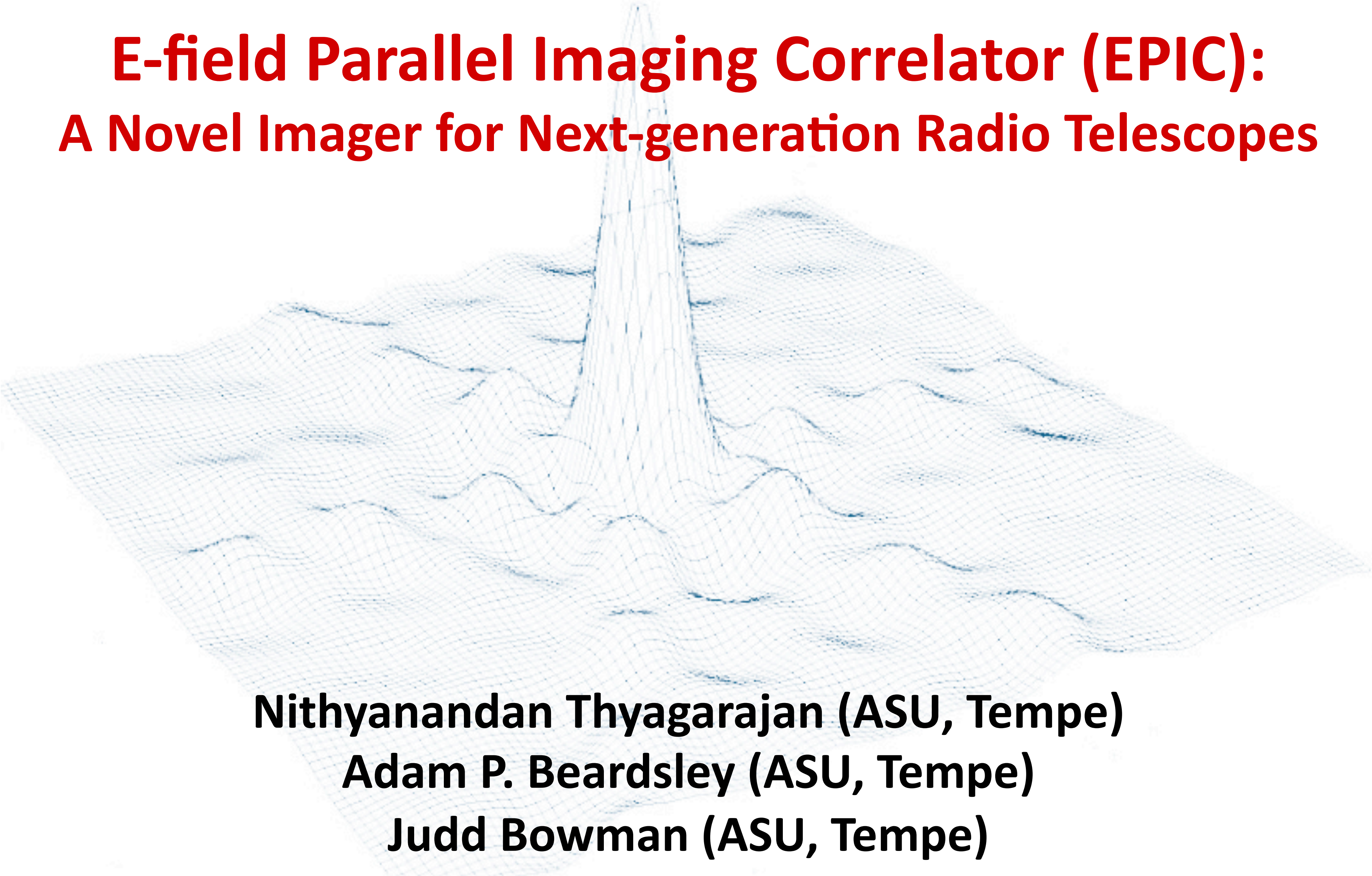
E-field Parallel Imaging Correlator (EPIC):
A Novel Imager for Next-generation Radio Telescopes



