Real-time, All-sky, Extreme Time-resolution Imaging from the LWA-Sevilleta Telescope Using the EPIC Architecture

NSF-ATI (Award 1710719)

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Key Science Drivers of Radio Astronomy: Large-N Small Diameter (LNSD) Paradigm

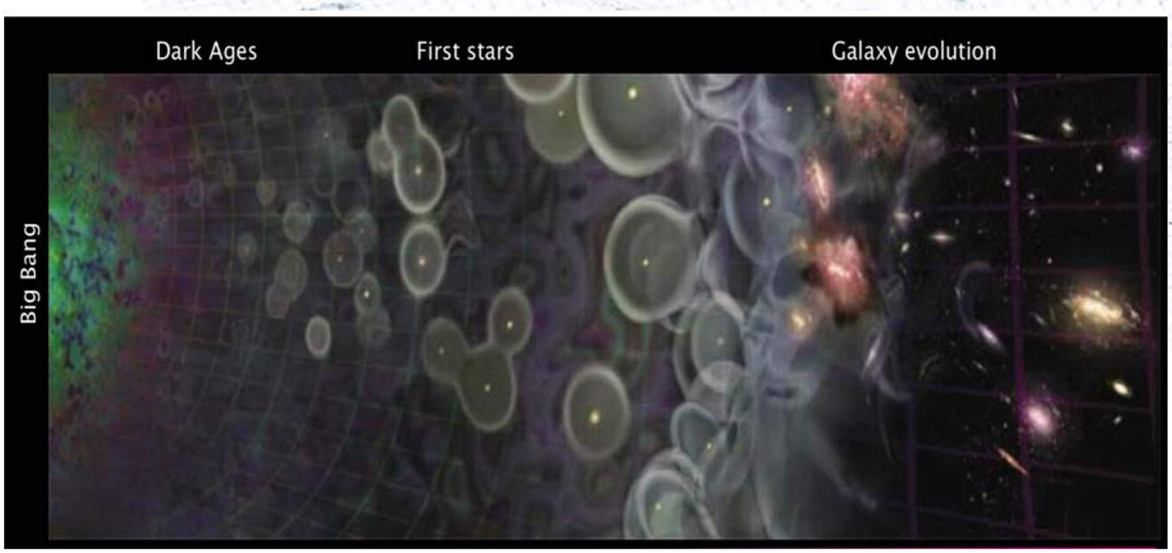
Cosmology

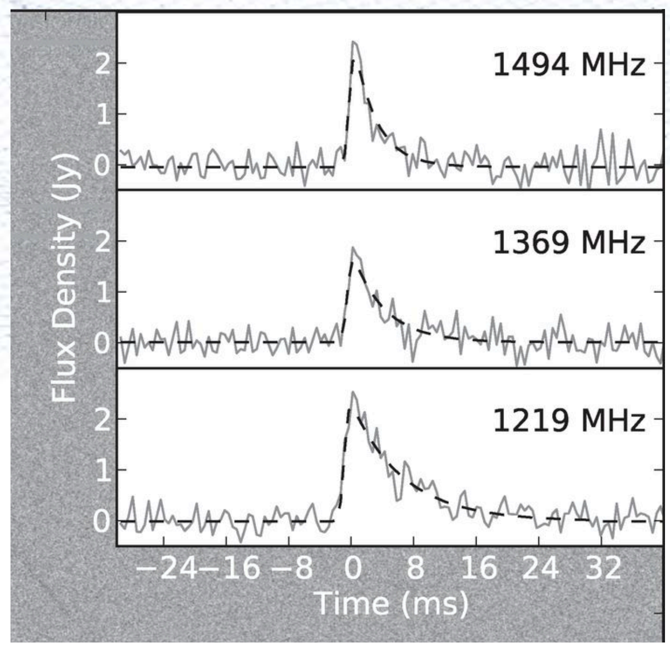
Large scale structure

- Wide fields of view
- Compact Aperture Size
- Large Number of antennas for Collecting area

Transients/Time-domain

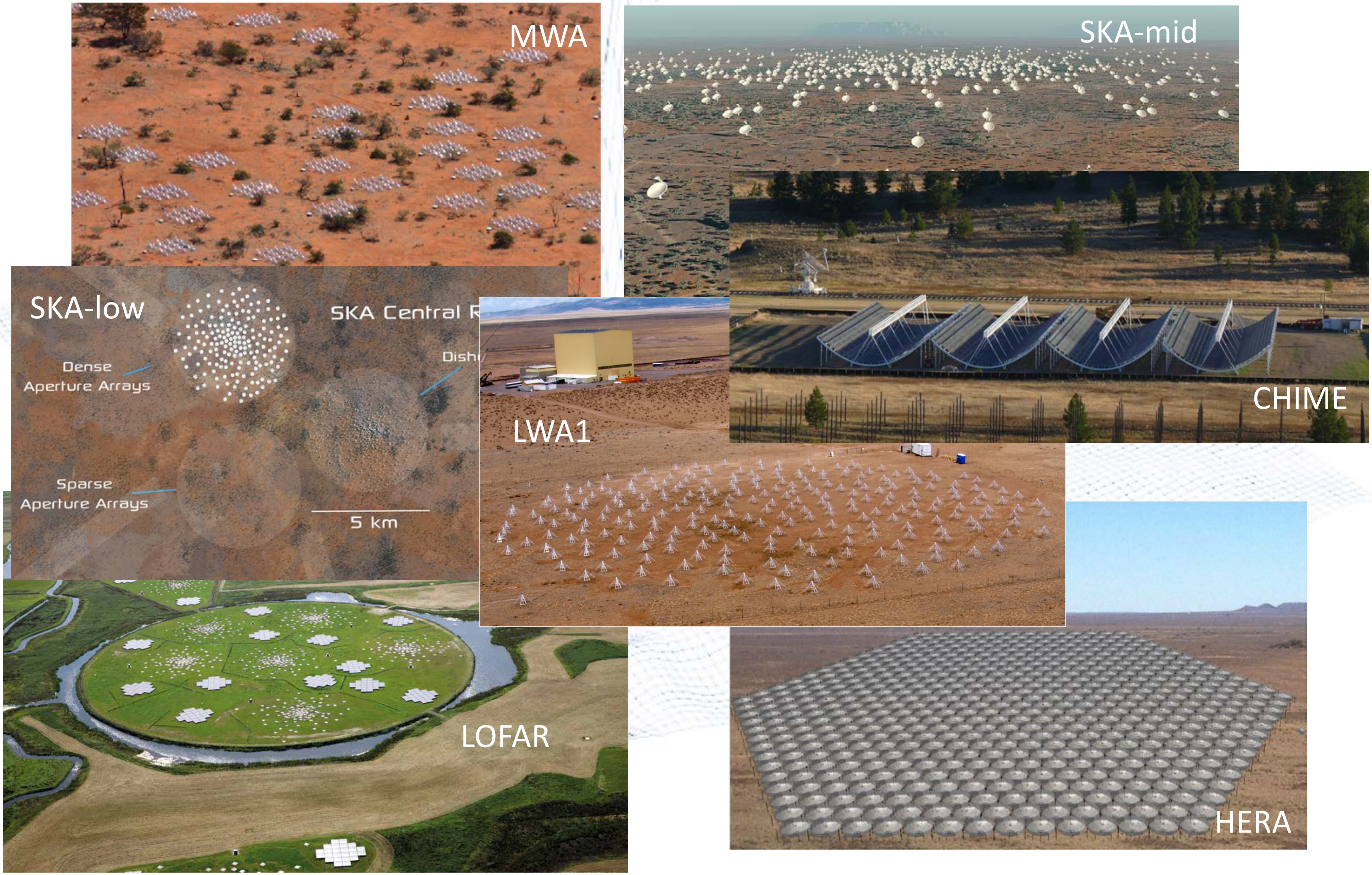
- Wide fields of view
- Large number of antennas for collecting area
- High time cadence, fast writeouts



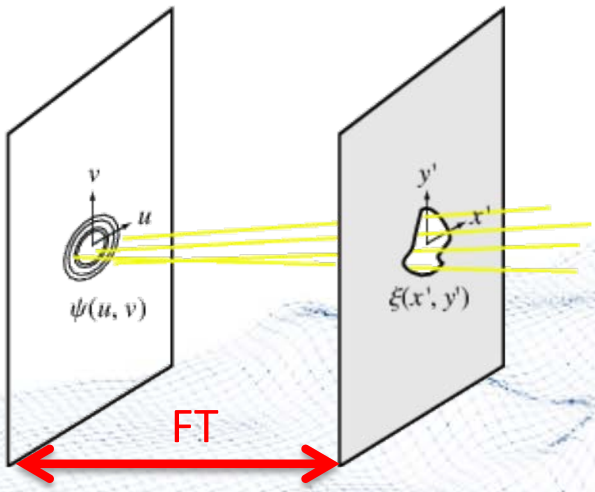


Thornton et al. (2013)

