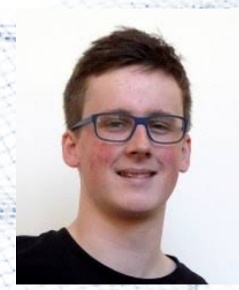
A novel direct imaging (EPIC) mode on the LWA

NSF-ATI (Award 1710719)

PI: Nithyanandan Thyagarajan, Adam Beardsley

Co-I: Judd Bowman, Greg Taylor, Jayce Dowell

Nithyanandan Thyagarajan
Jansky Fellow
(NRAO)



James Kent
(Cambridge)

Jayce Dowell
(UNM)

Adam Beardsley
NSF Fellow
(ASU)

Judd Bowman
(ASU)

Greg Taylor
(UNM)

Gregg Hallinan (OVRO-LWA, Caltech)

Miguel Morales (UW)

Aaron Parsons (HERA, Berkeley)

Dan Werthimer (Berkeley)

Peter Williams (CfA)

Casey Law (Berkeley)

Ralph Wijers (LOFAR, Amsterdam)

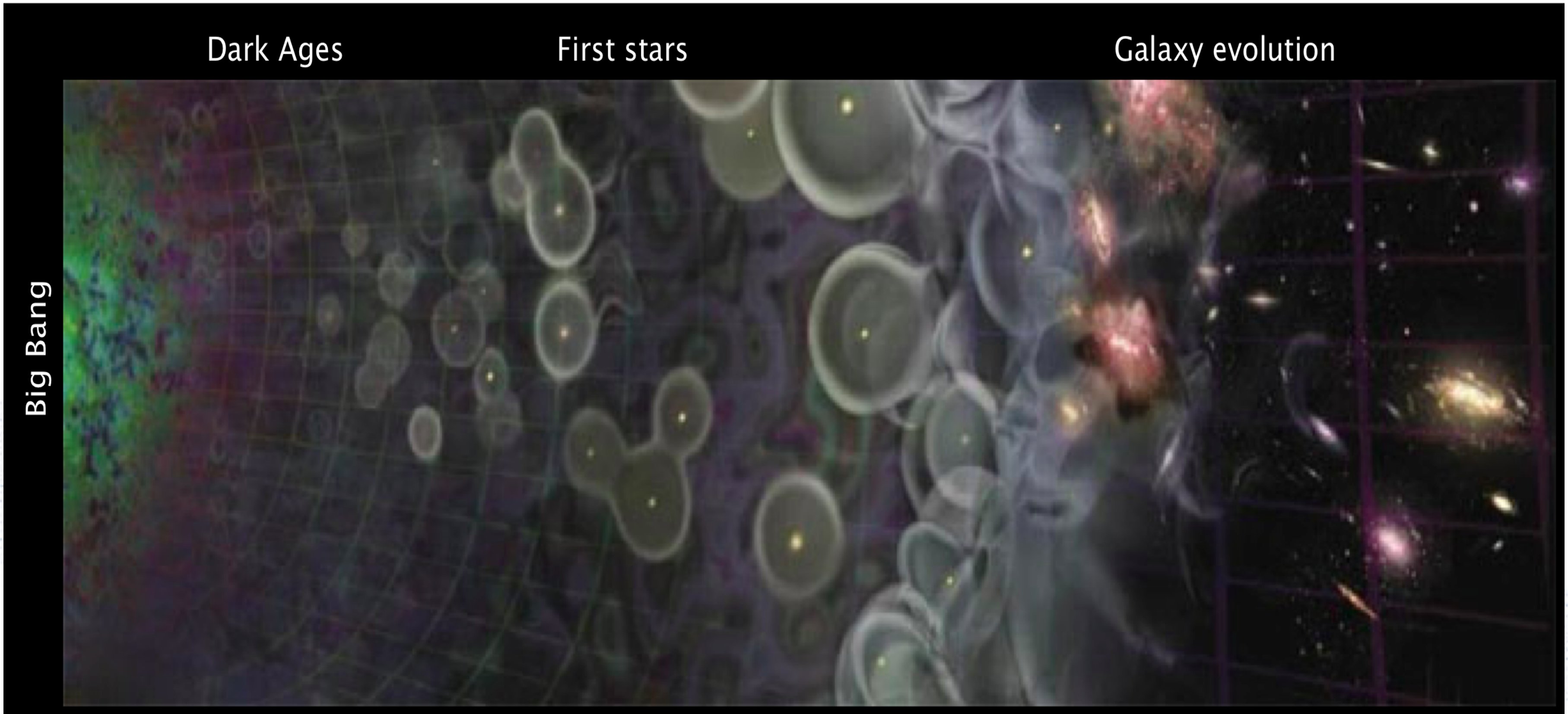
References

- **Astro2020 Decadal White Paper:** Thyagarajan et al. 2019, Submitted to the Astro2020 Decadal White Paper, "A Roadmap for Efficient Direct Imaging with Large Radio Interferometer Arrays"
- **LWA Implementation:** Kent et al. 2019, MNRAS, 486, 5052, "A real-time, all-sky, high time resolution, direct imager for the long wavelength array"
- **Imaging:** Thyagarajan et al. 2017, MNRAS, 467, 715, "A Generic and Efficient E-field Parallel Imaging Correlator for Next-generation Radio Telescopes"
- **Calibration:** Beardsley et al. 2017, MNRAS, 470, 4720, "An efficient feedback calibration algorithm for direct imaging radio telescopes"
- **Formalism:** Morales 2011, PASP, 123, 1265, "Enabling Next-generation Dark Energy and Epoch of Reionization Observatories with the MOFF Correlator"

Outline

- Motivation for EPIC on LWA and large-N arrays
- Deployment on LWA-SV
  - First light (Meteor reflection)
  - Jovian Burst
  - Performance
- Prospects for future low frequency large-N arrays including LWA swarm

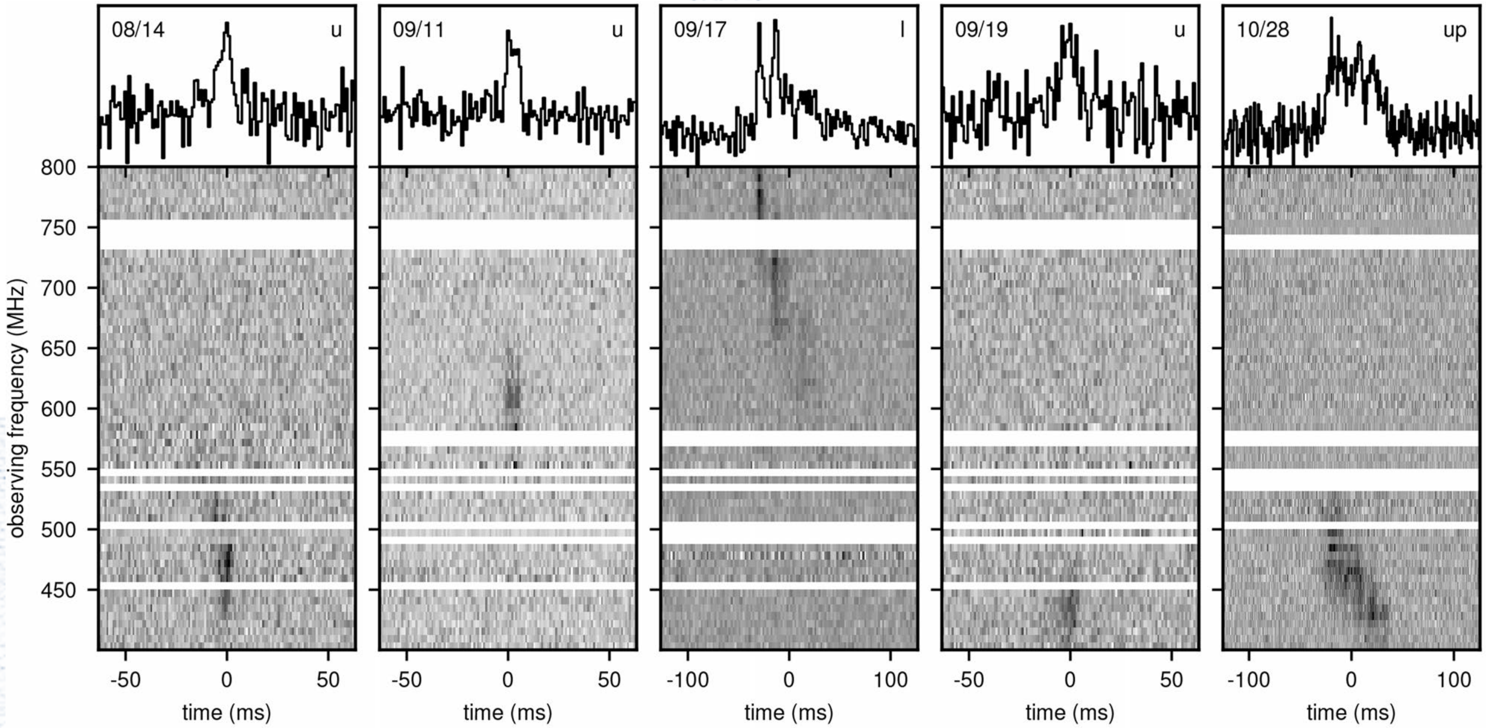
Need for new paradigm: Extreme-sensitivity Science