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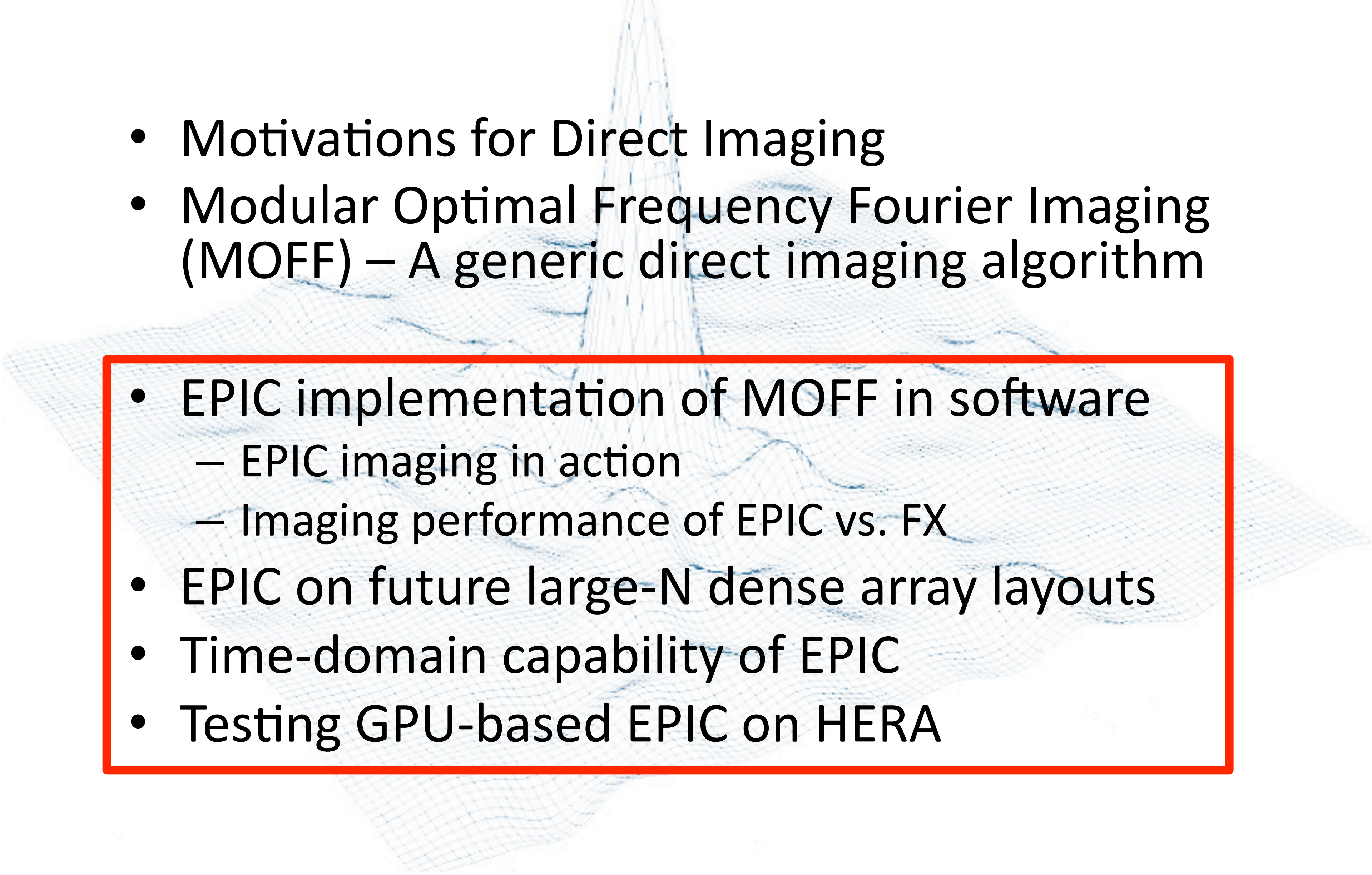
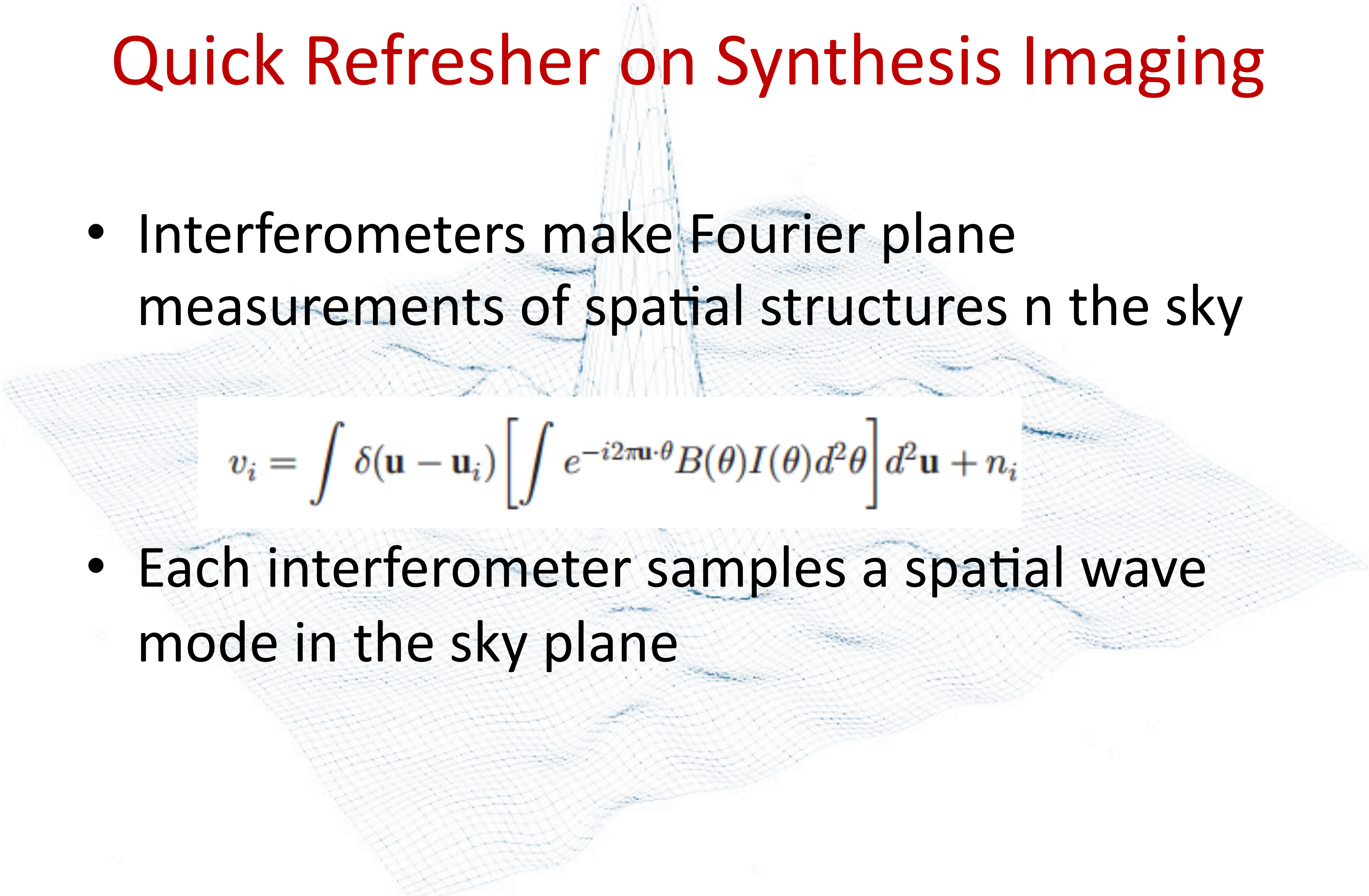
Outline



- Motivations for Direct Imaging
- Modular Optimal Frequency Fourier Imaging (MOFF) – A generic direct imaging algorithm
- EPIC implementation of MOFF in software
  - EPIC imaging in action
  - Imaging performance of EPIC vs. FX
- EPIC on future large-N dense array layouts
- Time-domain capability of EPIC
- Testing GPU-based EPIC on HERA

Quick Refresher on Synthesis Imaging



- Interferometers make Fourier plane measurements of spatial structures n the sky

$$v_i = \int \delta(\mathbf{u} - \mathbf{u}_i)\left[\int e^{-i2\pi\mathbf{u}\cdot\theta} B(\theta) I(\theta) d^2\theta\right] d^2\mathbf{u} + n_i$$