Modern Radio Telescopes



Aperture Synthesis in Existing Radio Interferometry Architecture



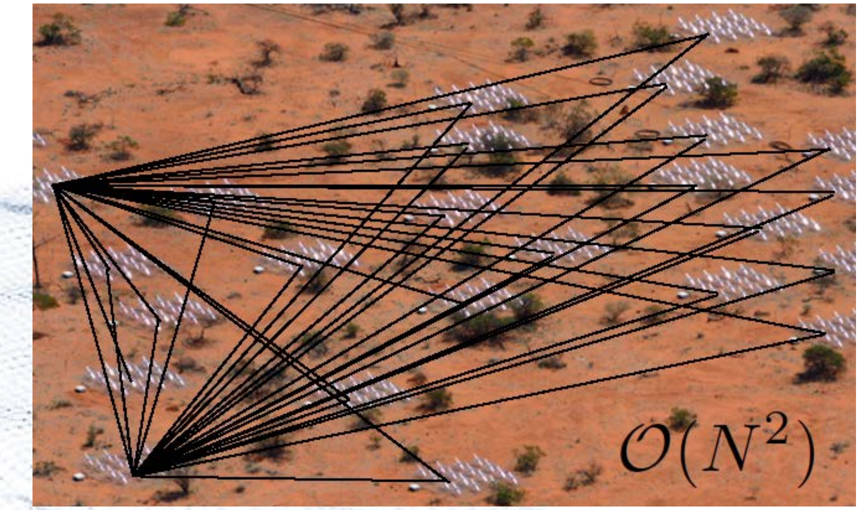


Image credit: Adam Beardsley

- Aperture / image planes related by FT
- Spatial correlation: Computationally expensive for Large-N telescopes
- Architectural redesign?
- Convolution theorem of Fourier Transform:

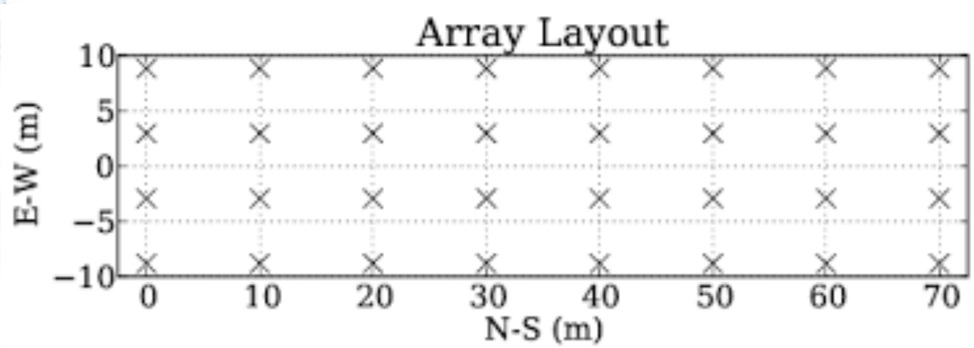
  FT(Correlation) ←→ FT(.) x FT(.)

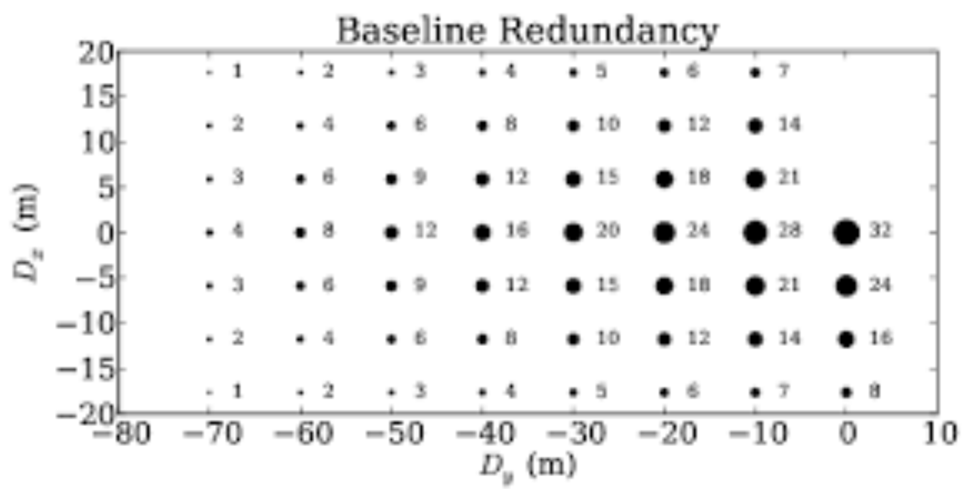
Traditional / Correlation-based

Direct Imaging (FT and square)

A limited implementation of Direct Imaging

- Antennas placed on a grid and perform spatial FFT of antenna voltages on grid to get complex voltage images
- Square the transformed complex voltage image to obtain real-valued intensity images
- Current implementation:
  - 8x8 array in Japan (Daishido et al. 2000)
  - 4x8 BEST-2 array at Radiotelescopi de Medicina, Italy (Foster et al. 2014)





Foster et al. (2014)

Need for <u>generic</u> direct imaging

Hurdles with current implementations

- Uniformly arranged arrays have poor point spread functions – thus not ideal for imaging
- Aliasing of objects from outside field of view
- Assumptions of identical antennas => poor calibration
- Calibration still requires antenna correlations

MOFF algorithm

Morales (2011)

- Antennas need not be on a grid but still exploit FFT efficiency
- Can customize to science needs
- Accounts for non-identical antennas
- Calibration does not require forming visibilities
- Can handle complex imaging issues - w-projection, time-dependent wide-field refractions and scintillations
- Optimal images

EPIC: E-field Parallel Imaging Correlator
EPIC implementation of Direct Imaging

FX

Traditional / Correlation-based

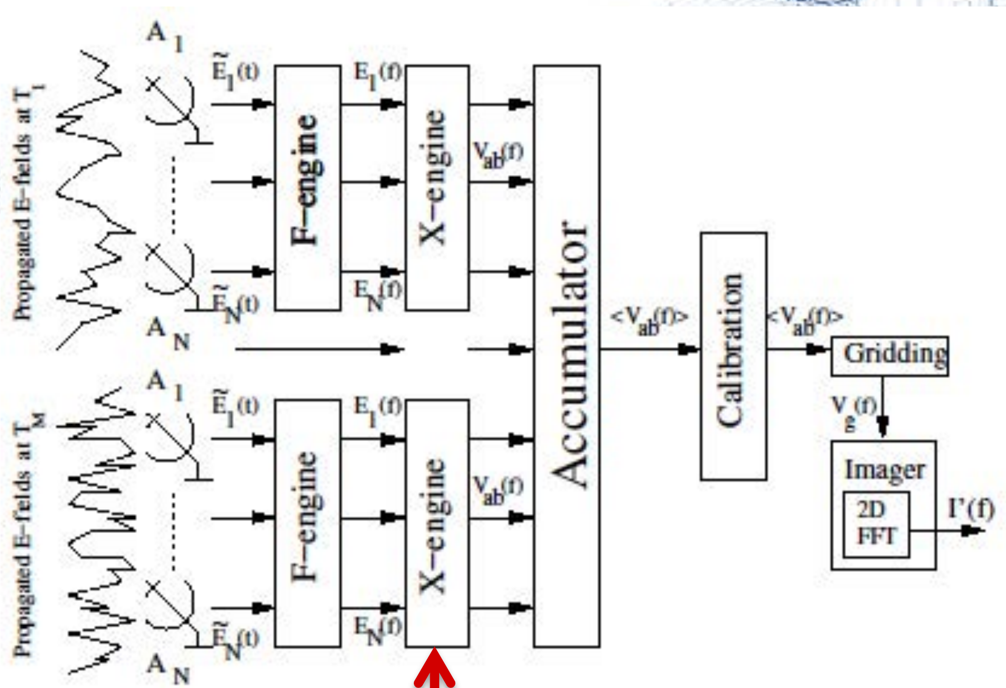
FT(Correlation)

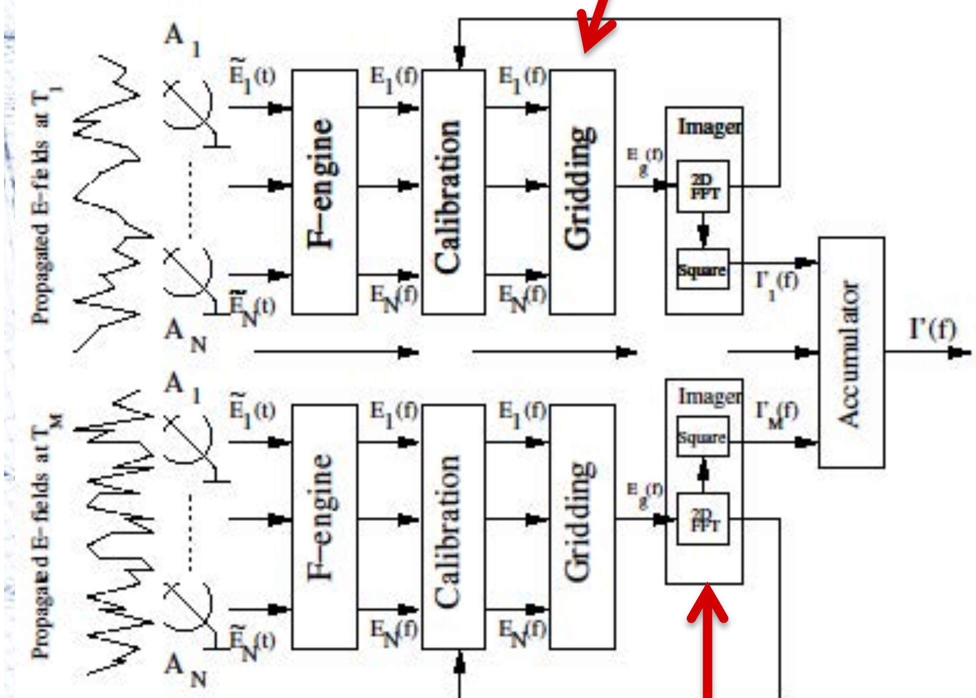
EPIC

Direct Imaging

FT(.) x FT(.)