- Cosmology
- Large scale structure

- Dynamic range in imaging > 10^5:1
- Wide fields of view
- Compact Aperture Size
- Large Number of antennas for Collecting area

Need for new paradigm: Extreme time-domain phenomena



The CHIME / FRB collaboration (2019)

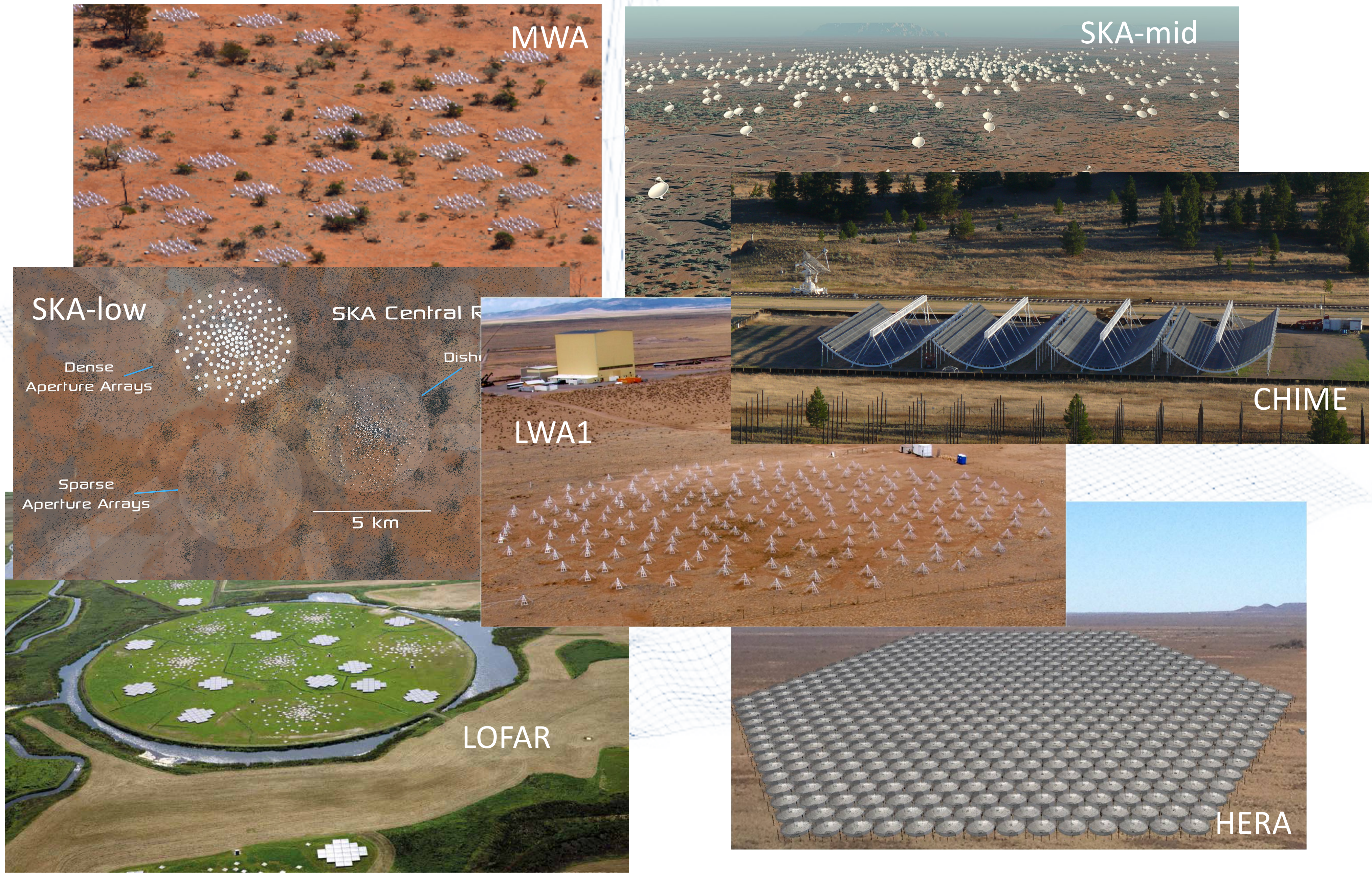
Fast radio Bursts (FRB)

- Extreme explosive astrophysical phenomena
- Very bright, but very short duration (< 1 ms)
- Unknown but very distant origin in the Universe
- Probes for Dark matter, matter under extreme densities

Time domain requires…

- Wide fields of view
- Large number of antennas for collecting area
- High time cadence, fast writeouts
- Transform from serendipitous to systematic discovery

Need for new paradigm: Massive radio arrays



Modern Radio Astronomy: A radically changing landscape

- Extreme sensitivity / dynamic range (> 10^5:1)

- Large collecting areas (> 1000 antennas)
- Wide fields of view (even all-sky)
- Extreme time cadence / time resolution (< 1 ms)

- High angular resolution (large aperture sizes / antenna separations)

Playing the role of Nature more efficiently

Direct Imaging

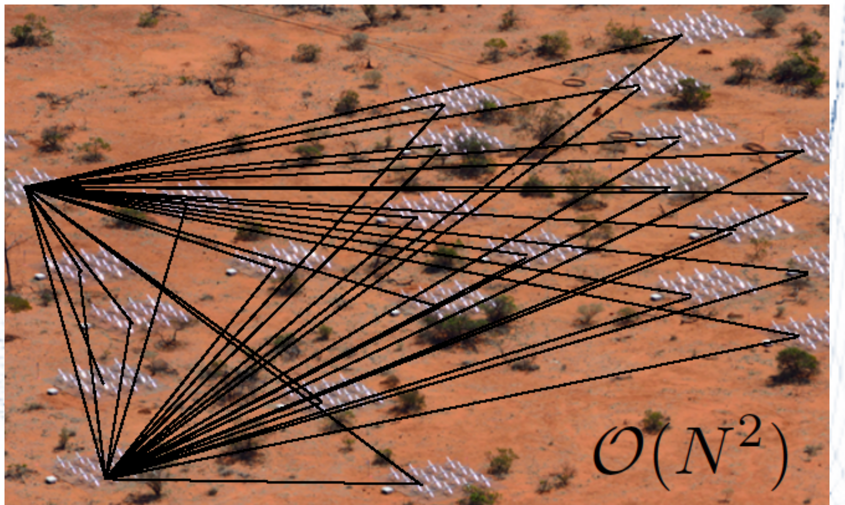
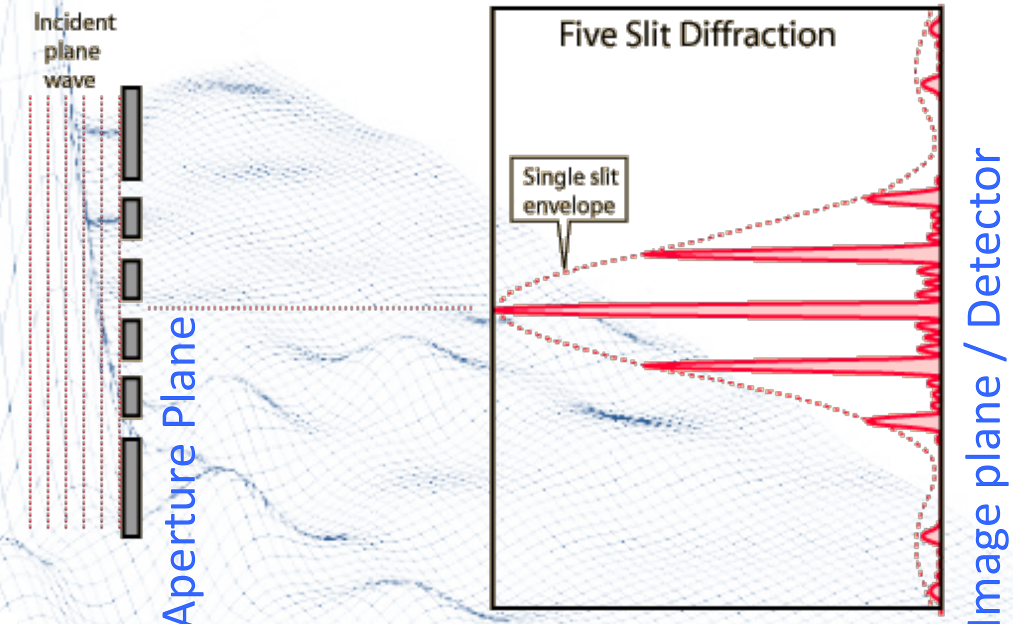