- Each interferometer samples a spatial wave mode in the sky plane

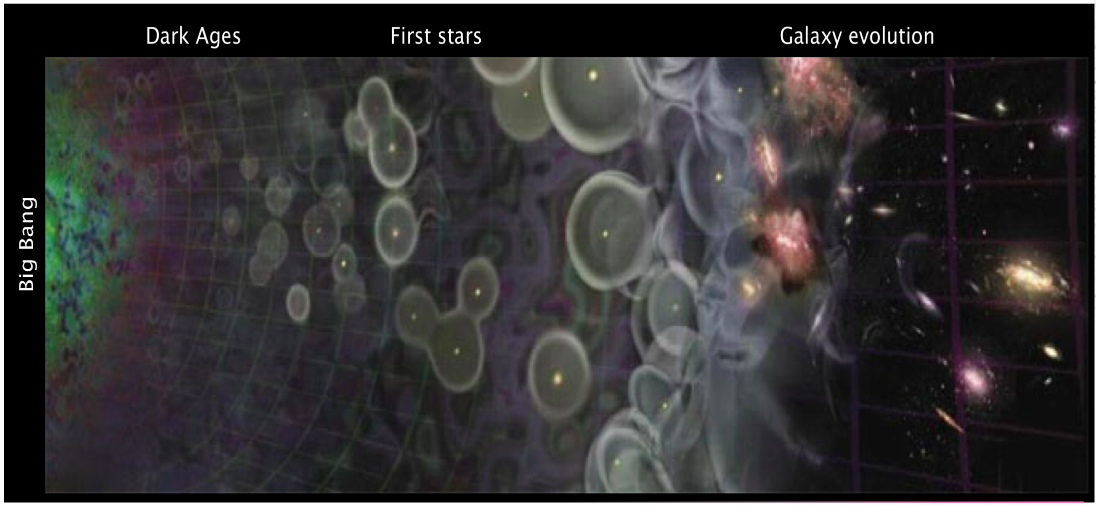
Motivations for Direct Imaging

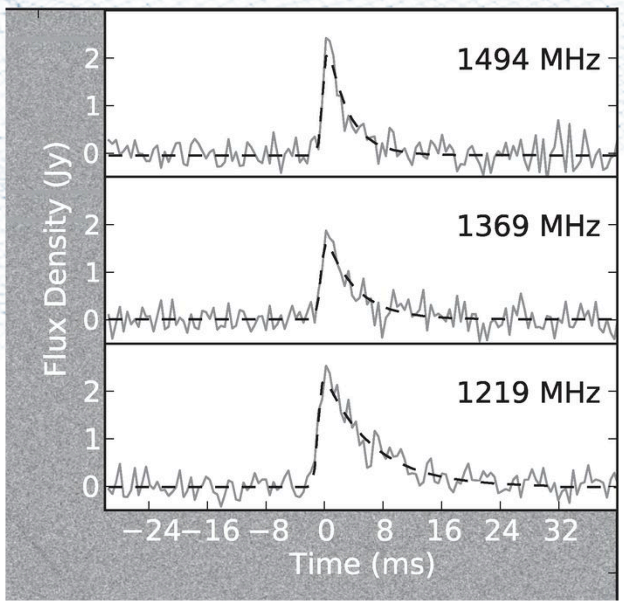
Technological

- Large collecting areas require large-N arrays
- Cost of the correlator scales as N^2

Scientific

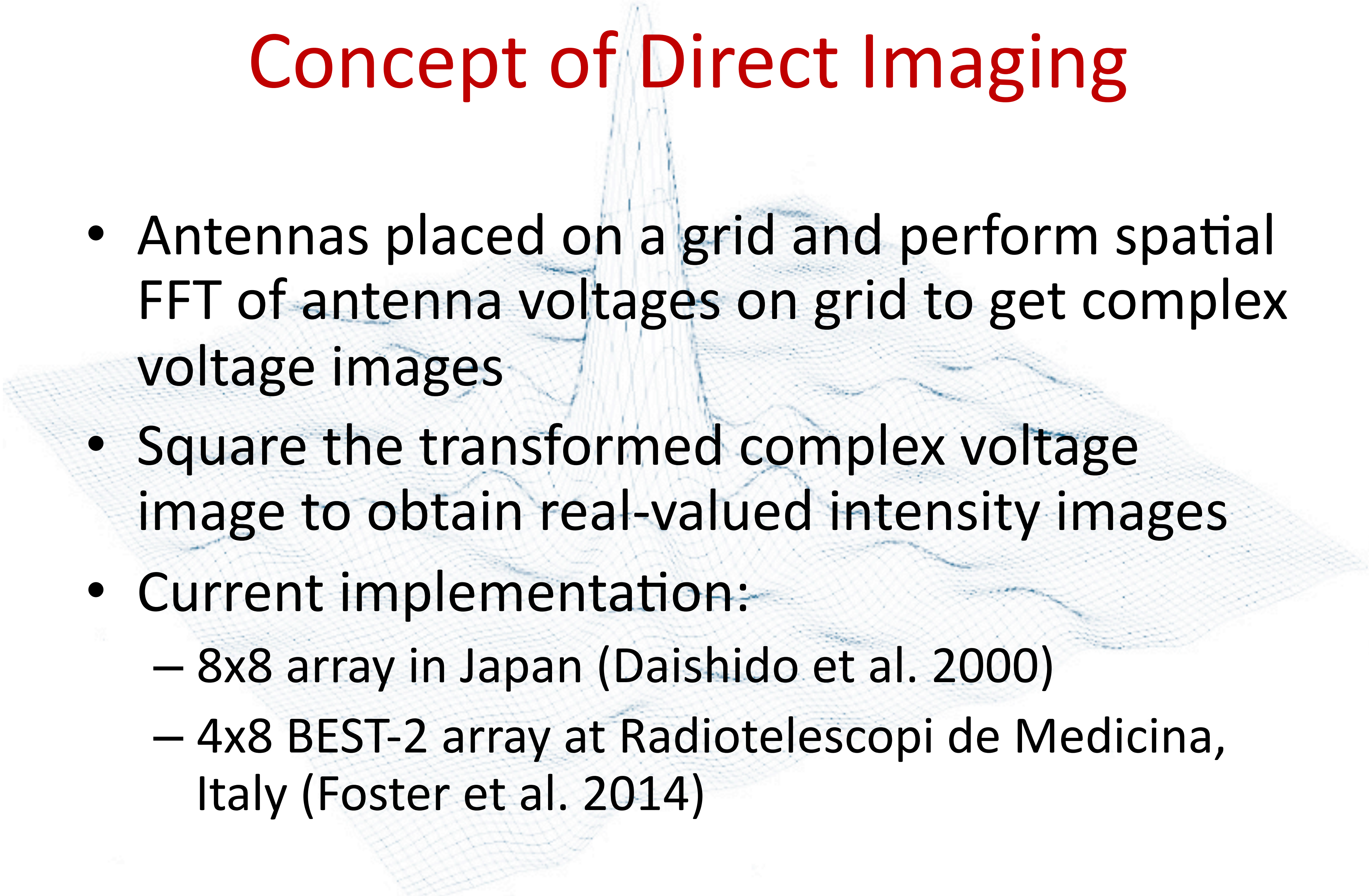
- EoR studies favor dense array layouts
- Transient studies require fast writeouts
- Ionospheric monitoring





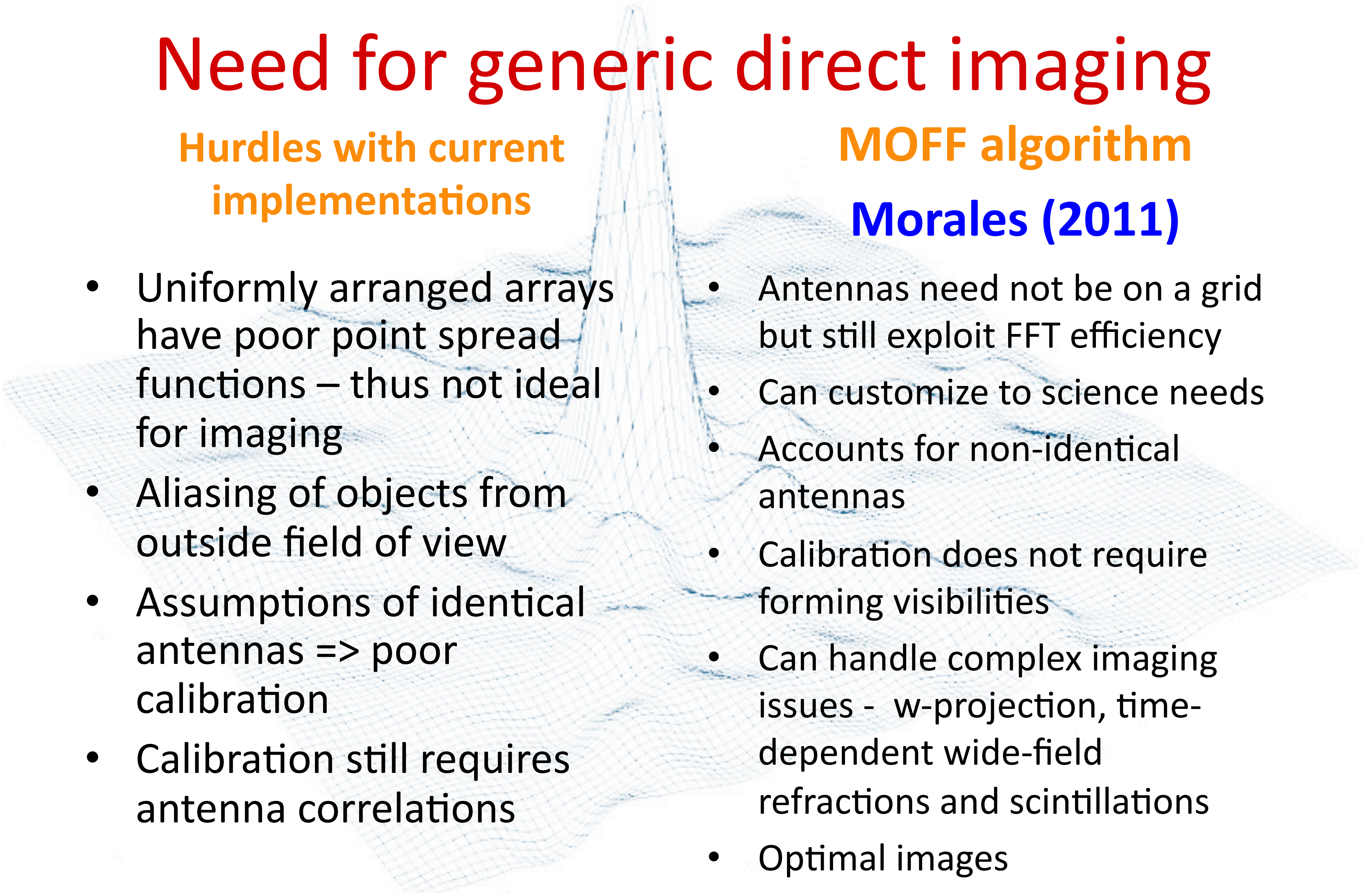
Thornton et al. (2013)

