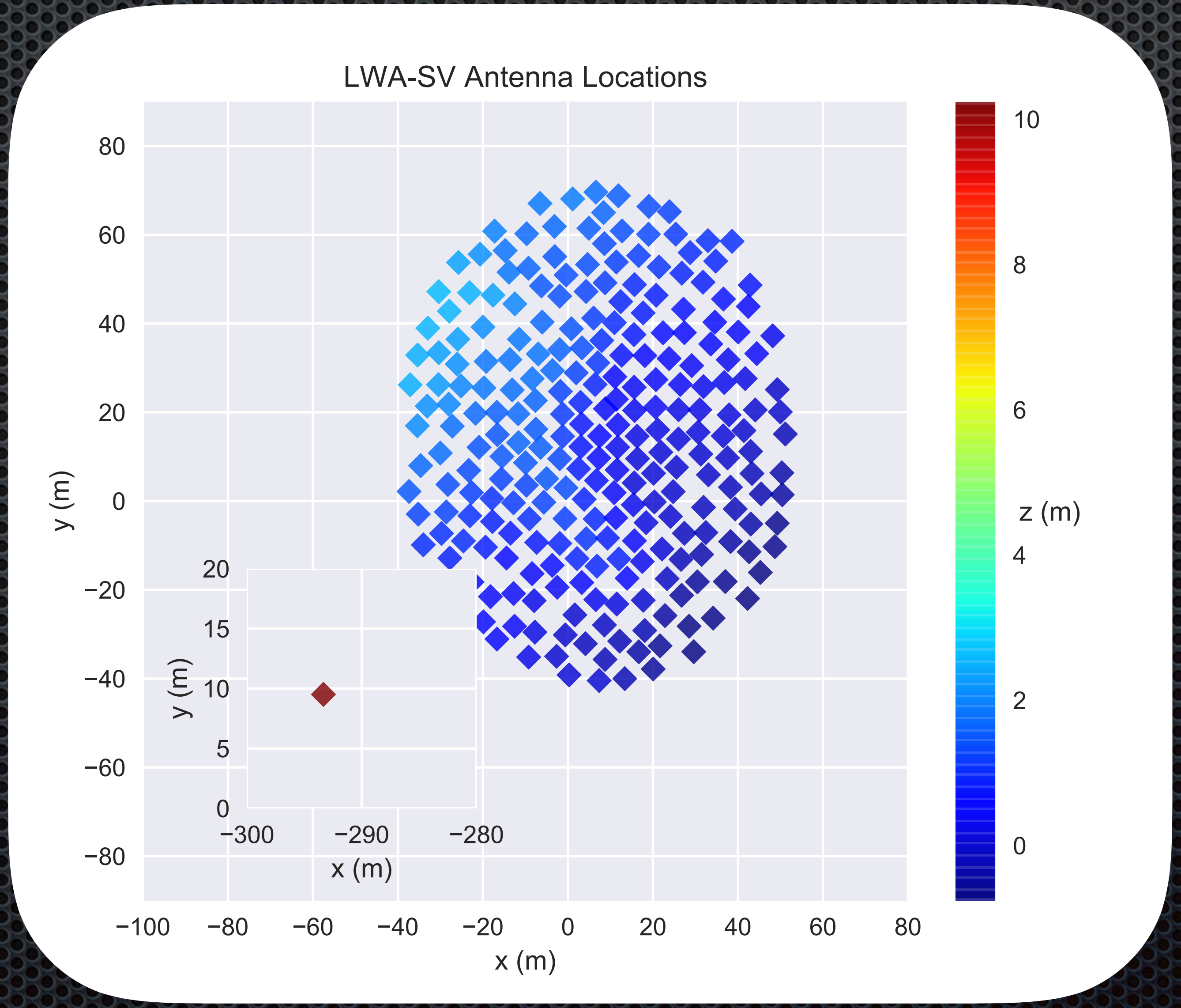
Long Wavelength Array

- Two stations active in New Mexico, USA
- Operates at 10-88 MHz
- 256 Dipole Antennas per station.
- Overall build out to consist of 53 stations across the southwest of the USA.