Image credit: Adam Beardsley



$$I(l,m) = \iint \mathcal{V}(u,v)e^{2\pi i(ul+vm)}dudv$$

Spatial correlation: Computationally expensive for Large-N telescopes

$$\vec{E} = \vec{E}_o e^{i(\vec{k}.\vec{r}-wt)}$$

Superpose Propagated EM Waves = Fourier Transform

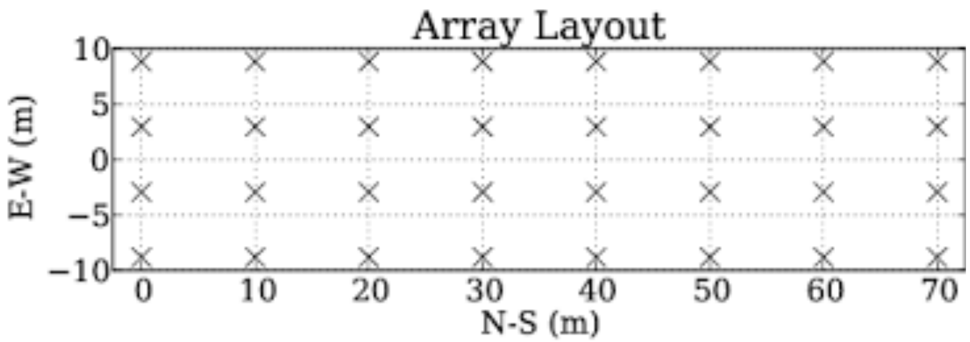
- Architectural redesign?
- Convolution theorem of Fourier Transform:

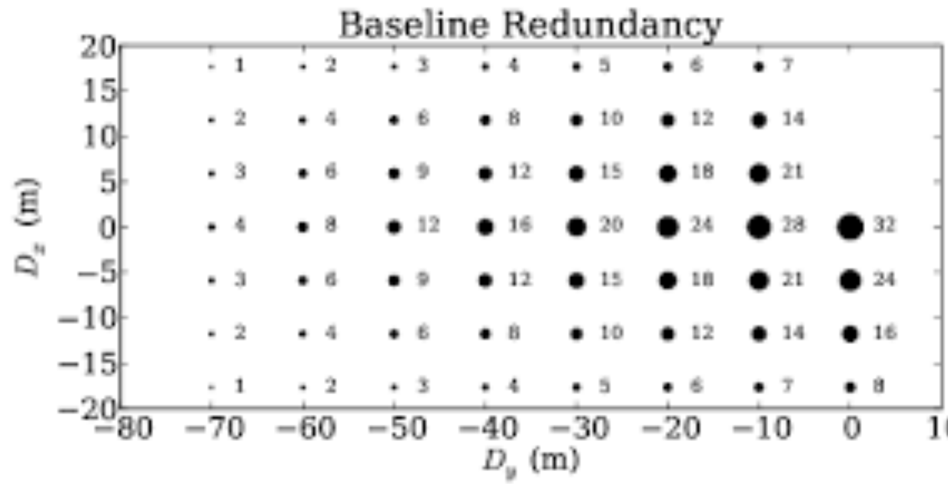
FT(Correlation) ←→ FT(.) x FT(.) = |FT(.)|^2

Traditional / Correlation-based

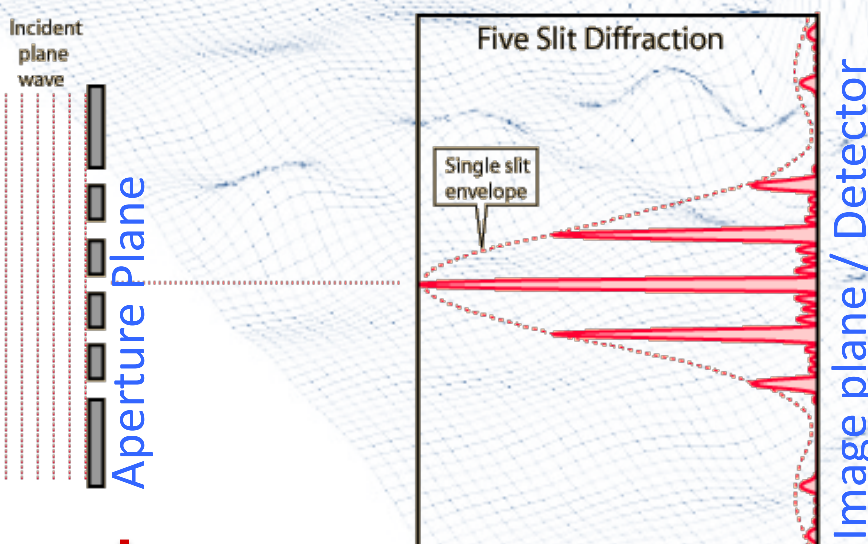
Direct Imaging (FT and square)

A naïve version of Direct Imaging





Foster et al. (2014)



$$\vec{E} = \vec{E}_o e^{i(\vec{k}.\vec{r} - wt)}$$

Superpose Propagated EM Waves
= Fourier Transform

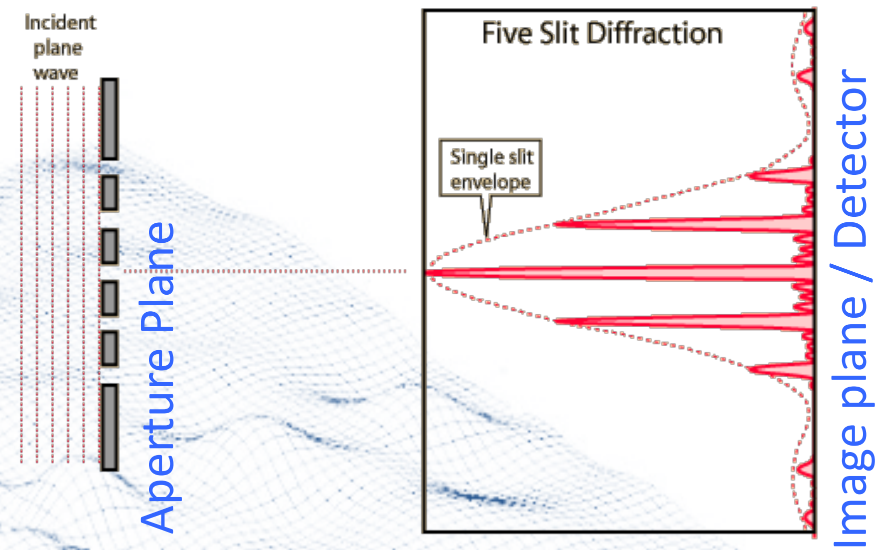
Disadvantages

- 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

A generic version of Direct Imaging
EPIC: E-field Parallel Imaging "Correlator"

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



$$\vec{E} = \vec{E}_o e^{i(\vec{k}.\vec{r}-wt)}$$

Superpose Propagated EM Waves
= Fourier Transform

Gridding is key!