Concept 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)

Need for generic direct imaging



Hurdles with current implementations

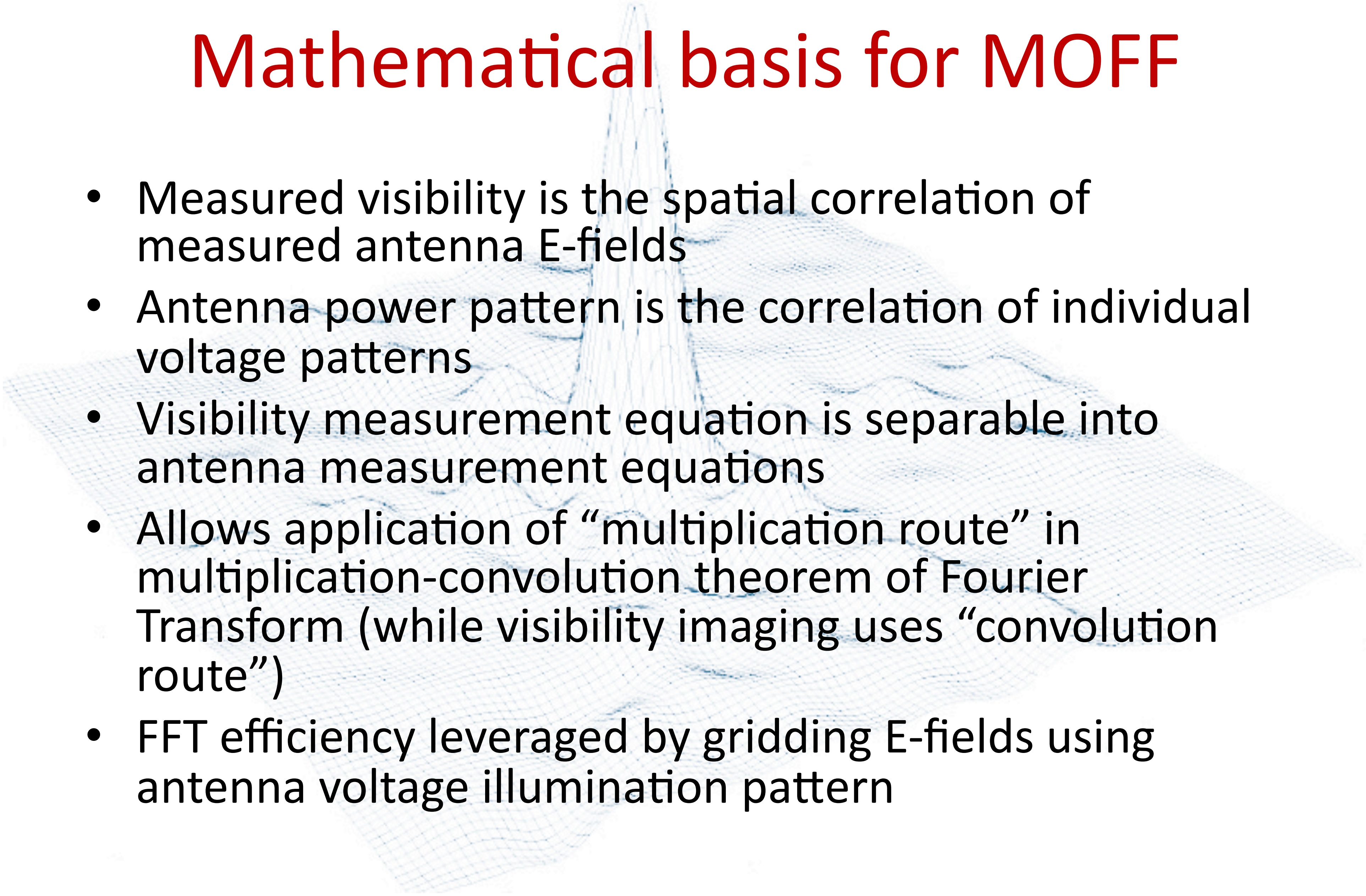
- Uniformly arranged arrays have poor point spread functions – thus not ideal for imaging
- Aliasing of objects from outside field of view
- Assumptions of identical antennas => poor calibration
- Calibration still requires antenna correlations