Gridding makes it generic





$O(N_a^2)$

Thyagarajan et al. (2017)

$O(N_g \log N_g)$

Fast Imaging

(With calibration)

EPIC implementation of MOFF imaging

Gridding

Homogeneous Array

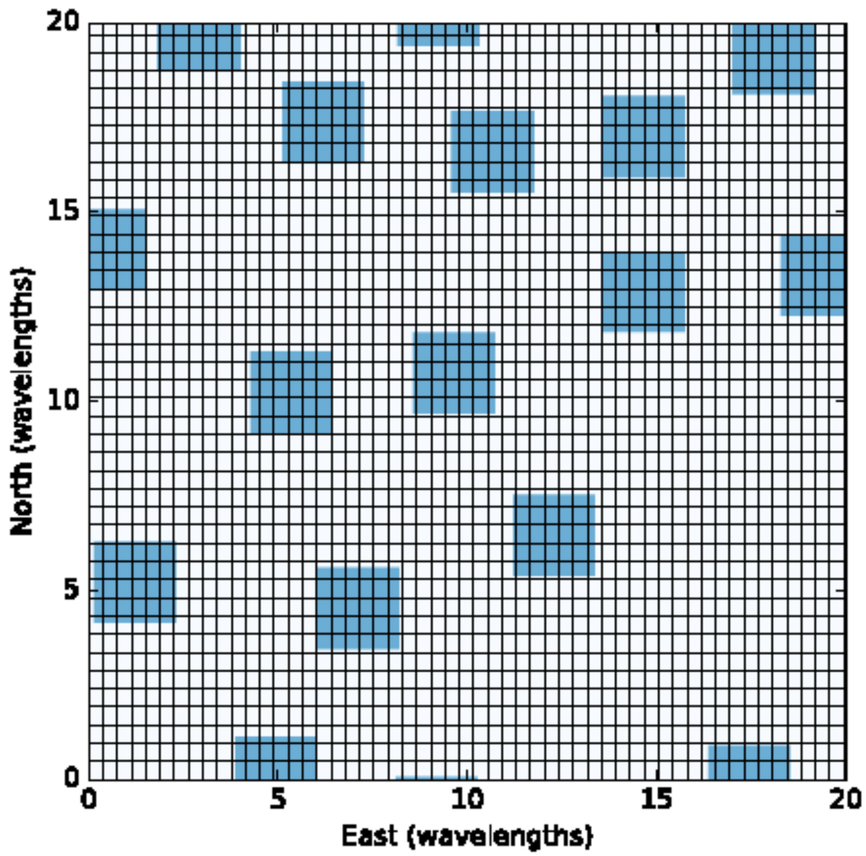


Image: Beardsley et al. (2017)

Heterogeneous Array

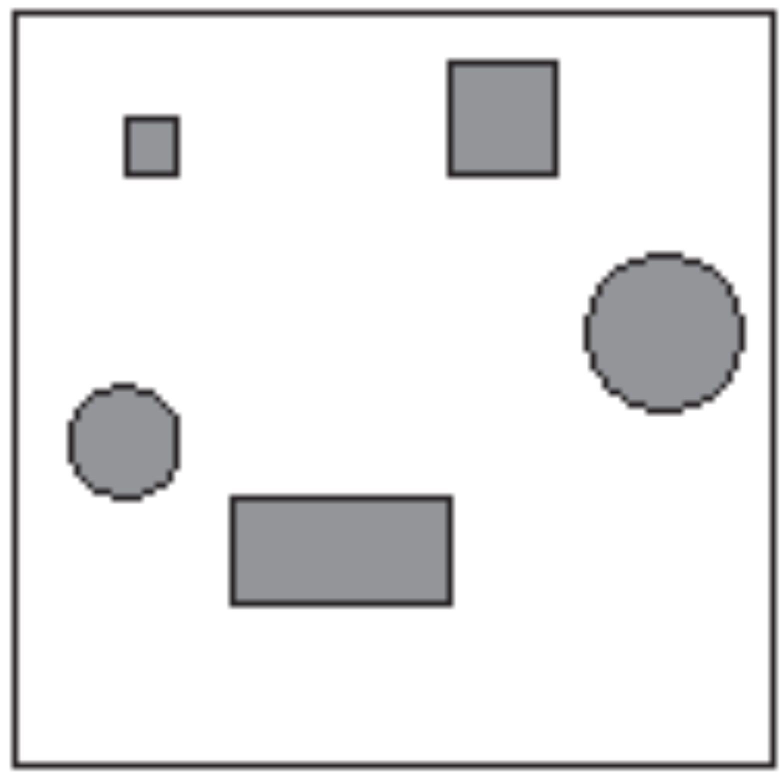


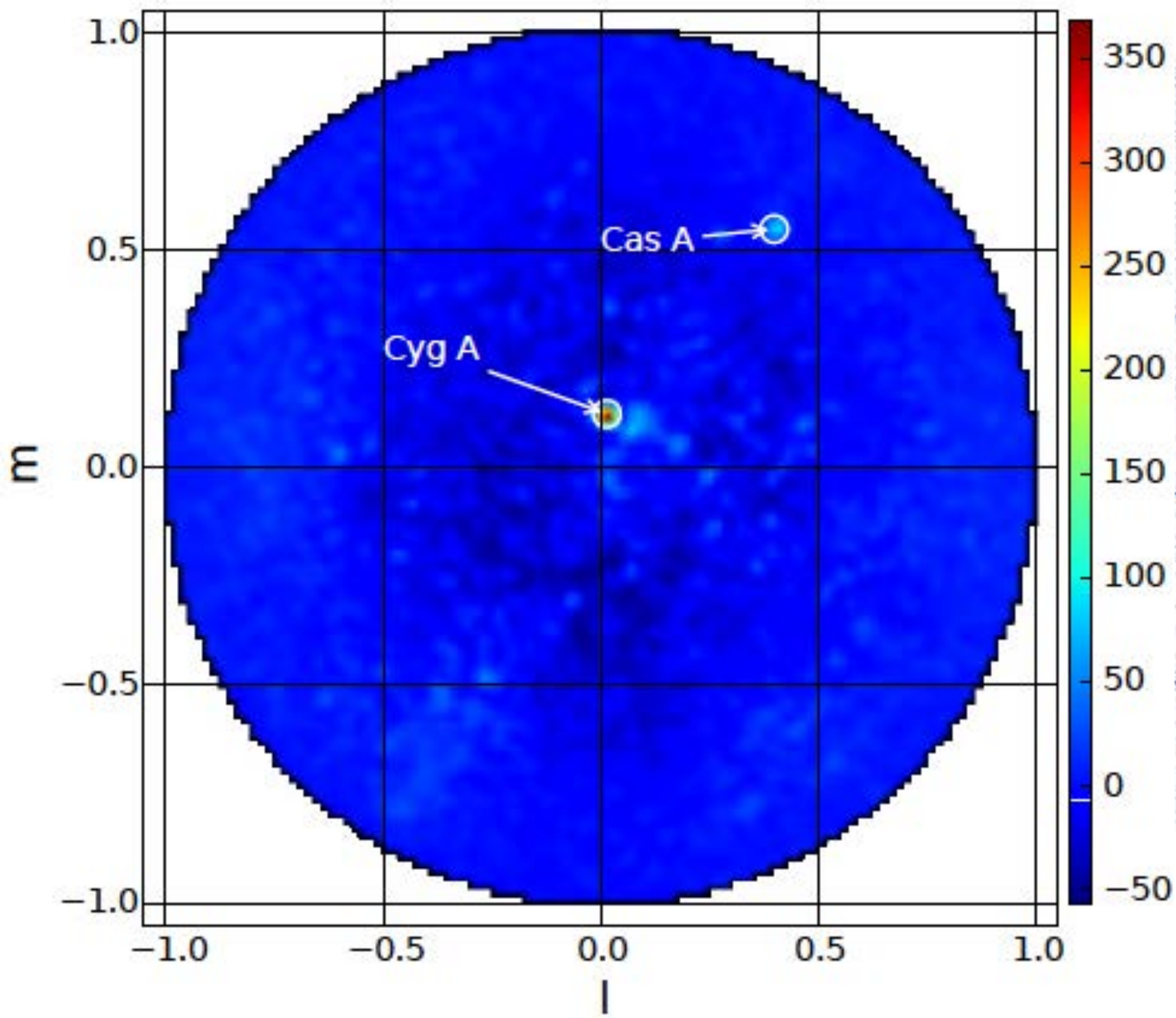
Image: Thyagarajan et al. (2017)