Arbitrary Layout

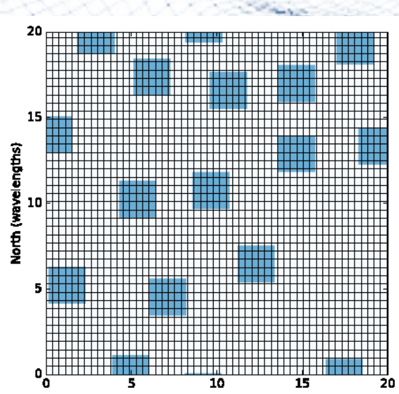


Image:
Beardsley et al. (2017)

Heterogeneous Array

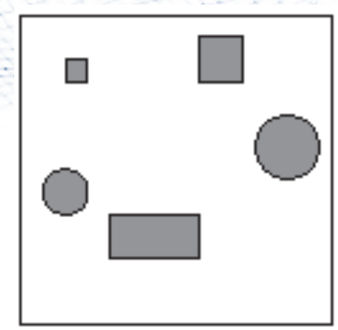


Image:
Thyagarajan et al. (2017)

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

FX

Traditional / Correlation-based

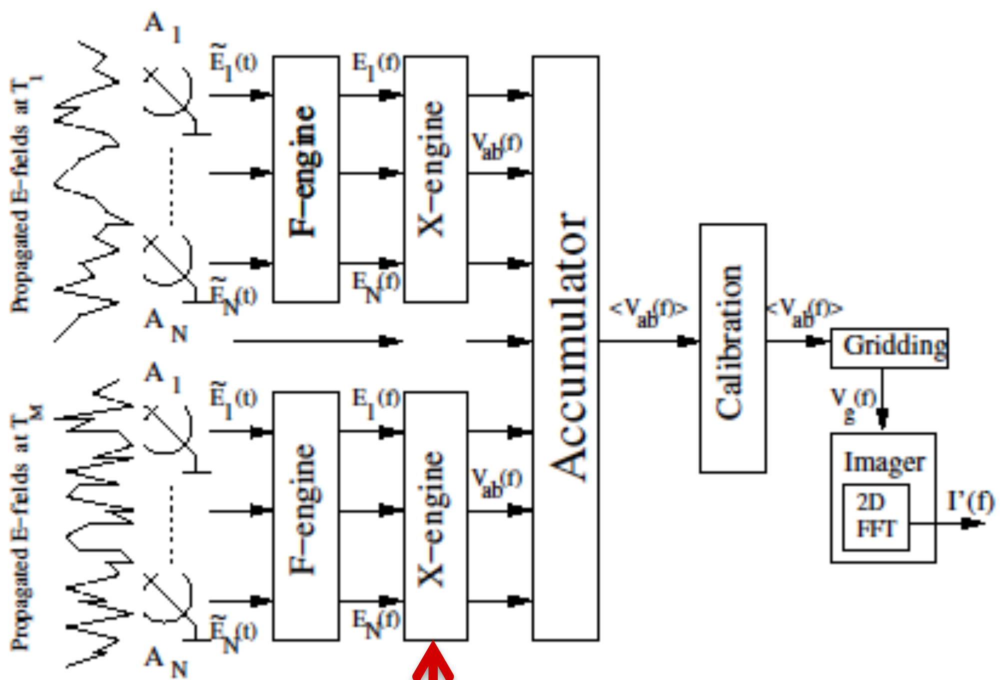
FT(Correlation)

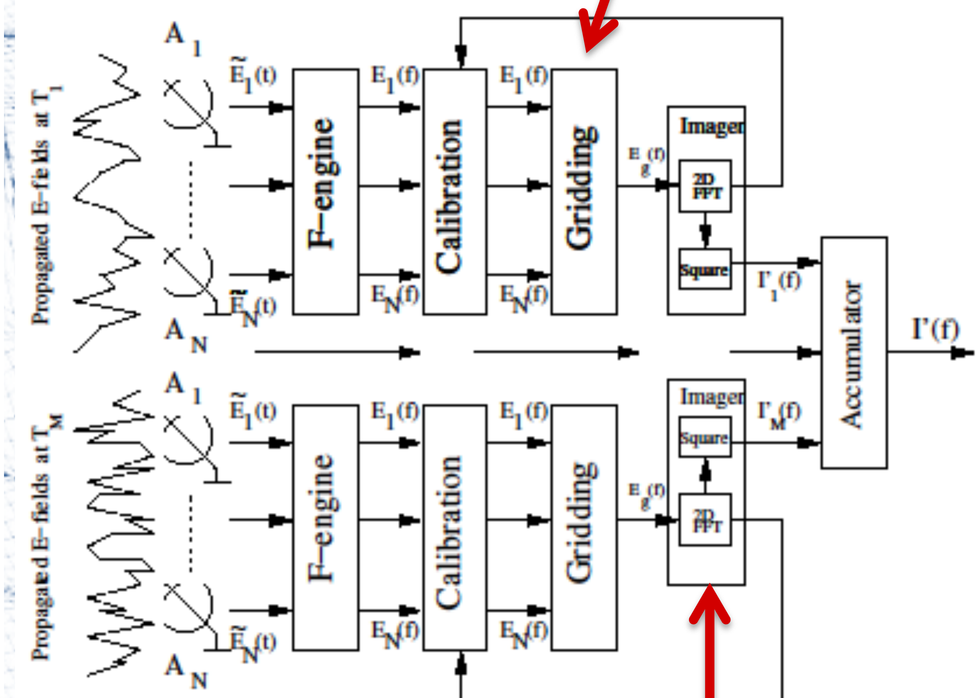
EPIC

Direct Imaging

FT(.) x FT(.)

Gridding makes it generic





$O(N_a^2)$

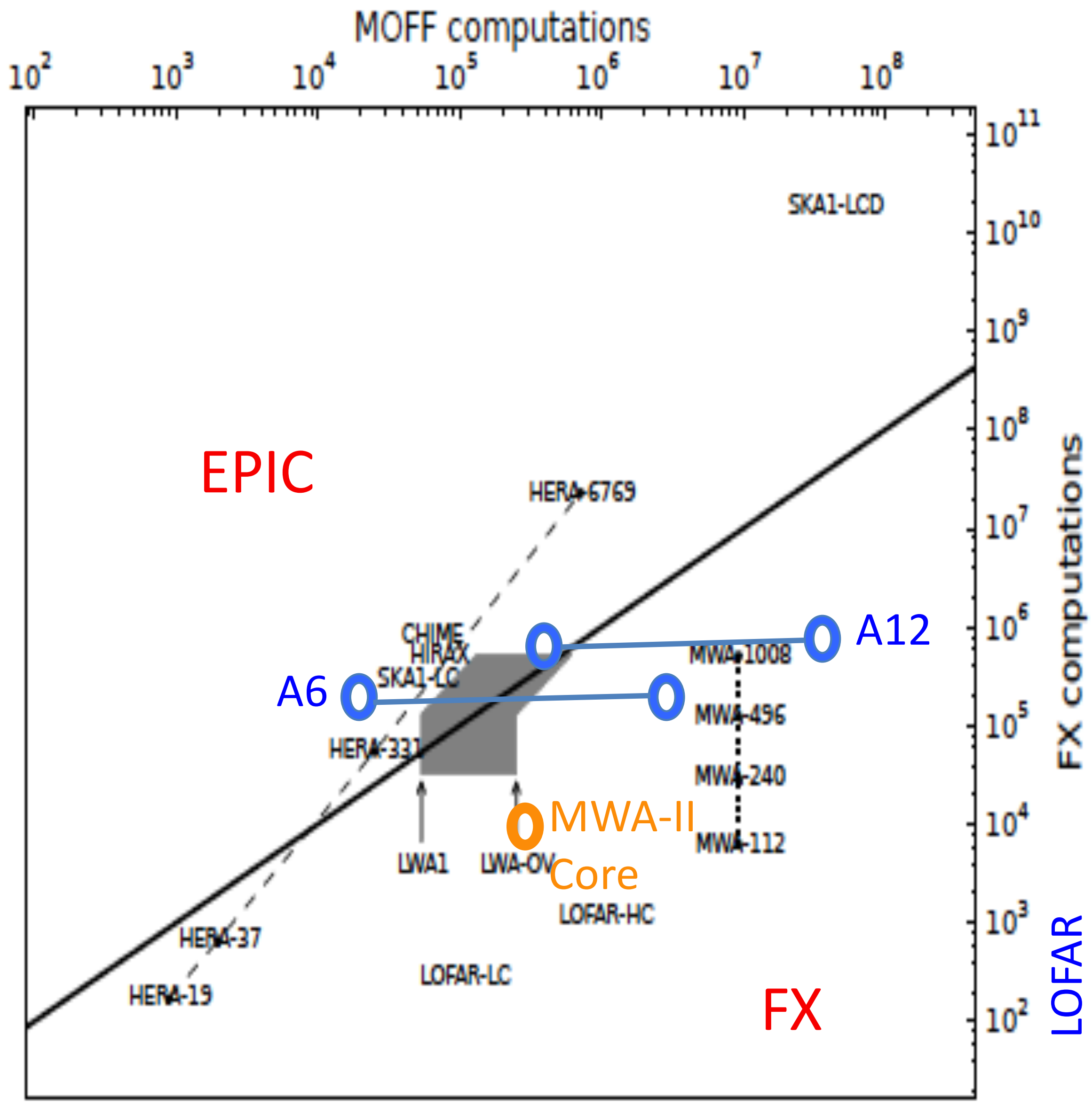
Thyagarajan et al. (2017)