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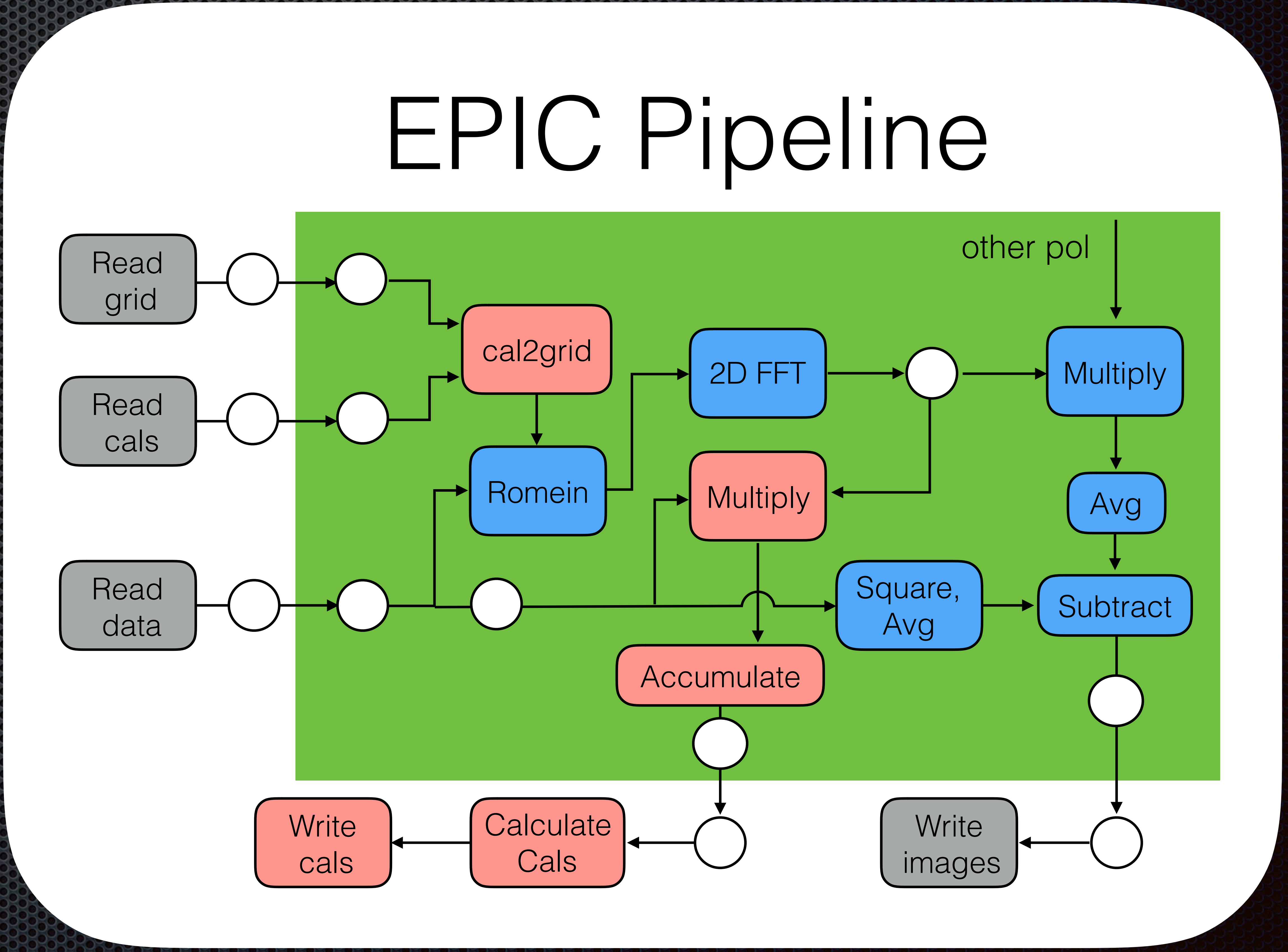
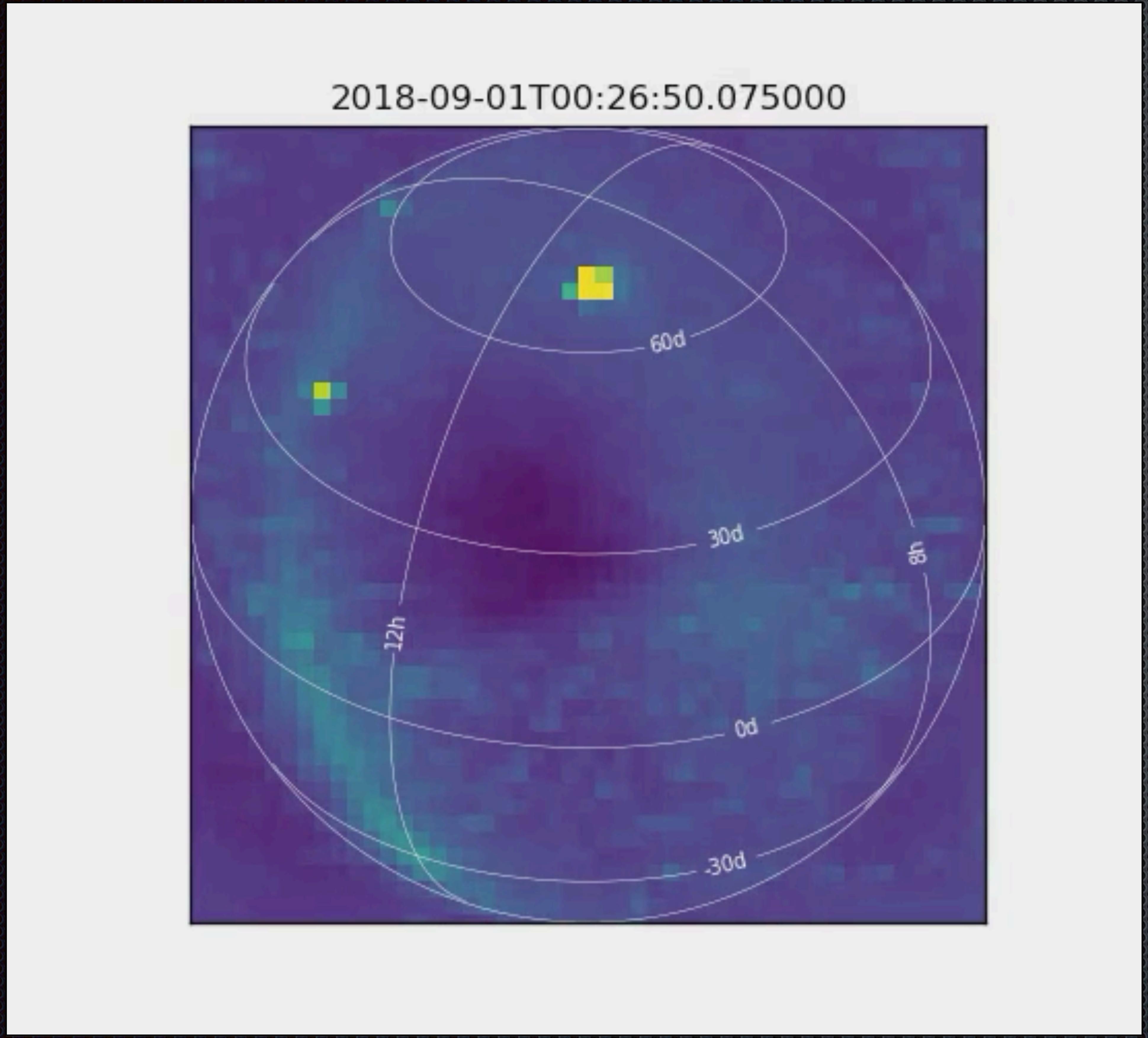