EPIC – Generic Direct "Fourier Optics" Imaging for Radio Interferometry

- Allows arbitrary layouts (diverse science goals)
- Allows heterogeneous arrays (non-identical antennas) e.g. LWA1—LWASV – VLA, or antenna-to-antenna variations
- Works trivially and efficiently for redundant arrays such as HERA. E.g., FFT correlator/FFT imager being developed for HERA is just a special case of EPIC architecture.
- Simultaneous all-sky beamforming

Fast, generic, wide-field radio camera for large-N arrays

EPIC on LWA1 Data



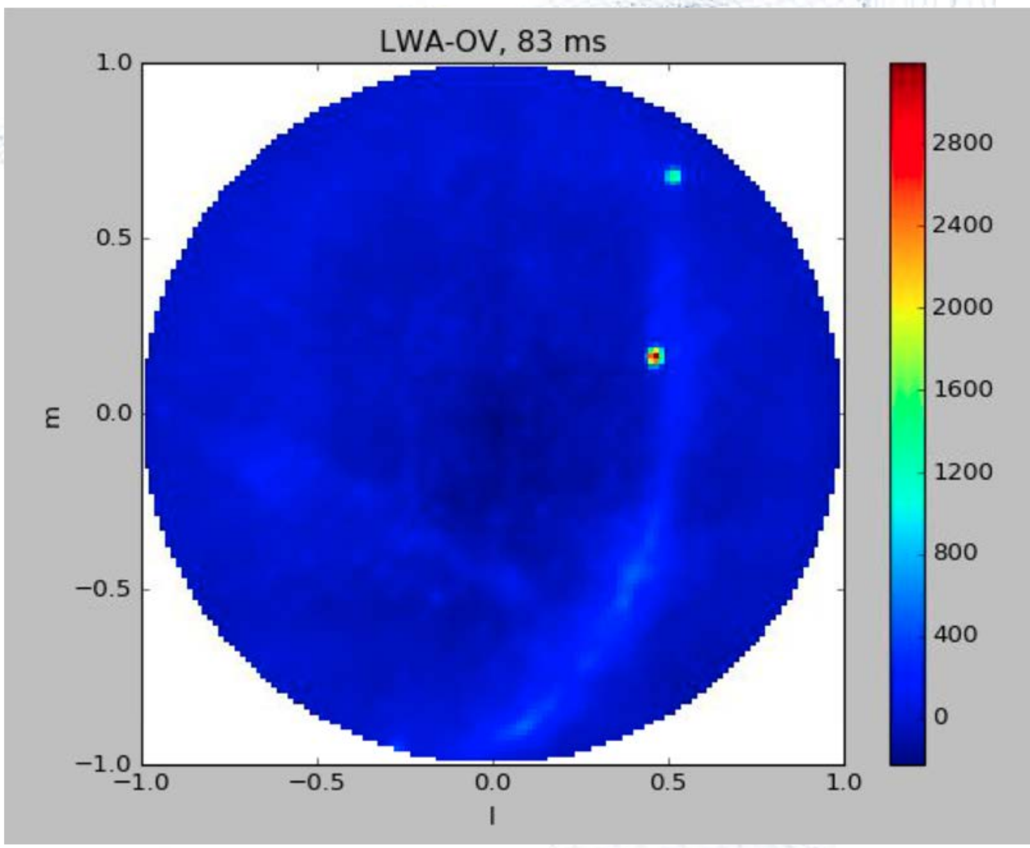
Data credit: LWA1 team, Jayce Dowell, Greg Taylor

- TBN data with a total of 2s and 100 kHz
- Image obtained with 20 ms, 80 kHz
- Cyg A and Cas A prominently visible

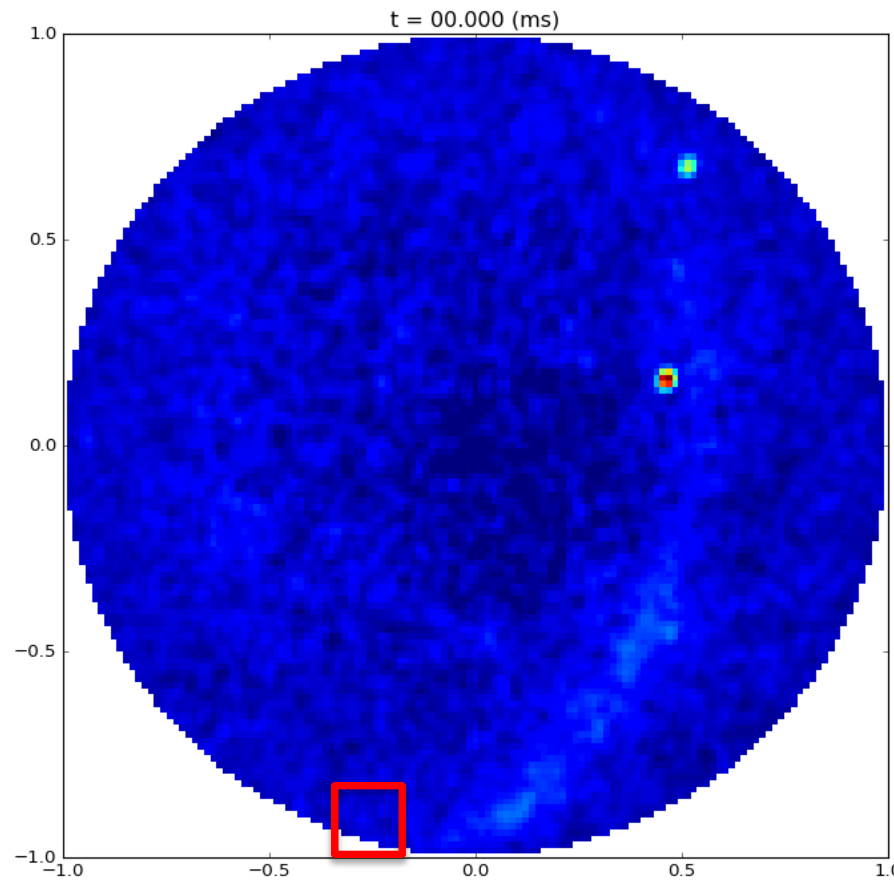
Thyagarajan et al. (2017)

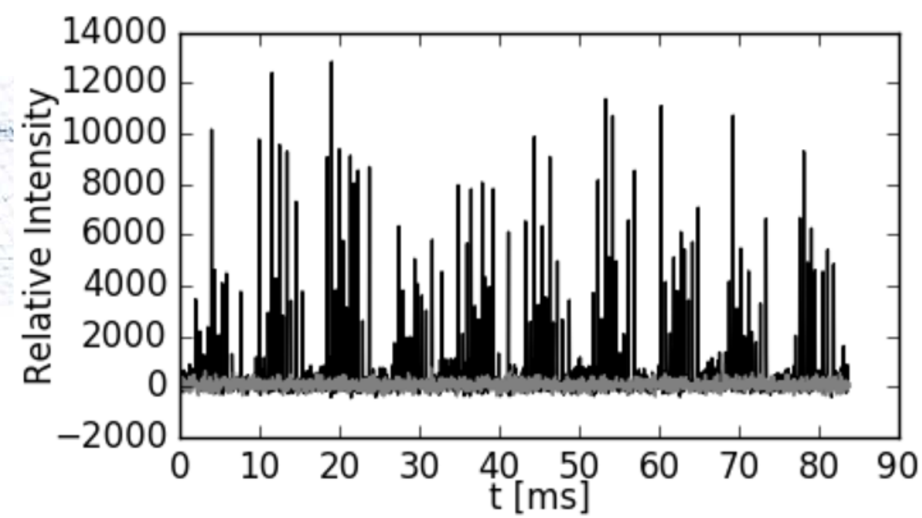
Fast Transient Capabilities: EPIC on OVRO-LWA Data