$O(N_g \log N_g)$

Fast Imaging

(With calibration)

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

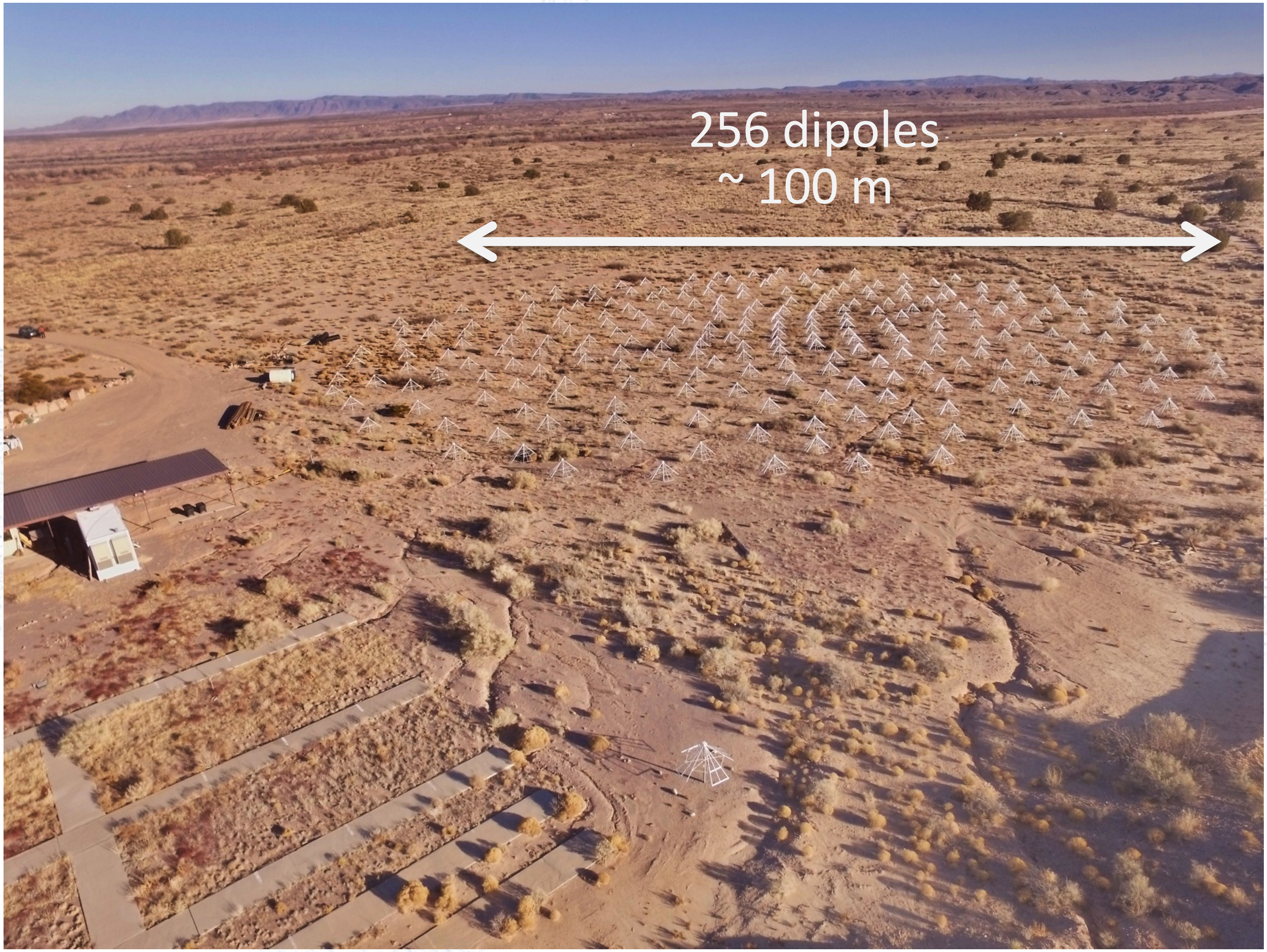
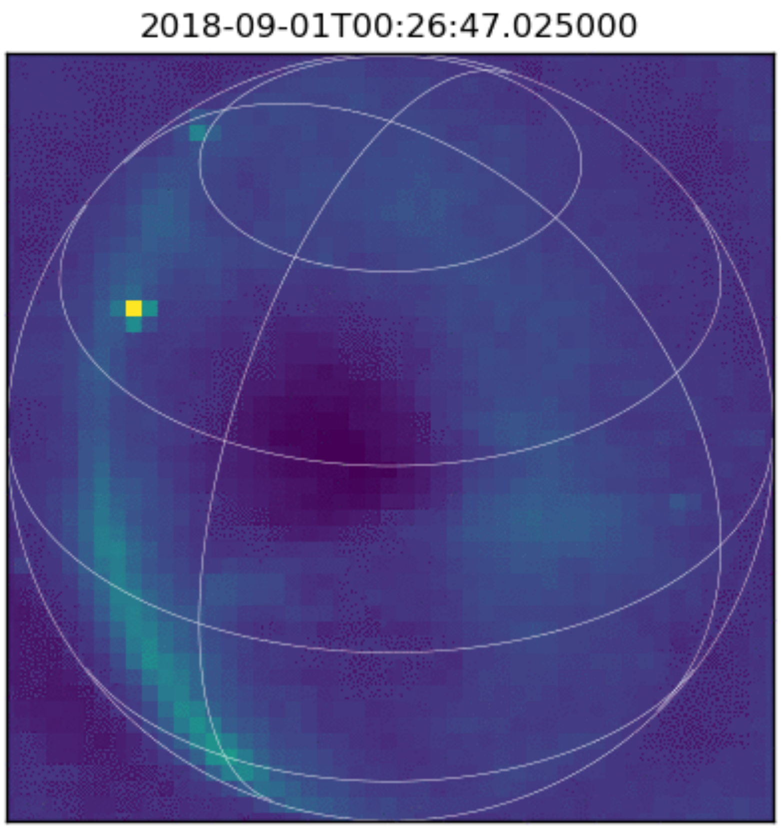
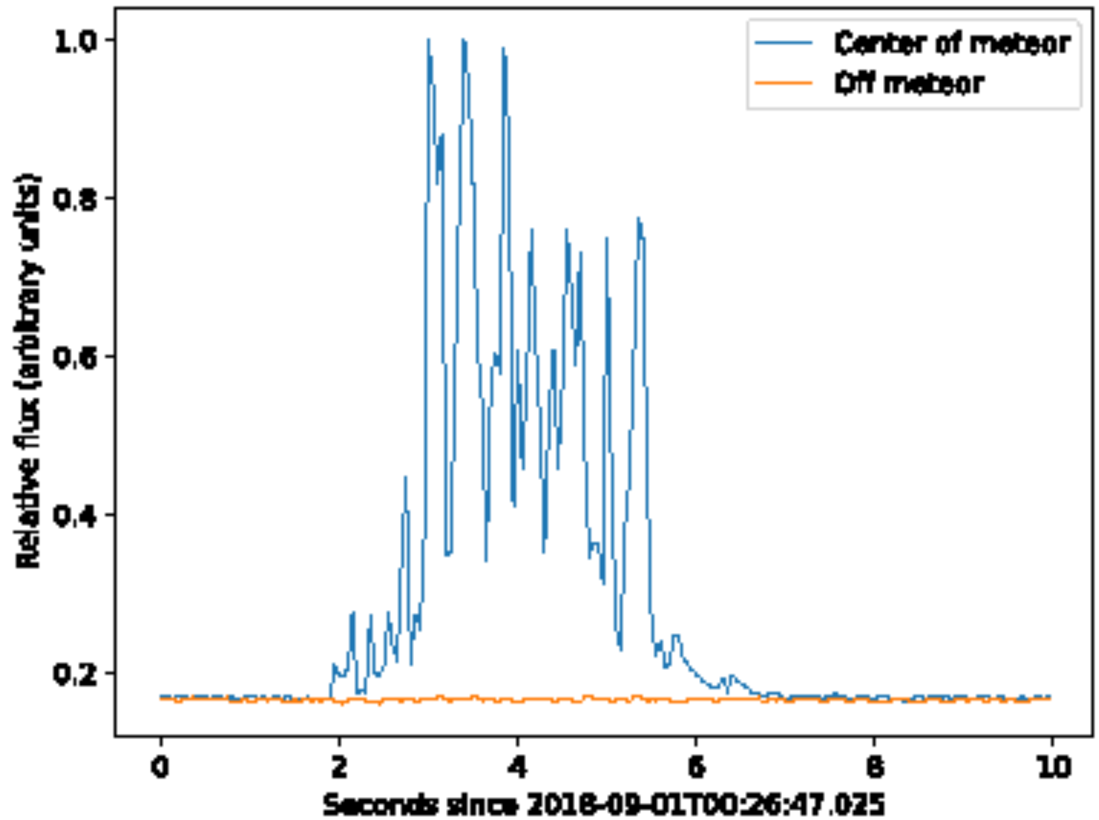