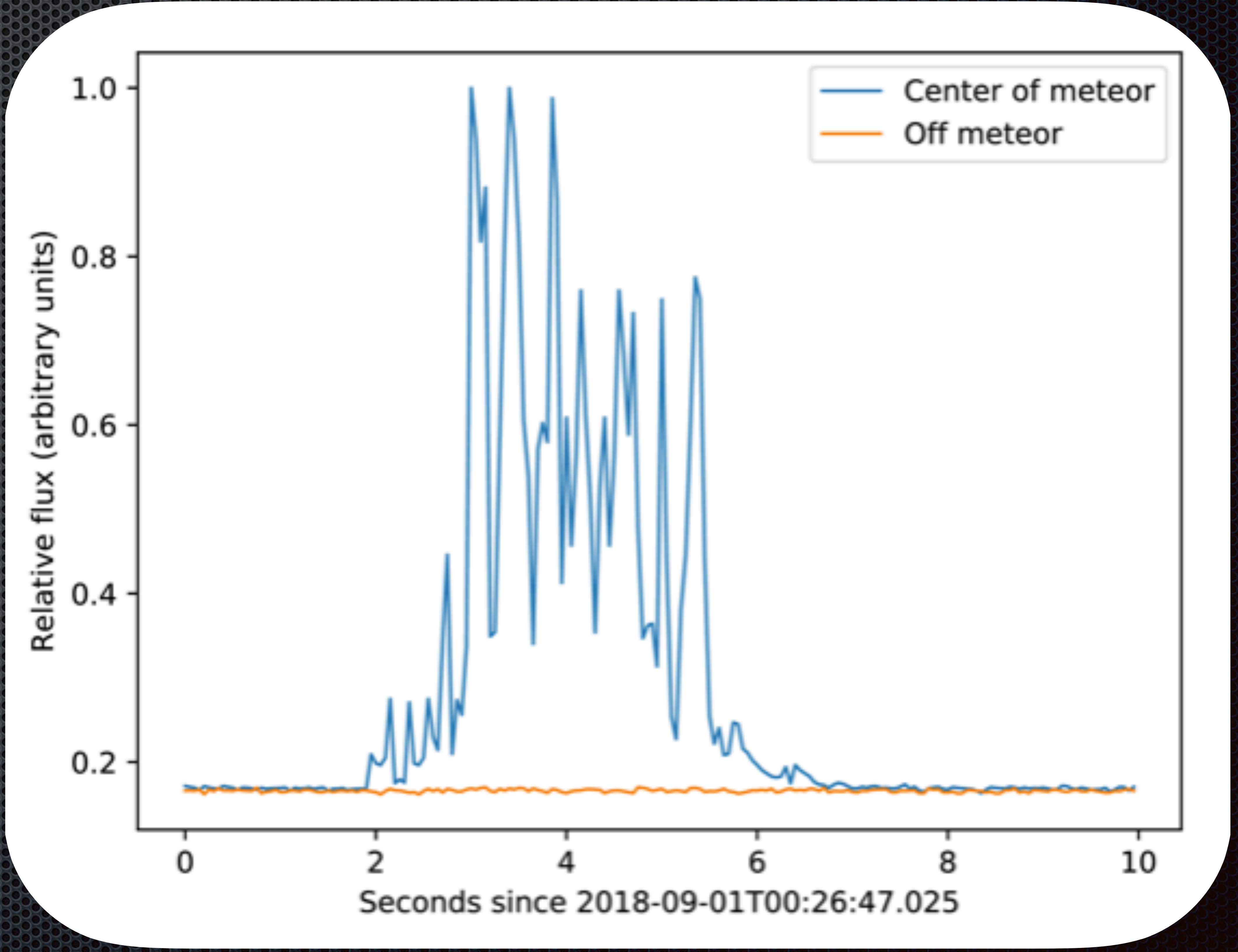
Implementation