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

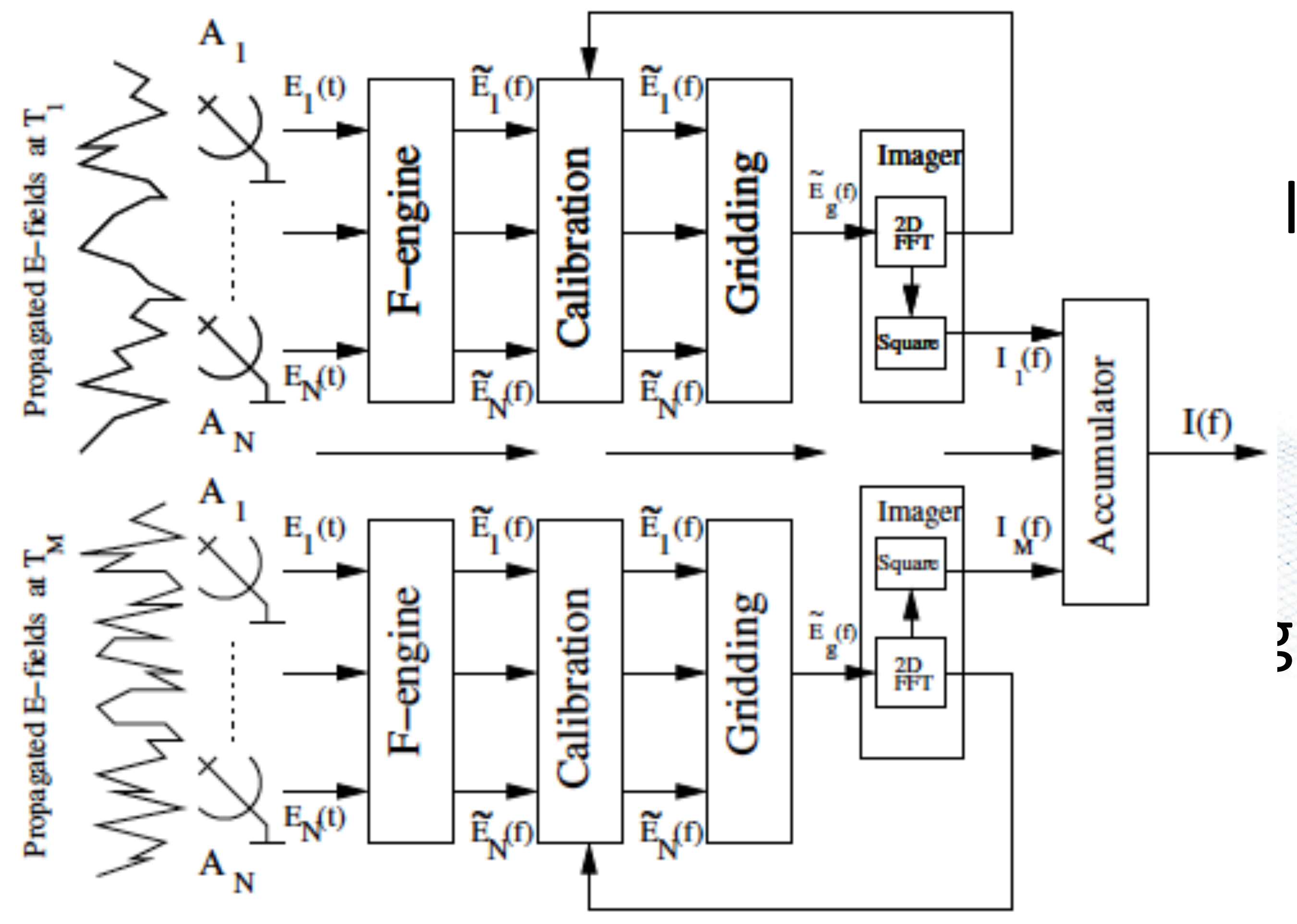
Mathematical basis for MOFF



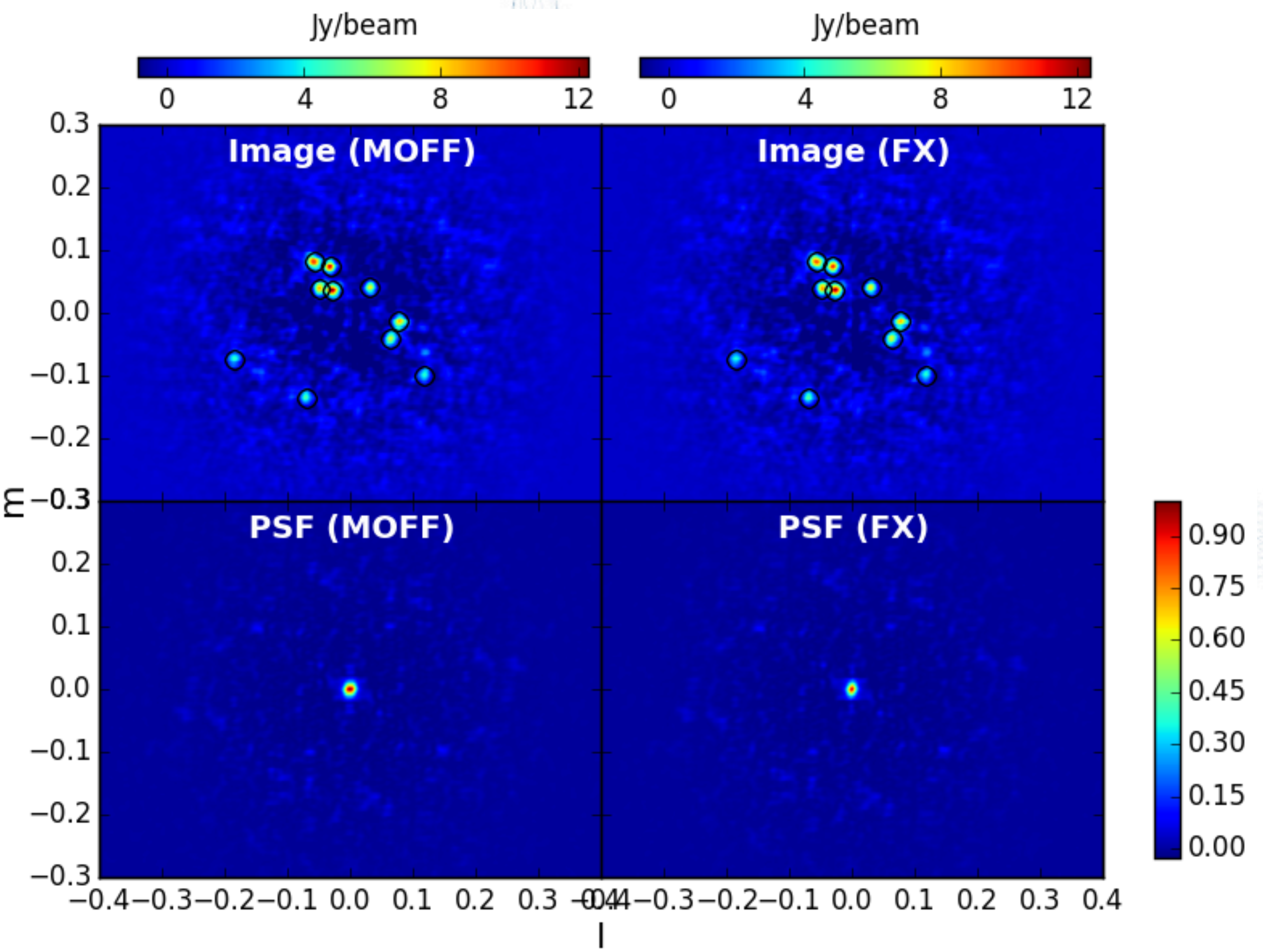
- Measured visibility is the spatial correlation of measured antenna E-fields
- Antenna power pattern is the correlation of individual voltage patterns
- Visibility measurement equation is separable into antenna measurement equations
- Allows application of “multiplication route” in multiplication-convolution theorem of Fourier Transform (while visibility imaging uses “convolution route”)
- FFT efficiency leveraged by gridding E-fields using antenna voltage illumination pattern