Image Credit: Greg Taylor (PI: LWA-SV)

EPIC on LWA-SV:
First Light with EPIC on LWA-SV
(Meteor Example)





Time cadence: 50 ms

Image credit: EPIC team

Kent et al., 2019

Significant Time-domain Capability added to LWA-SV

Before EPIC: > 1 s, After EPIC: ~ few ms

EPIC on LWA-SV: Jovian Burst Example

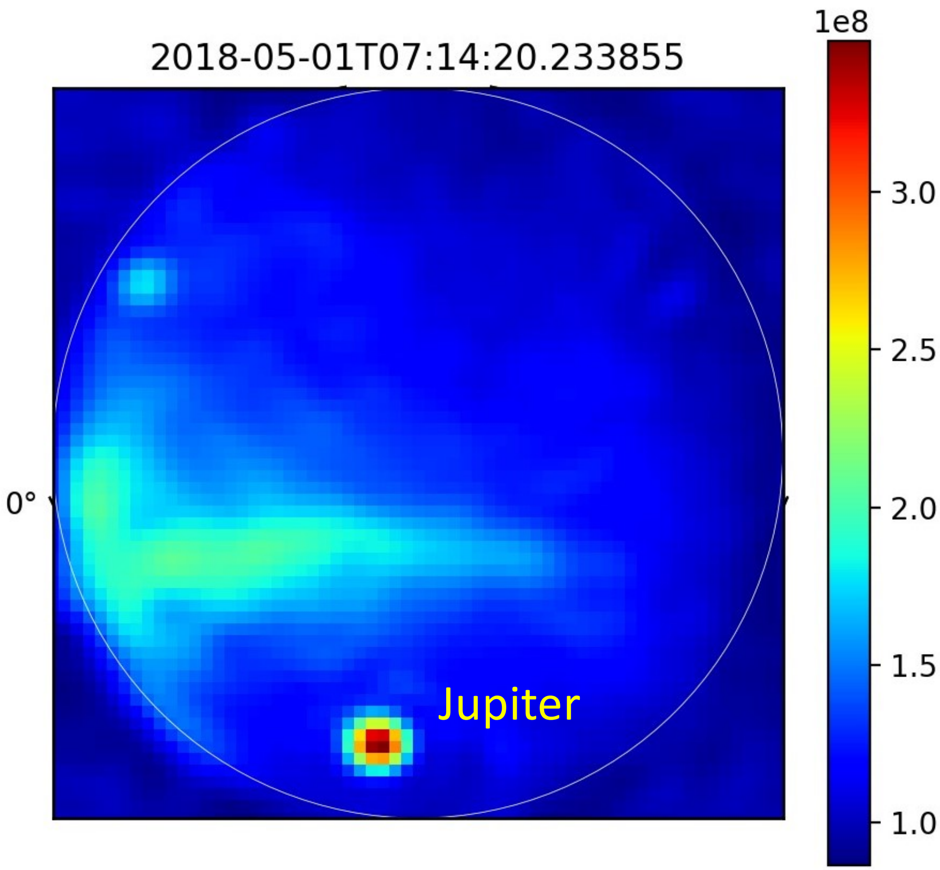
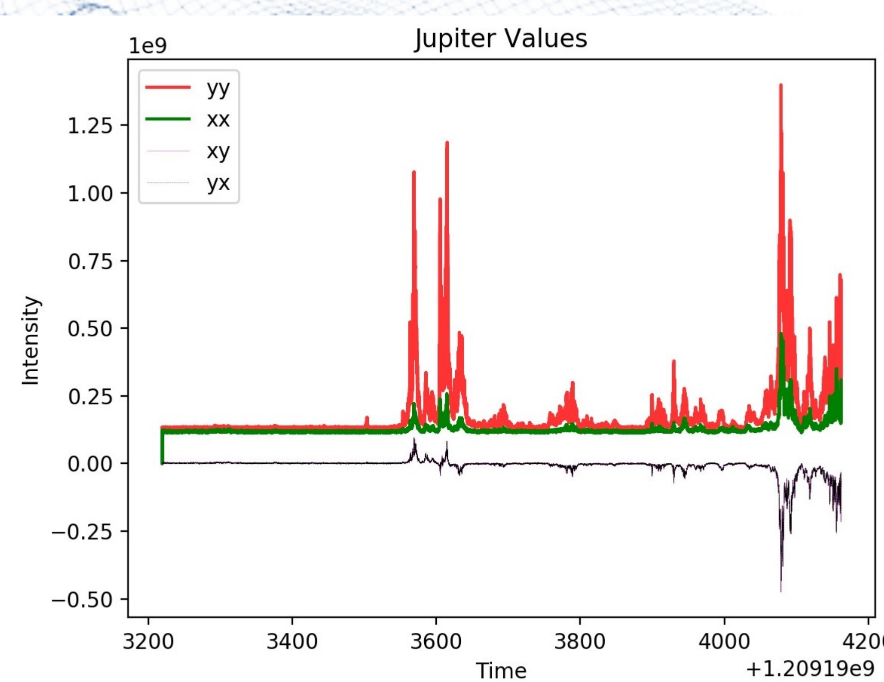


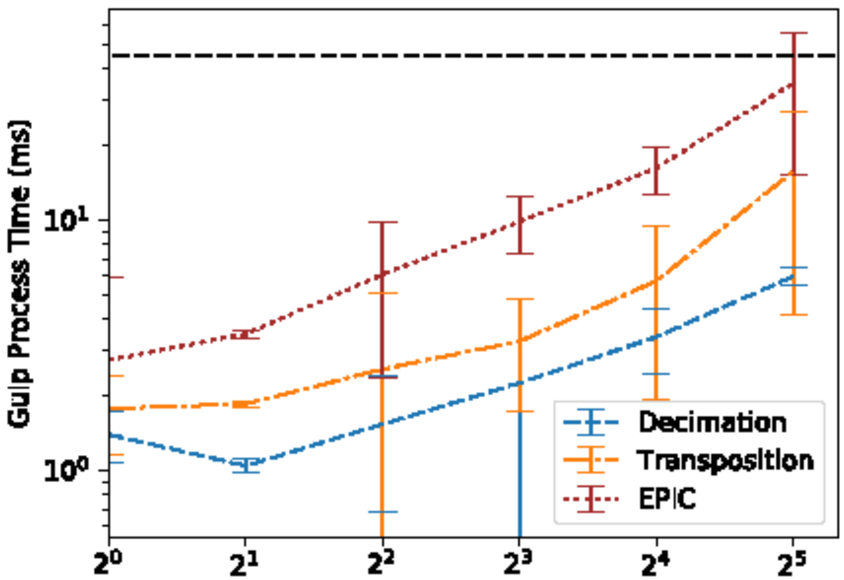
Image Credit: Ruben Ortiz (ASU), EPIC team