188 core antennas (200m dia.)
47 MHz, 2.6 MHz bandwidth
Cadence 0.04 ms



Data credit: OVRO-LWA team, Ryan Monroe, Gregg Hallinan





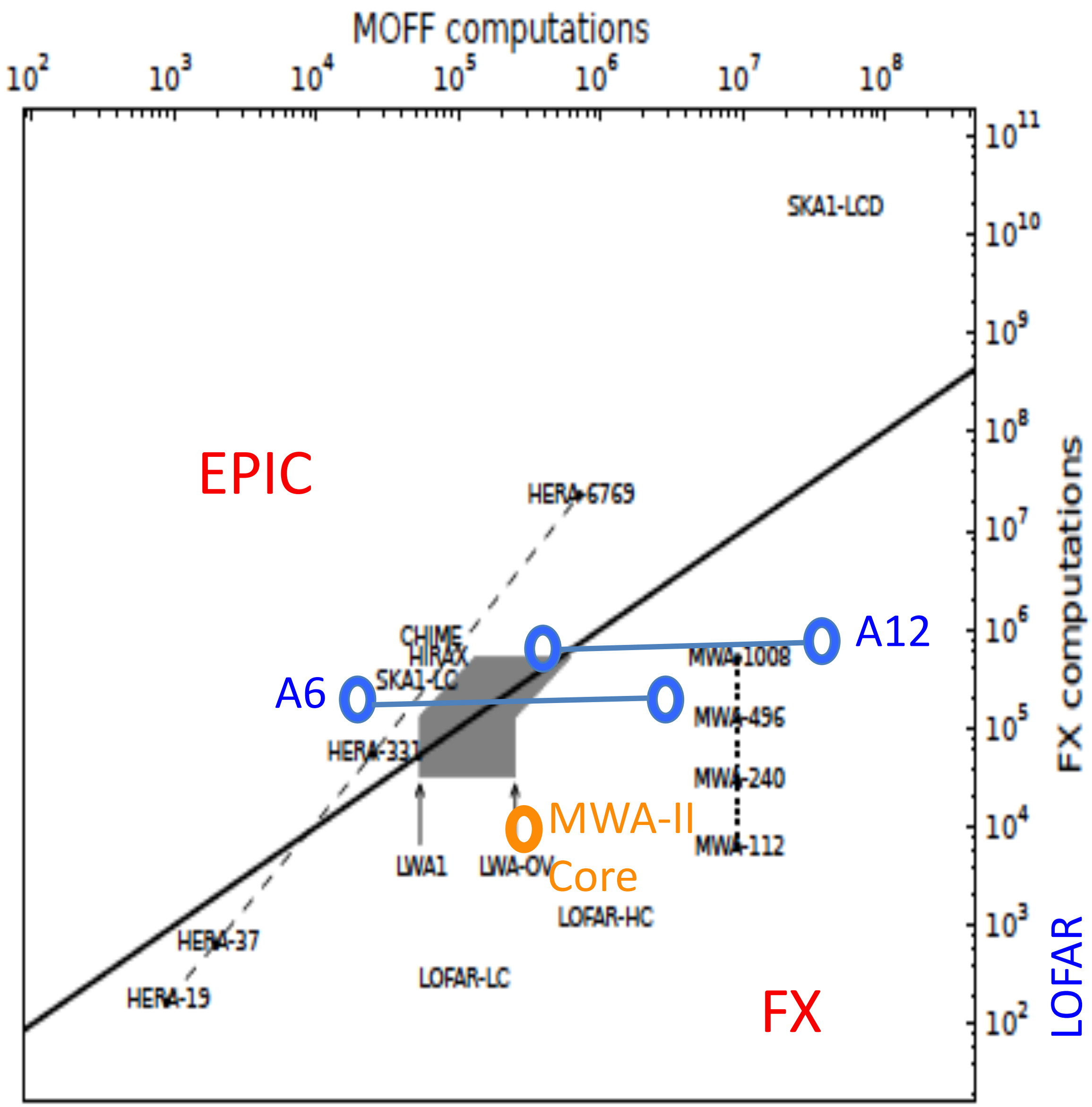
Economic Data Writeout Rates

Telescope	Data rate (EPIC) GB/s	Data rate (FX/XF) GB/s
LWA1	$\simeq 3$	$\simeq 24.3$
LWA-OV	$\simeq 12$	$\simeq 24.3$
HERA-19	$\lesssim 0.19$	$\simeq 0.13$
HERA-37	$\lesssim 0.19$	$\simeq 0.5$
HERA-331	$\lesssim 3$	$\simeq 41$
CHIME	$\lesssim 6.1$	$\simeq 610$

Assumes writeout timescale of 10 ms

- Data rate ~N_g for EPIC
- Data rate ~N_a^2 for visibilities to be written out
- EPIC lowers data rates significantly in modern/future telescopes
- EPIC also yields "Science-ready" calibrated images on short timescales
- Ideal for bright, fast (e.g. FRB, MSP) and slow transients with large-N dense arrays

Current and future telescopes in EPIC-FX parameter space



- Top left is where MOFF is more efficient than FX
- Dashed line shows where expanded HERA will be
- Shaded area is where LWA will evolve to be
- Large-N dense layouts favor EPIC
- EPIC will benefit most of future instruments (LNSD)

A6: 0.1 TFLOPS (10 MHz)
13 TFLOPS (90 MHz)
A12: 2.4 TFLOPS (10 MHz)
272 TFLOPS (90 MHz)