EPIC implementation of MOFF imaging

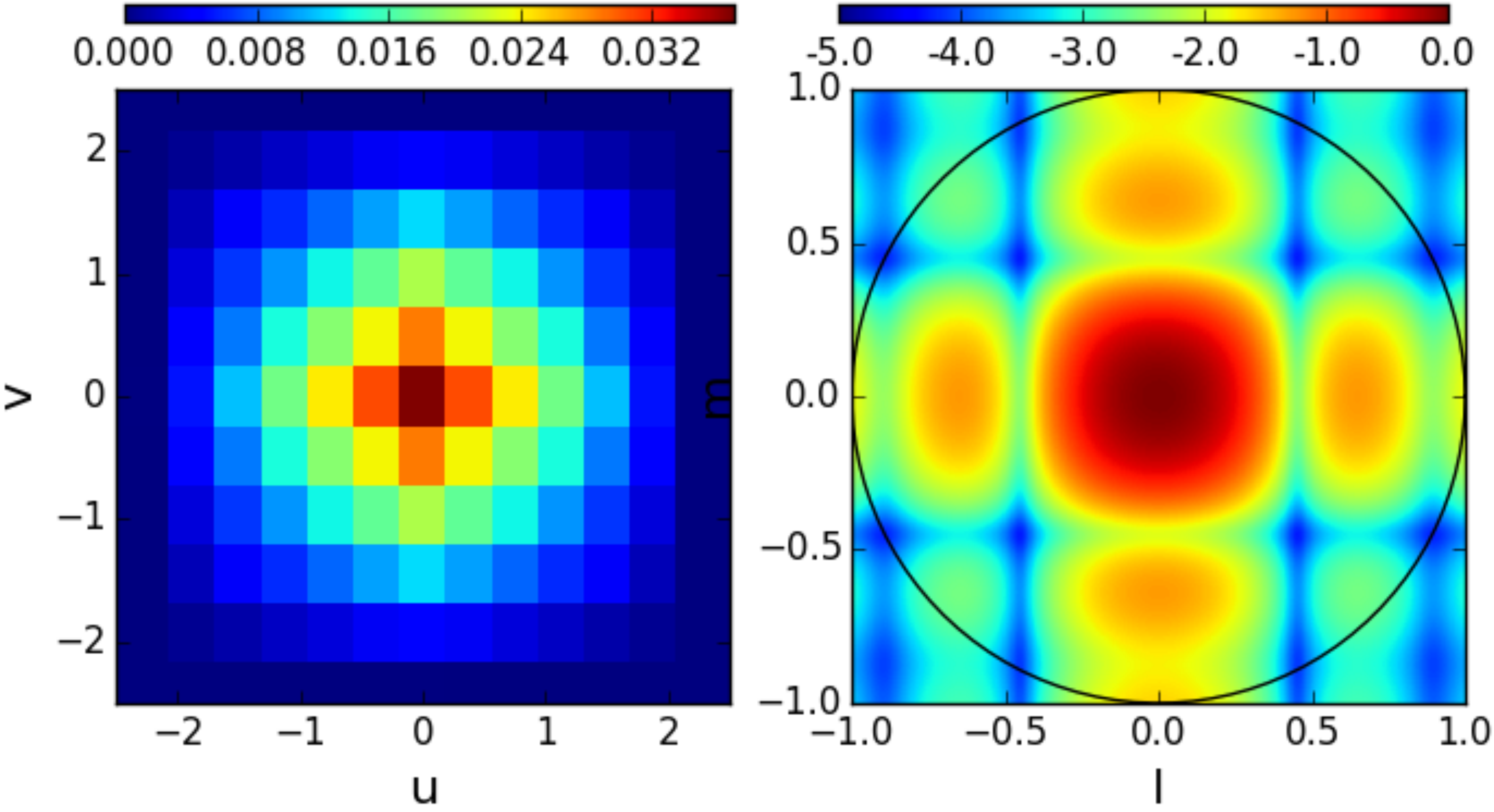
- Obje
- Paral l-
  life te
- Imple
- Acco
- Calib ges
- Cont
  imag