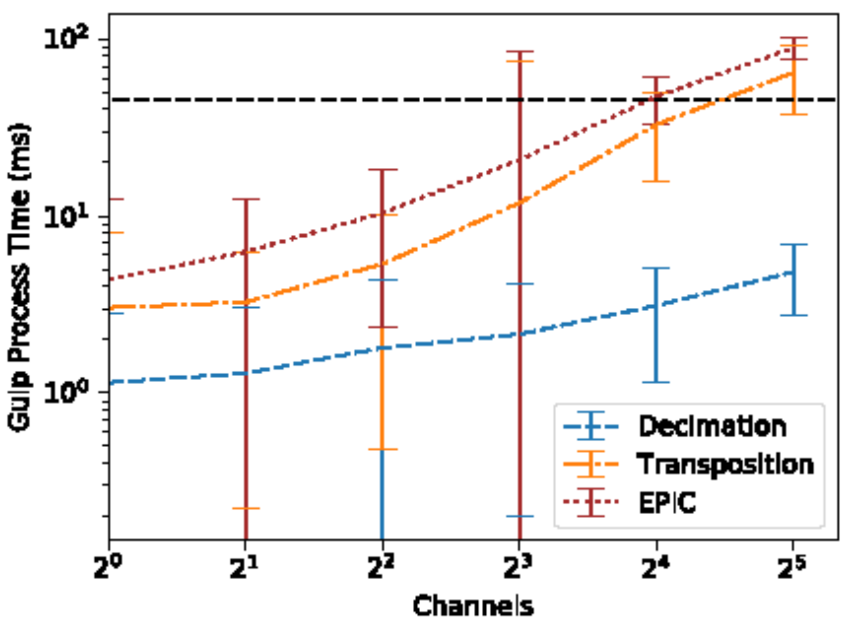
Jovian Burst Movie

- Band center ~26 MHz
- ~100 kHz BW
- 50 ms cadence

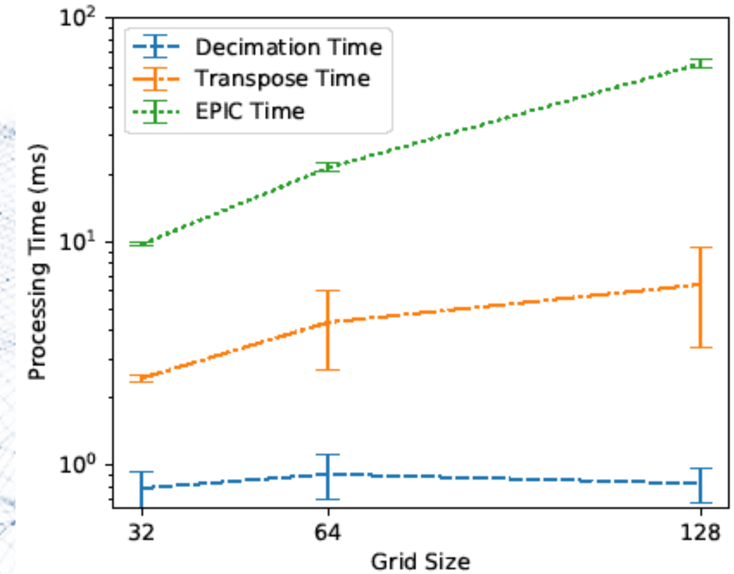


EPIC on LWA-SV: Performance
(One NVIDIA GTX 980 GPU Card)





Kent et al., 2019



- 64^2 grid: 100 kHz in dual pol for Gulp size=25 ms, Process time 90% gulp size

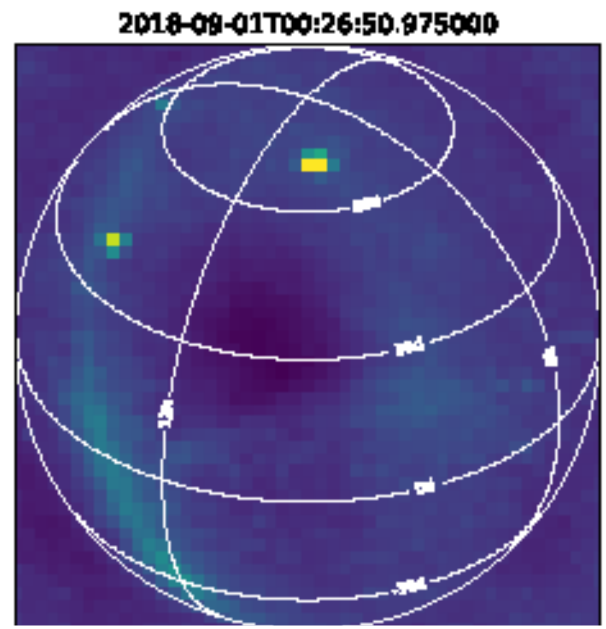
- 64^2 grid: 800 kHz in single pol, 400 kHz in dual pol for Gulp size=50 ms, Process time 90% gulp size

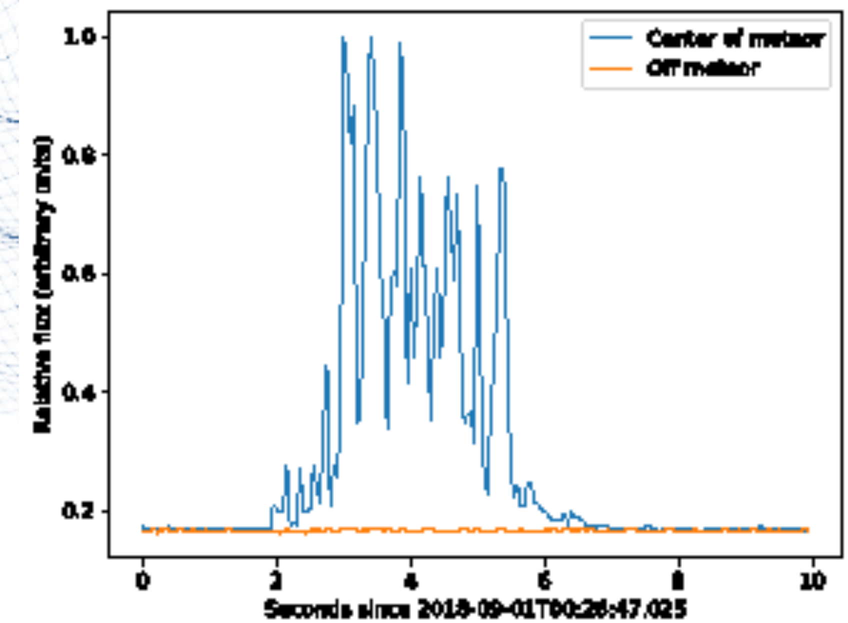
EPIC observing mode on LWA-SV

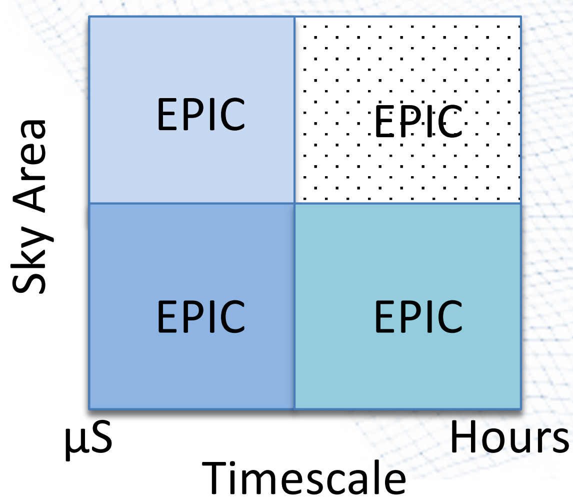
- Experimental
  - Needs EPIC/LWA team for observational set up
  - Few minor post-processing steps
- Currently operational
  - Real-time at cadence < 50 ms (down to few ms)
  - All-sky imaging
  - 4 instrumental Stokes images
  - Up to ~ 1 MHz BW (on a single NVIDIA GTX 980 GPU card)
  - Continuous operation (tested for 24 hours)
- Improvements
  - Optimization
  - Robust operations with minimal intervention
  - Will handle more BW ~10 MHz (with new NVIDIA GeForce RTX 2080 GPUs)

EPIC Parameter Space Coverage

- All-sky
- Real-time
- High time-resolution
- Continuous operation
- All timescales: Tens of microseconds – milliseconds – seconds – minutes – hours
- Ideal for continuous monitoring and blind search over wide fields and wide range of timescales, e.g. MSP, FRB, exoplanets, other new transients.