LWA-Sevilleta (LWA-SV), New Mexico

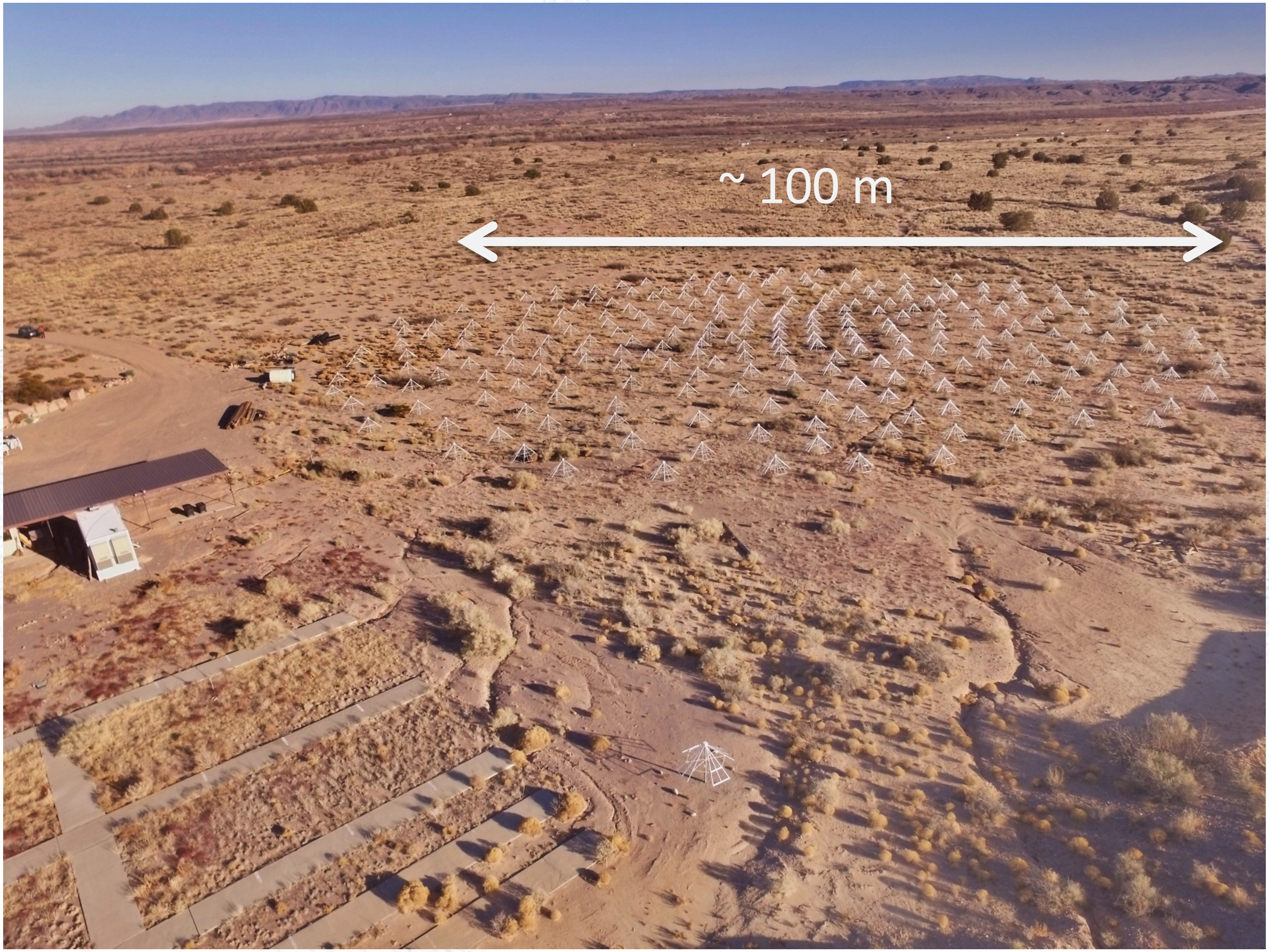


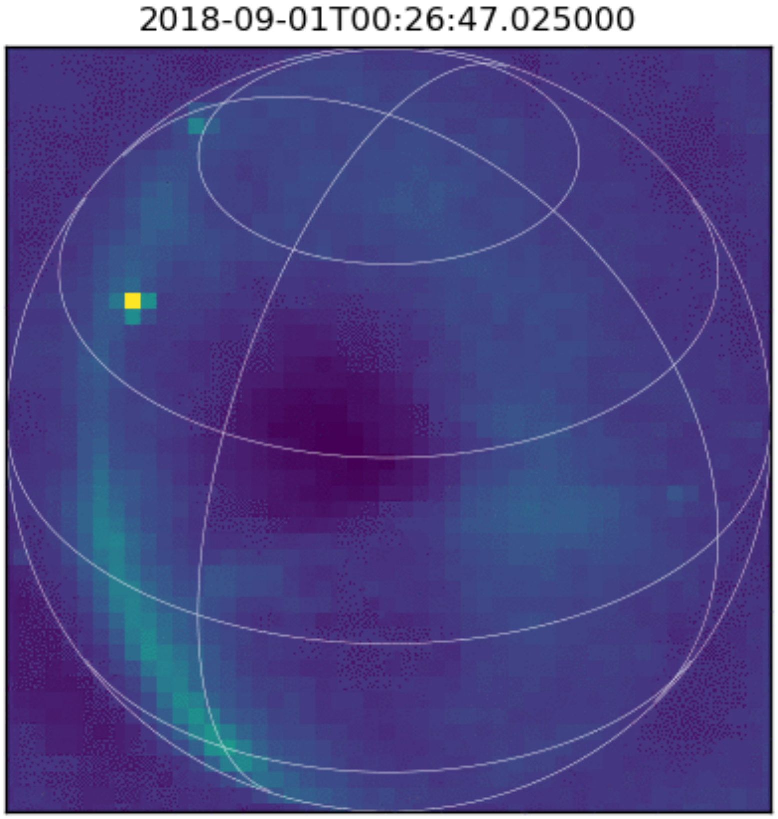
Image Credit: Greg Taylor (PI: LWA-SV)

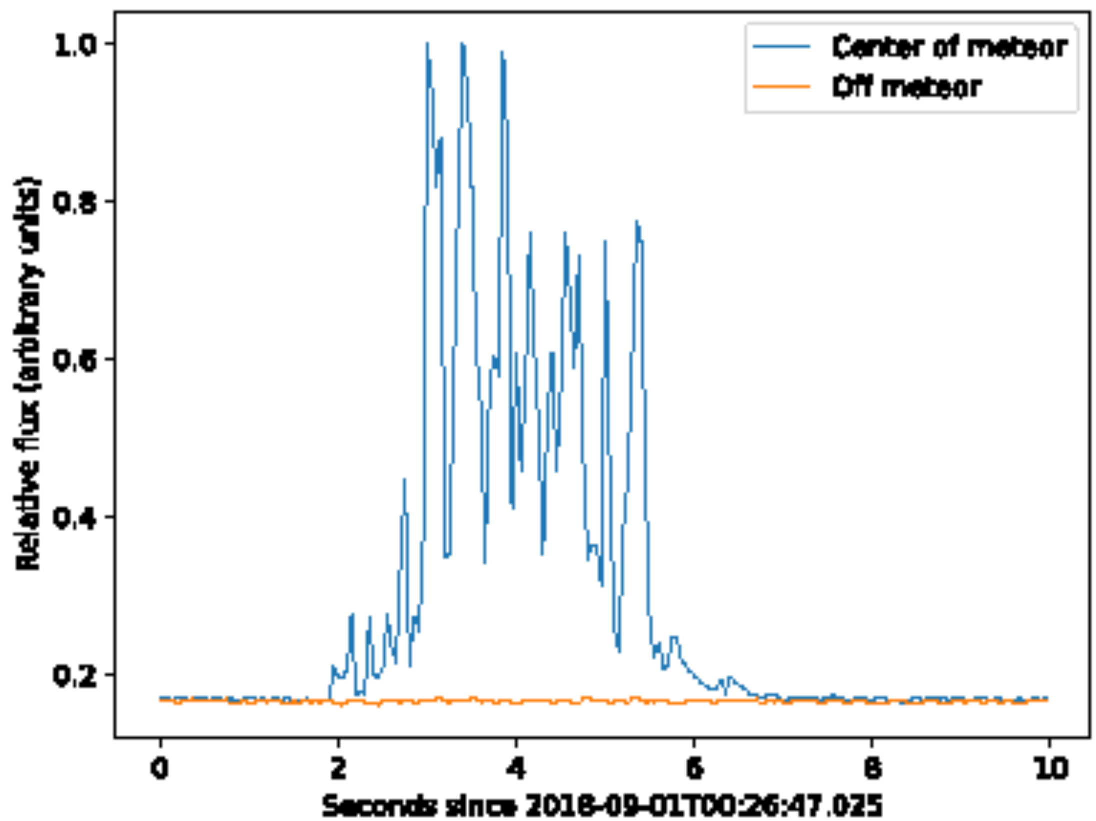
LWA-SV Parameters

- 257 dual polarization LWA dipoles
- Dense 110 m x 100 m aperture
- 10-88 MHz frequency coverage
- 20 MHz bandwidth (beamforming + imaging)
- New Digital Processor using 16 Roach 2 boards and 7 GPU servers
- Bifrost architecture for Data processing

Image Credit: Greg Taylor

EPIC in action:
First Light with EPIC on LWA-SV



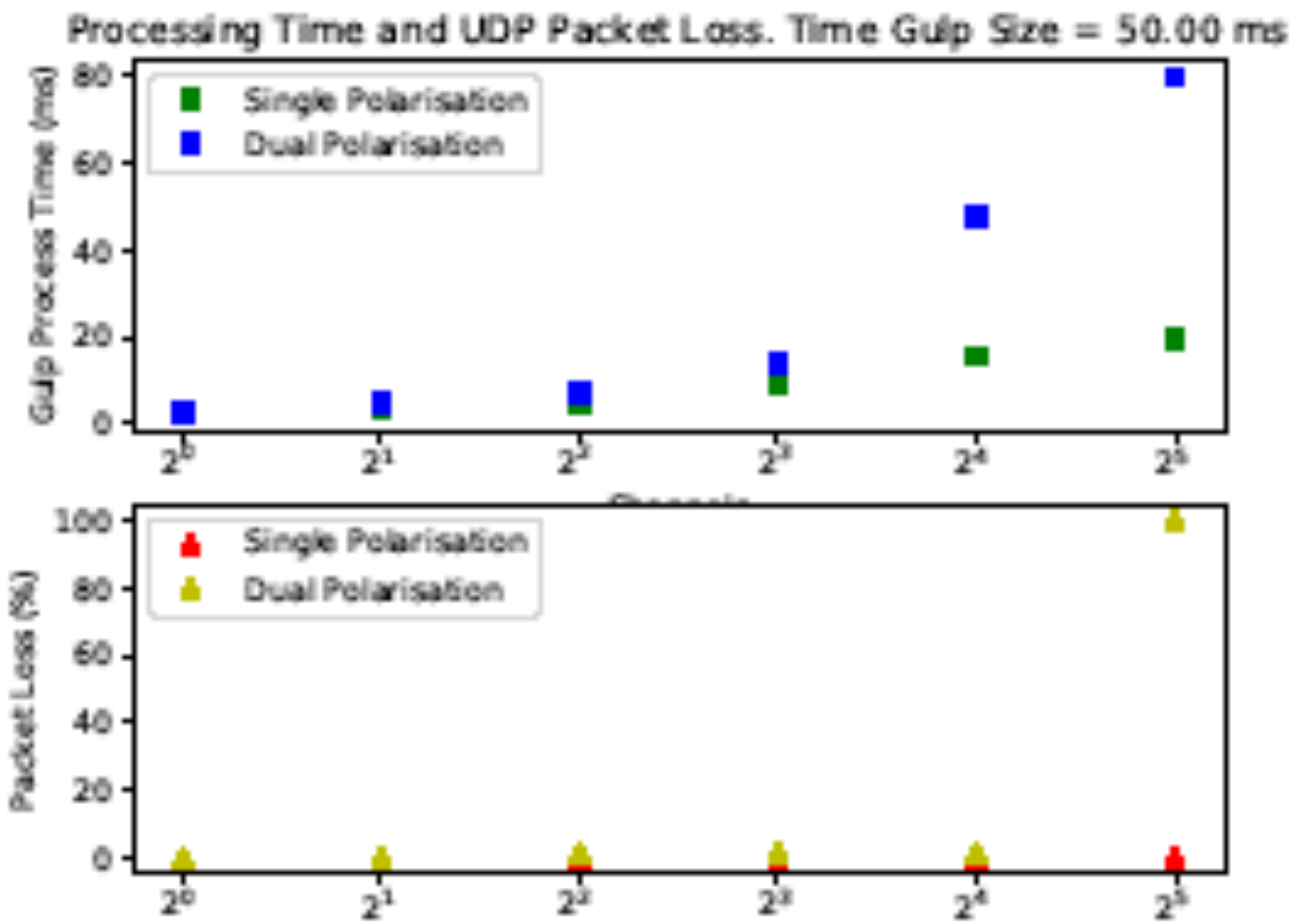


Time cadence: 50 ms

Image credit: EPIC team

Kent, ..., **NT** et al. (in prep.)