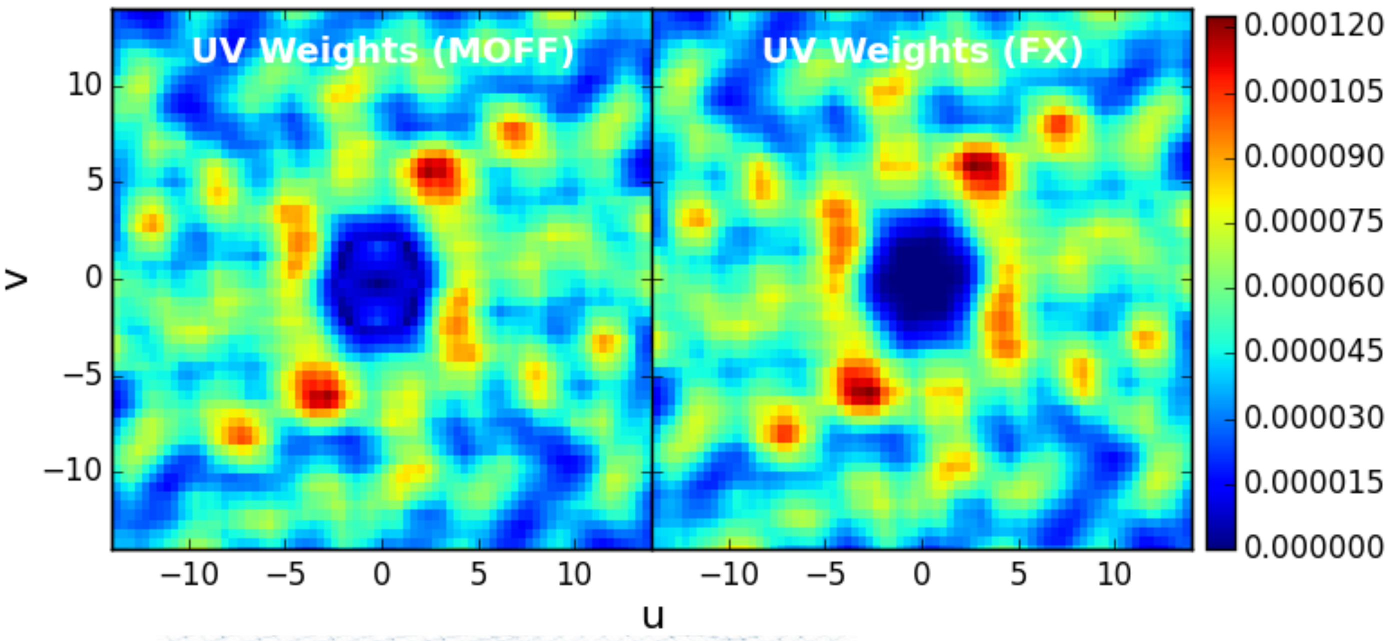
Imaging with EPIC vs. FX



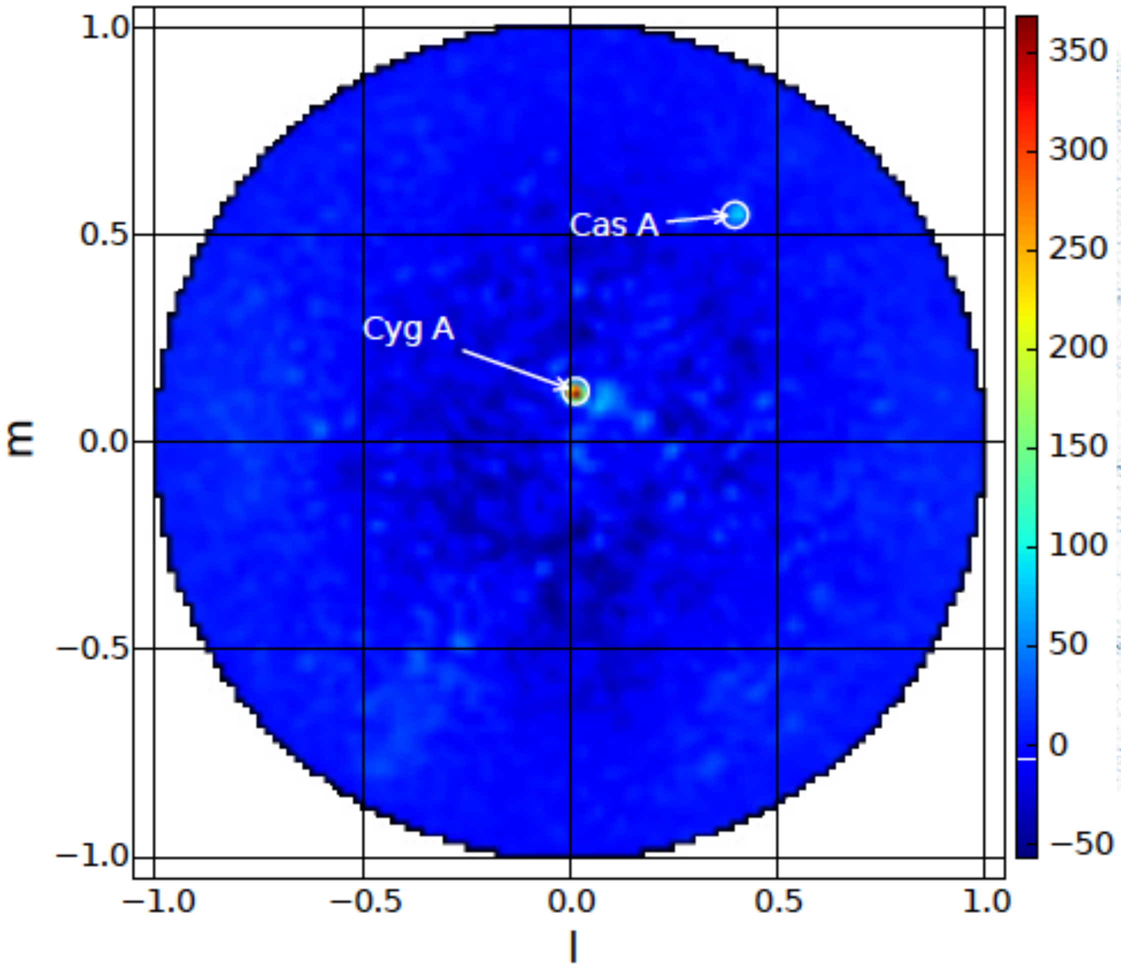
Imaging with EPIC vs. FX (zero spacing)



Gridding differences in MOFF vs. FX

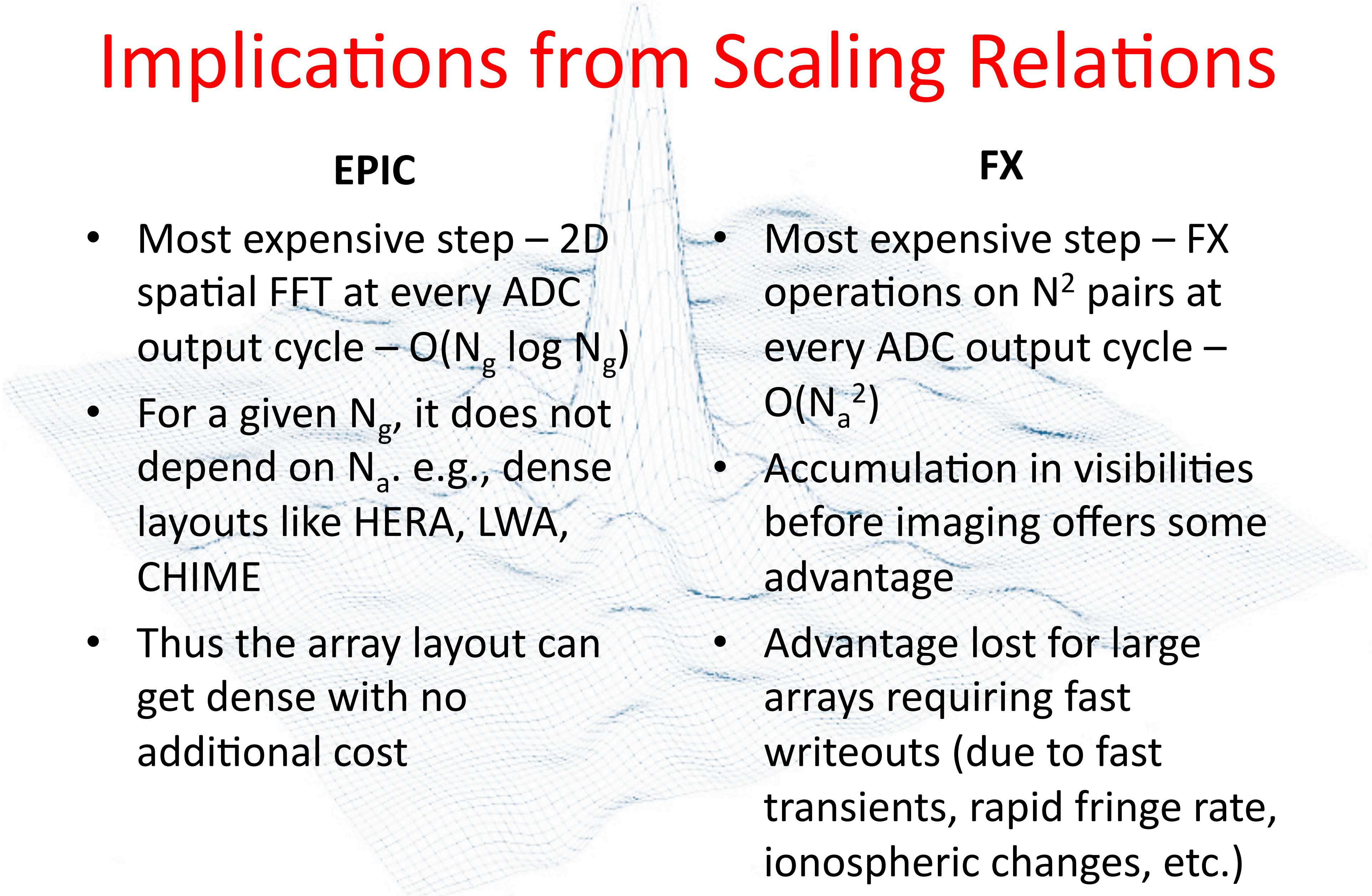


EPIC on actual LWA Data



- LWA1 TBN data with a total of 2s and 100 kHz
- Image obtained with 20 ms, 80 kHz
- Cyg A and Cas A prominently visible