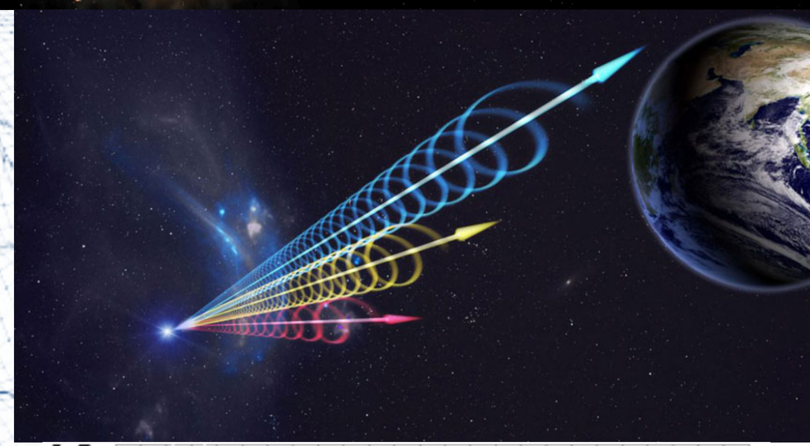


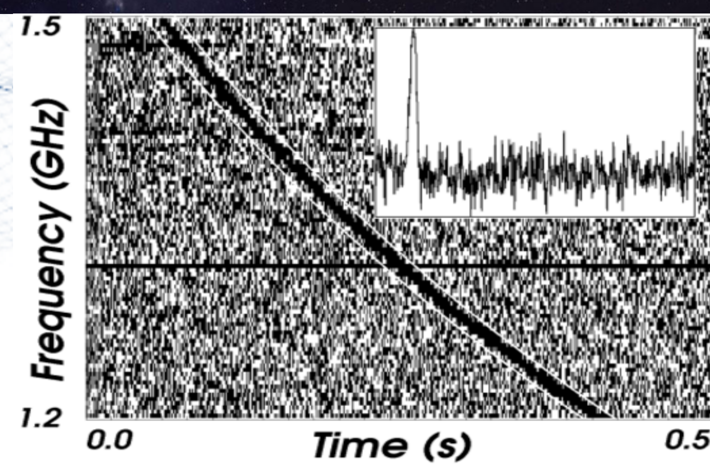
EPIC on LWA-Sevilleta: NSF Grant Objectives

Circular polarization to monitor exoplanets for auroral bursts

Implement a blind search for transients

- Start with low DM De-dispersion (local FRBs, Galactic pulsars)
- Monitor ~6-7 known MSP with the LWA, search for more

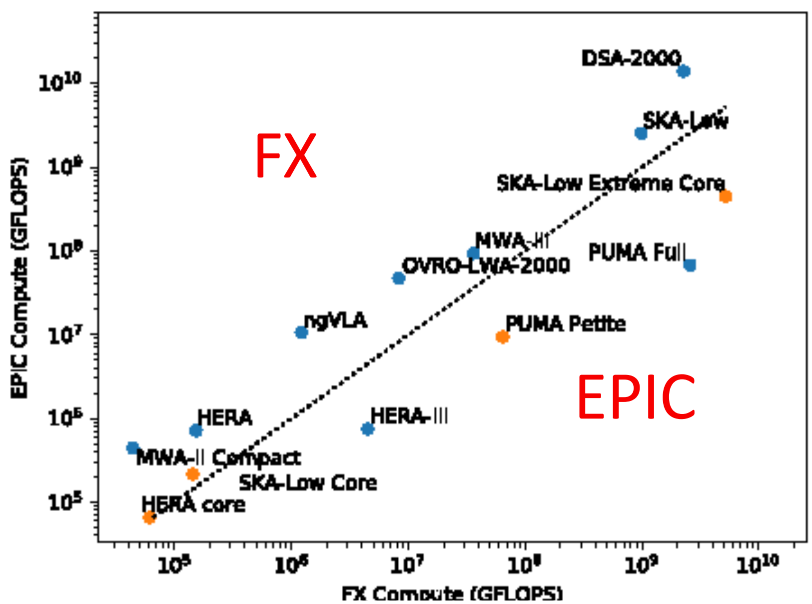


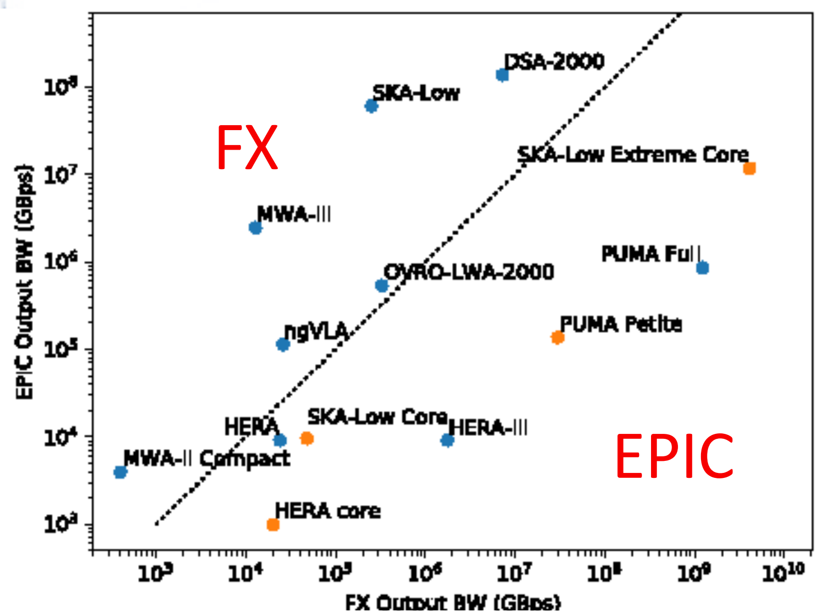


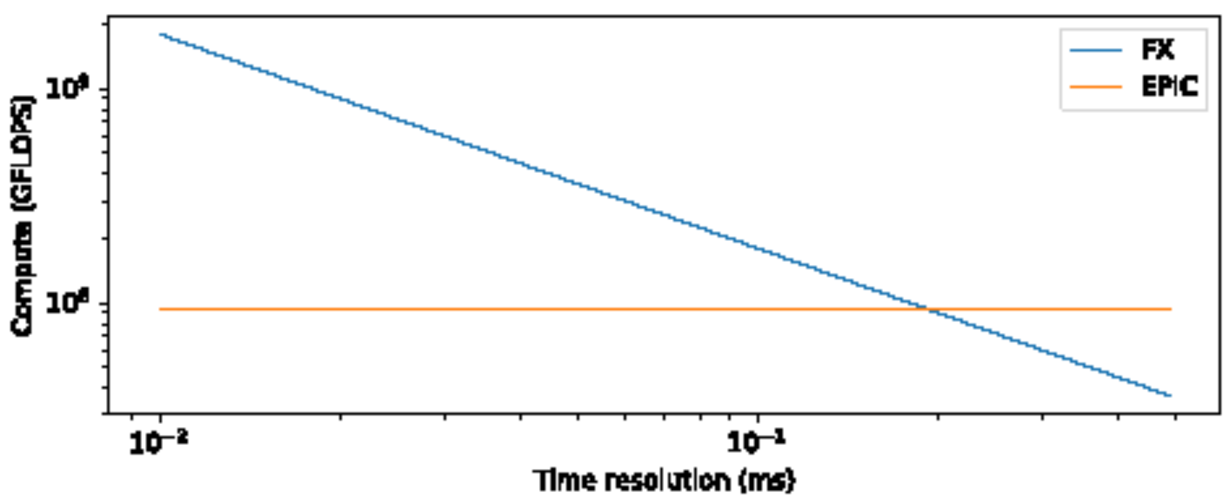
EPIC for modern large-N arrays

Thyagarajan et al. 2019, Astro2020 White Paper:

A Roadmap for Efficient Direct Imaging with Large Radio Interferometer Arrays







EPIC can benefit the LWA swarm

- Individual stations can be used as synthesized apertures for diffuse, large scale radio structures
- Sample different lines of sight for different phenomena and precise localization using triangulation
- Confidence building with independent verification from individual stations (e.g. coincidence testing)
- Hybrid imaging technology driver –
  - Station scale (dense): EPIC
  - Array scale (sparse): FX or high-resolution beamforming
- Commensal mode and instantaneous triggers
  - EPIC on dense stations (low-res) triggers immediate follow-up with LWA network for accurate position information

EPIC Summary

- EPIC is a generic / fast / efficient version of a direct imager and inherently a science-ready interferometric imaging architecture
- NSF-funded deployment on LWA-Sevilleta underway
- First light observed with EPIC on LWA-Sevilleta in real-time
- Opens up parameter space for new science/technology applications
- EPIC is promising for most modern/future telescopes (LWA, LWA Swarm, ngLOBO-low, SKA1-low, HERA, CHIME, MWA II/III core, PUMA, etc.) that have dense layouts
  - Time domain Universe
    - Continuous Wide-field, real-time, high cadence search and monitoring (MSP, FRB)
    - Fast writeouts
    - Economic data rates
  - Cosmology studies
    - Large-N dense arrays for sensitivity to large scales
- Highly parallelized EPIC implementation publicly available - https://github.com/epic-astronomy/EPIC/