EPIC Throughput

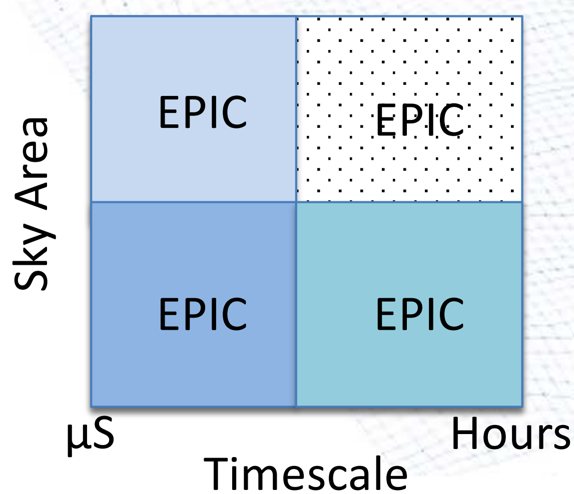


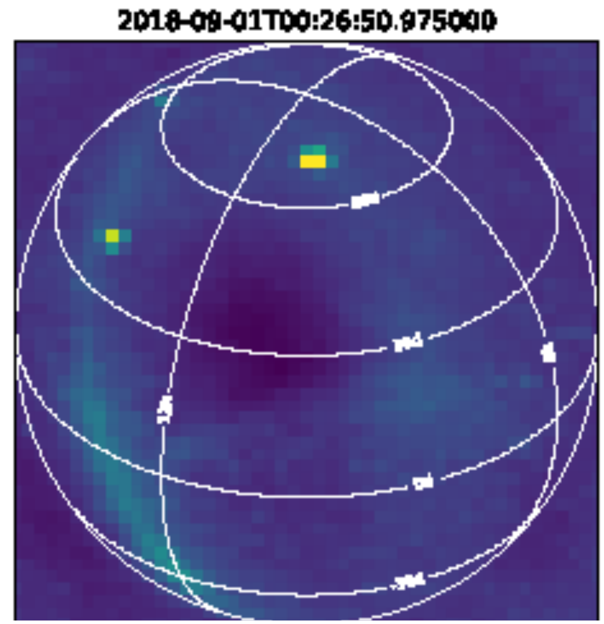
Kent, …, **NT** et al. (in prep.)

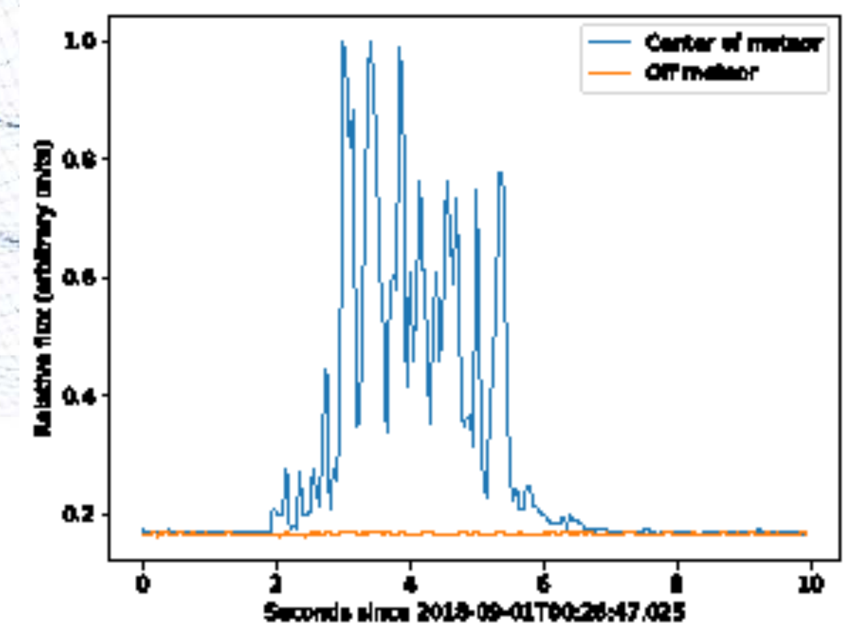
* Single GPU card

EPIC Parameter Space Coverage

- All-sky
- Real-time
- High time-resolution
- Continuous operation
- All timescales: Tens of microseconds – milliseconds – seconds – minutes – hours







EPIC on LWA-Sevilleta: NSF Grant Objectives

Task 1

- Process real data through "software EPIC" – verify it can handle real-world data and artifacts
  - LWA1
  - OVRO-LWA
  - LWA-SV
  - MWA-II Core VCS

(in progress)