- Implemented in high performance streaming framework: Bifrost
- Python front-end calls high performance C++/CUDA backend.
- Most signal processing functions already in Bifrost. Some specialised C++/CUDA routines were written as needed.



High Time Resolution PoC: Meteor Observations on 1st September 2018





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Images: Kent et al. (2019)

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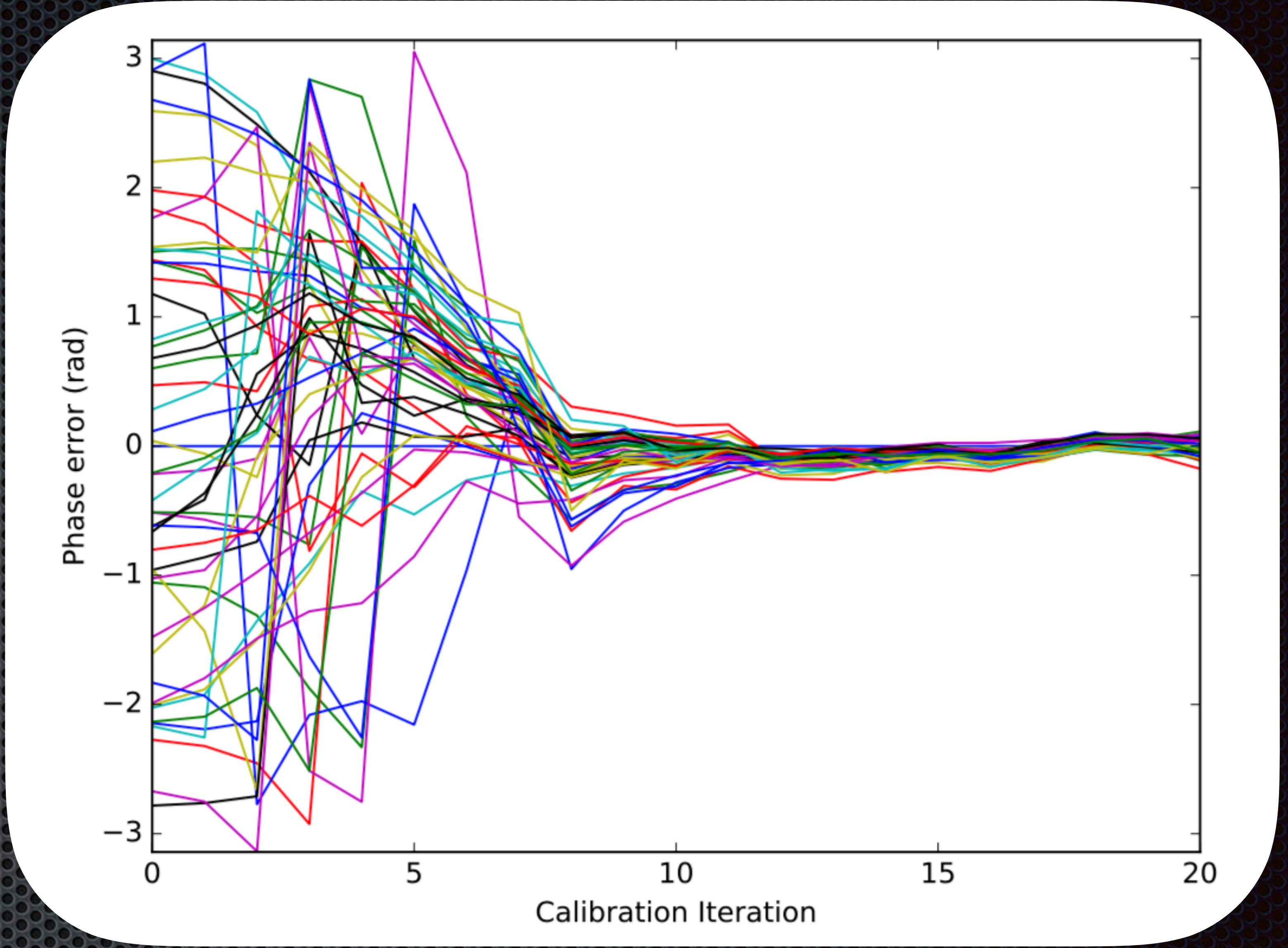
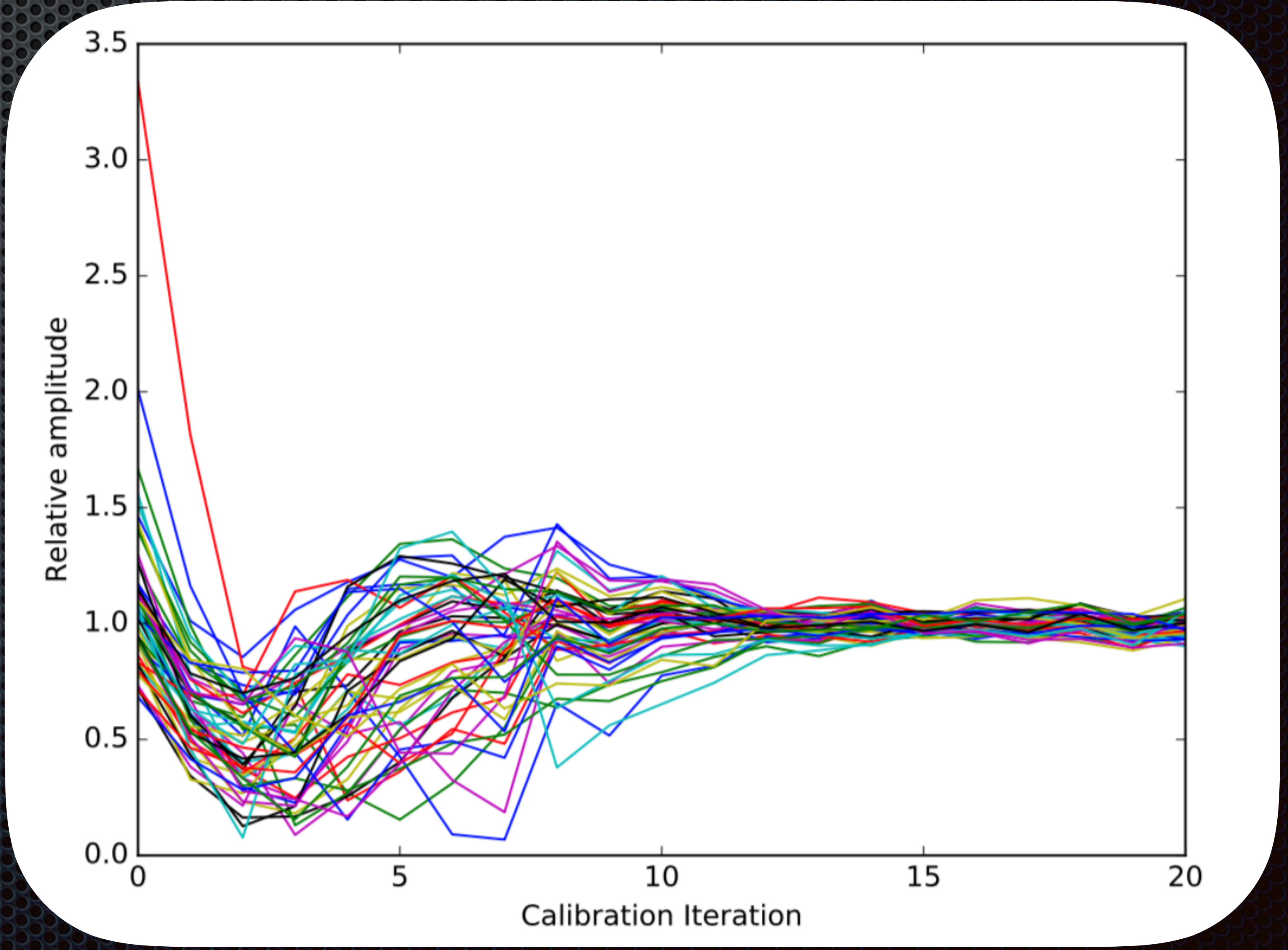
Direct Imaging Calibration