120 Antennas inside
250m x 250m core

MWA phase 2: core region

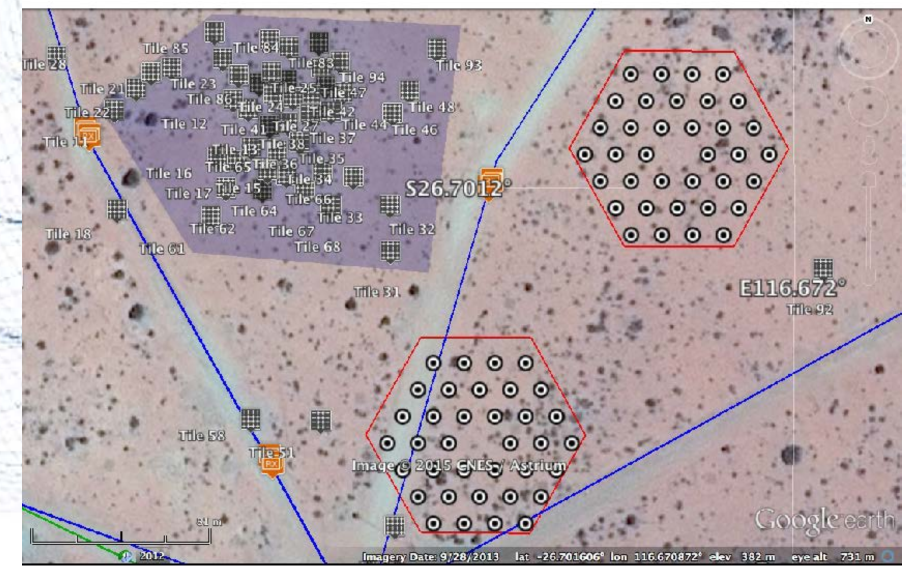


Image Credit: Randall Wayth

EPIC on LWA-Sevilleta: NSF Grant Objectives

<u>Task 2</u>

Implement GPU-based EPIC on LWA-SV
Implementation performance

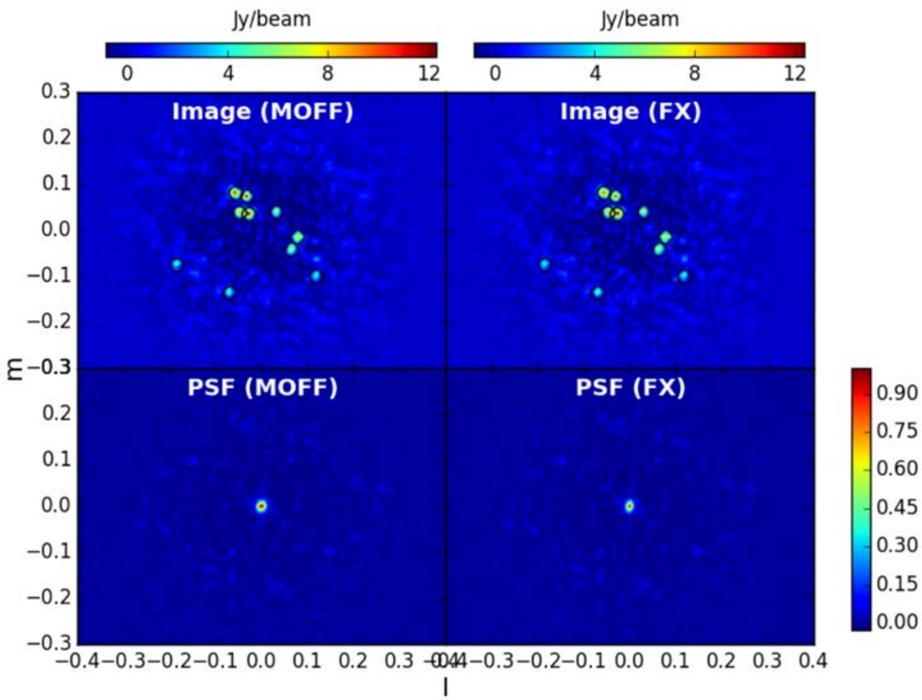
Optimize to LWA-SV system parameters

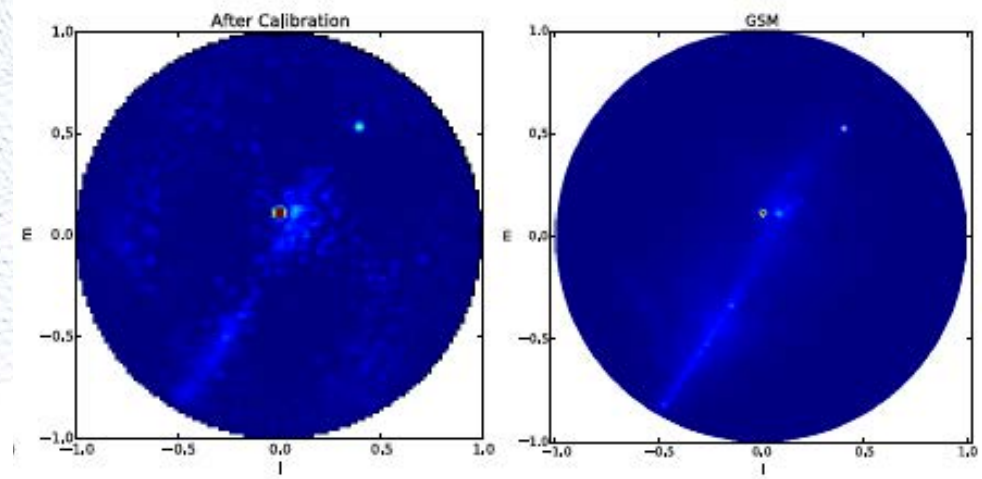
EPIC on LWA-Sevilleta: NSF Grant Objectives

<u>Task 3</u>

EPIC image quality verification with FX approach

Compare to known sky models



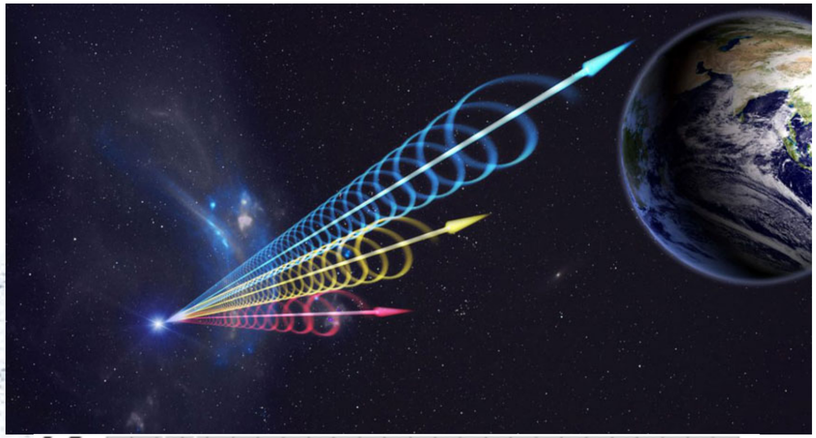


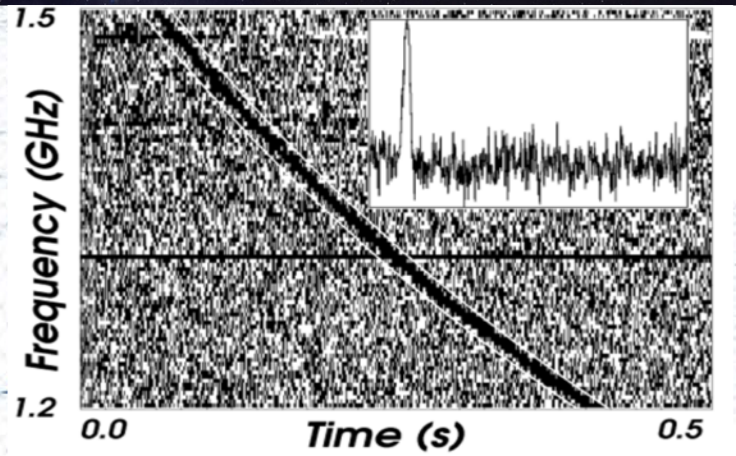
EPIC on LWA-Sevilleta: NSF Grant Objectives

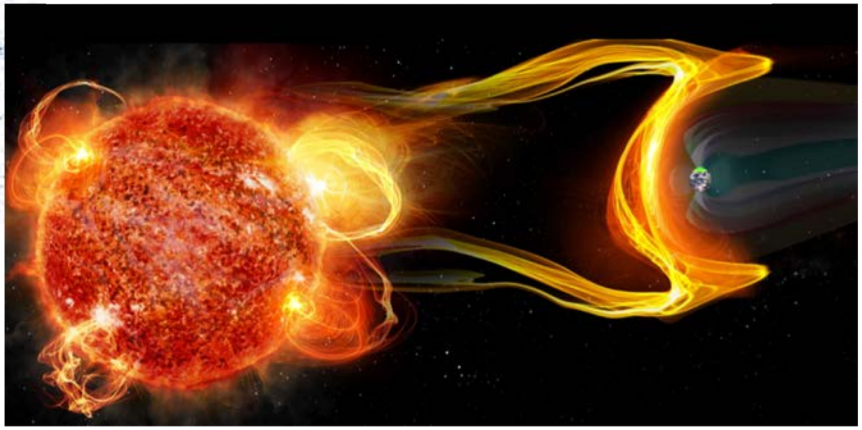
Task 4

Implement a blind search for transients

- Start with low DM De-dispersion (local FRBs, Galactic pulsars)
- Monitor 7 known millisecond pulsars with the LWA, search for more
- Circular polarization to monitor exoplanets for auroral bursts



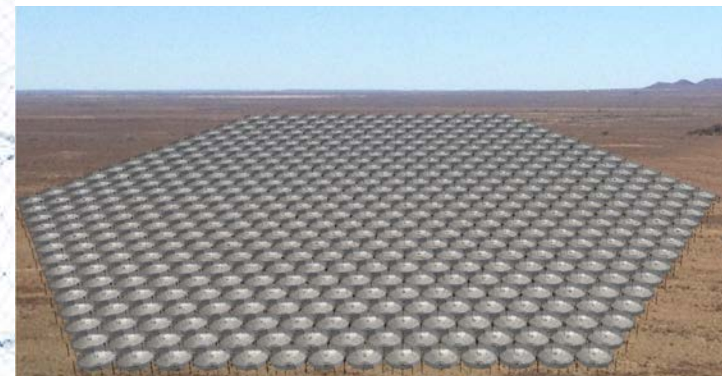


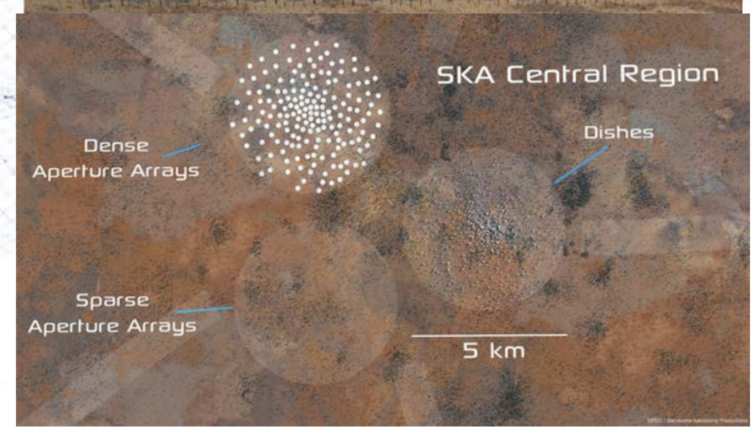


EPIC on LWA-Sevilleta: NSF Grant Objectives

Task 5

- Evaluate performance, potential and scalability for
  - SKA1
  - LWA swarm (network)
  - HERA-III
- Inputs to Astro2020 decadal survey





EPIC Summary

- EPIC is one of the most generic / fast / efficient versions of a direct imager and inherently a science-ready radio architecture
- EPIC is promising for most modern/future telescopes (LWA, LWA Swarm, ngLOBO-low, SKA1-low, HERA, CHIME, MWA II/III core, etc.) that have dense layouts
  - Time domain Universe
    - Fast writeouts
    - Economic data rates
    - Calibrated images at no additional cost
  - Cosmology studies
    - Large-N dense arrays for sensitivity to large scales
- NSF funded deployment on LWA-Sevilleta underway
- First light observed with EPIC on LWA-Sevilleta in real-time (Kent et al. in prep.)
- Opens up many science and technology applications currently not feasible
- EPIC paper - Thyagarajan et al. 2017, MNRAS, 467, 715
- Calibration paper (EPICal) - Beardsley et al. 2017, MNRAS, 470, 4720
- Highly parallelized EPIC implementation publicly available - https://github.com/nithyanandan/EPIC/
- Postdoc opportunities at ASU: https://sese.asu.edu/about/opportunities/other