- As direct imaging is done in real time, so is calibration.
- Requires reliable RFI detection.
- Beardsley et al. (2017) demonstrated a practical calibration solution, EPICal, for this.
- LWA Implementation ongoing.





Images: Beardsley et al (2017)

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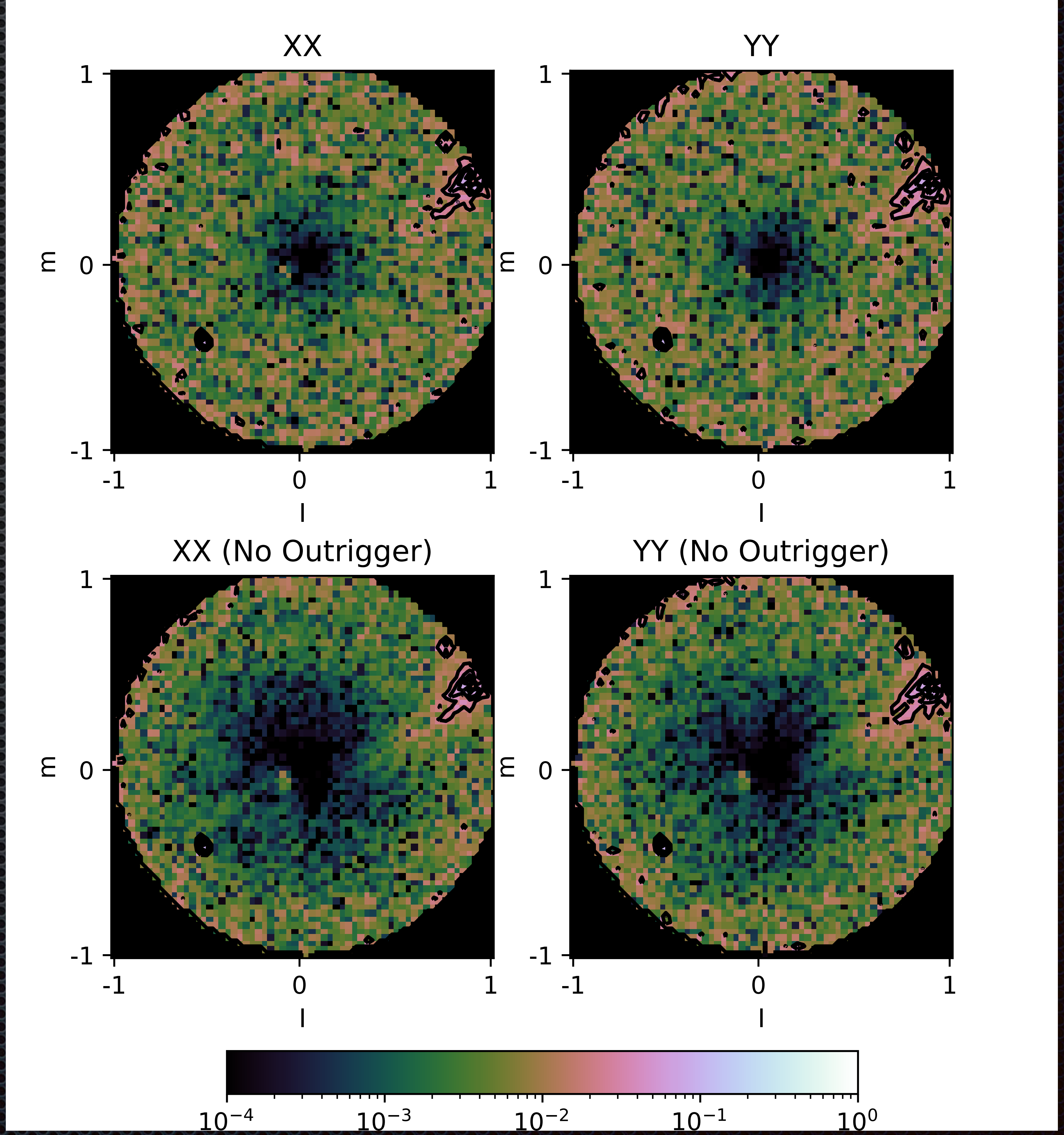
Direct Wide-Field Imaging

- Return to MOFF formulation:
  - $$I(l, m, w) = \left\langle \left| \iint E(u, v, w) \times \exp\left[2\pi i \left(ul + vm + w\left(\sqrt{1 - l^2 - m^2} - 1\right)\right)\right] du\, dv \right|^2 \right\rangle$$
- w-term results from non-coplanarity in the array, and breaks the flat-grid assumption of the FFT, and must be correctly accounted for.
- Failure to correct results in a loss of coherence in the image.

Same as visibilities? No.

- Several techniques are used to compensate for the w-term with visibility based imaging, e.g:
  - w-projection: Apply a w-kernel convolution to each visibility to correct for the w-term.
  - w-stacking: Generate a 'stack' of w-planes, and iteratively correct and sum together to generate a dirty image.
- Unfortunately these prove to be difficult to implement in direct imaging due to grid size limitations, and a hard compute time requirement for real-time direct imaging.



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Summary

- Direct imaging is not just possible but practical with no constraints on array geometry or homogeneity.
- Allows high time resolution interferometric direct imaging.
- Functioning prototype implementation on the LWA.
- Work to be done:
  - EPICal on LWA
  - Wide Field / Non-Coplanarity Correction
  - Deconvolution
  - Tons of software work, documentation etc etc.
- Planned science observations on LWA:
  - Solar Observations
  - Planetary Observations

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