Implications from Scaling Relations



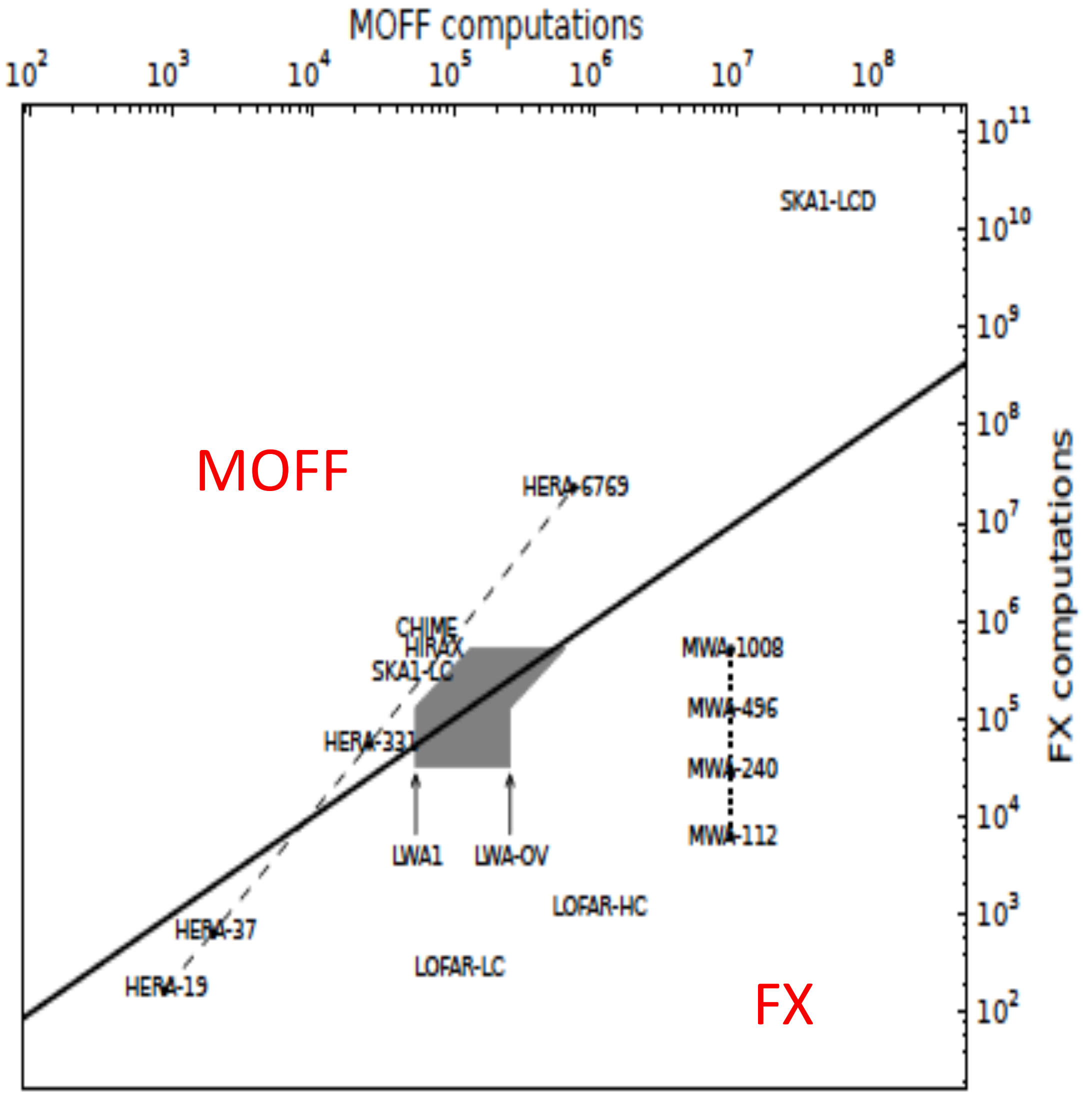
EPIC

- Most expensive step – 2D spatial FFT at every ADC output cycle – $O(N_g \log N_g)$
- For a given N_g, it does not depend on N_a. e.g., dense layouts like HERA, LWA, CHIME
- Thus the array layout can get dense with no additional cost

FX

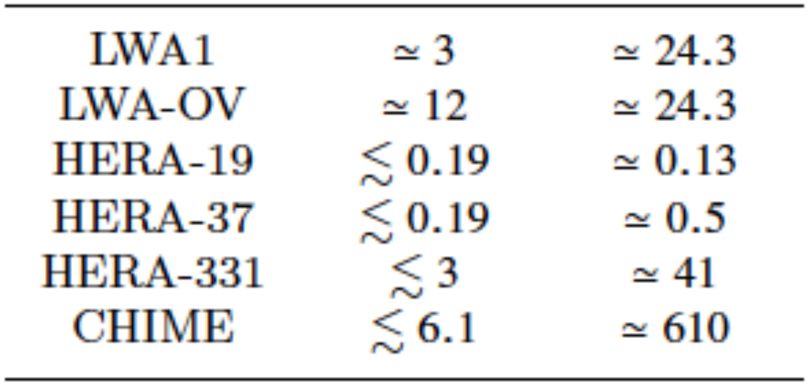
- Most expensive step – FX operations on N^2 pairs at every ADC output cycle – $O(N_a^2)$
- Accumulation in visibilities before imaging offers some advantage
- Advantage lost for large arrays requiring fast writeouts (due to fast transients, rapid fringe rate, ionospheric changes, etc.)

Current and future telescopes in MOFF-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

Writeout rates for Transients



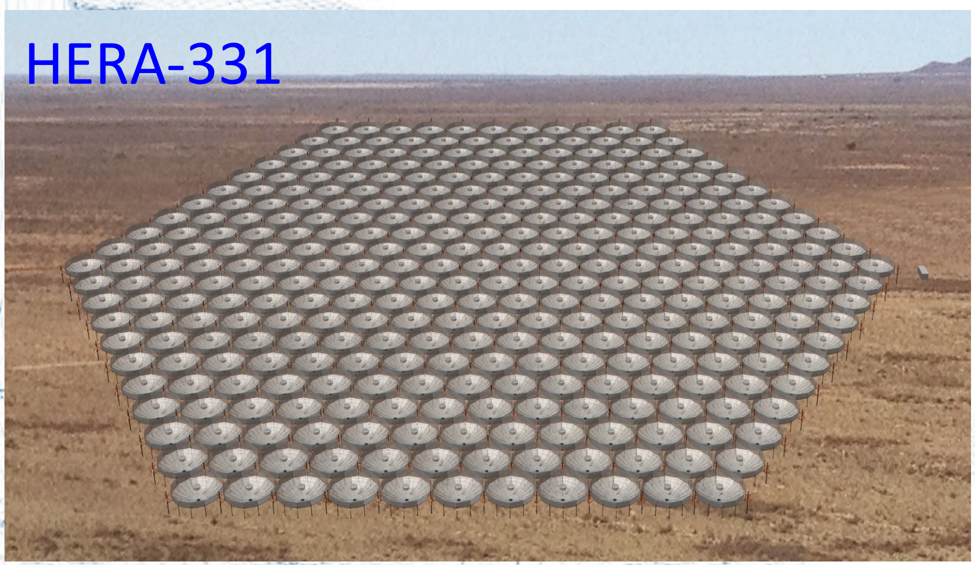
Telescope	Data rate (EPIC) GB/s	Data rate (FX/XF) GB/s
LWA1	$\simeq 3$	$\simeq 24.3$
LWA-OV	$\simeq 12$	$\simeq 24.3$
HERA-19	$\lesssim 0.19$	$\simeq 0.13$
HERA-37	$\lesssim 0.19$	$\simeq 0.5$
HERA-331	$\lesssim 3$	$\simeq 41$
CHIME	$\lesssim 6.1$	$\simeq 610$

Assumes writeout timescale of 10 ms

- Data rate ~N_g for MOFF with EPIC
- Data rate ~$N_a{}^2$ for visibilities to be written out
- MOFF using EPIC lowers data rates significantly in modern/future telescopes
- MOFF with EPIC also yields calibrated images on short timescales
- Ideal for bright, fast (FRBs) and slow transients with large-N dense arrays

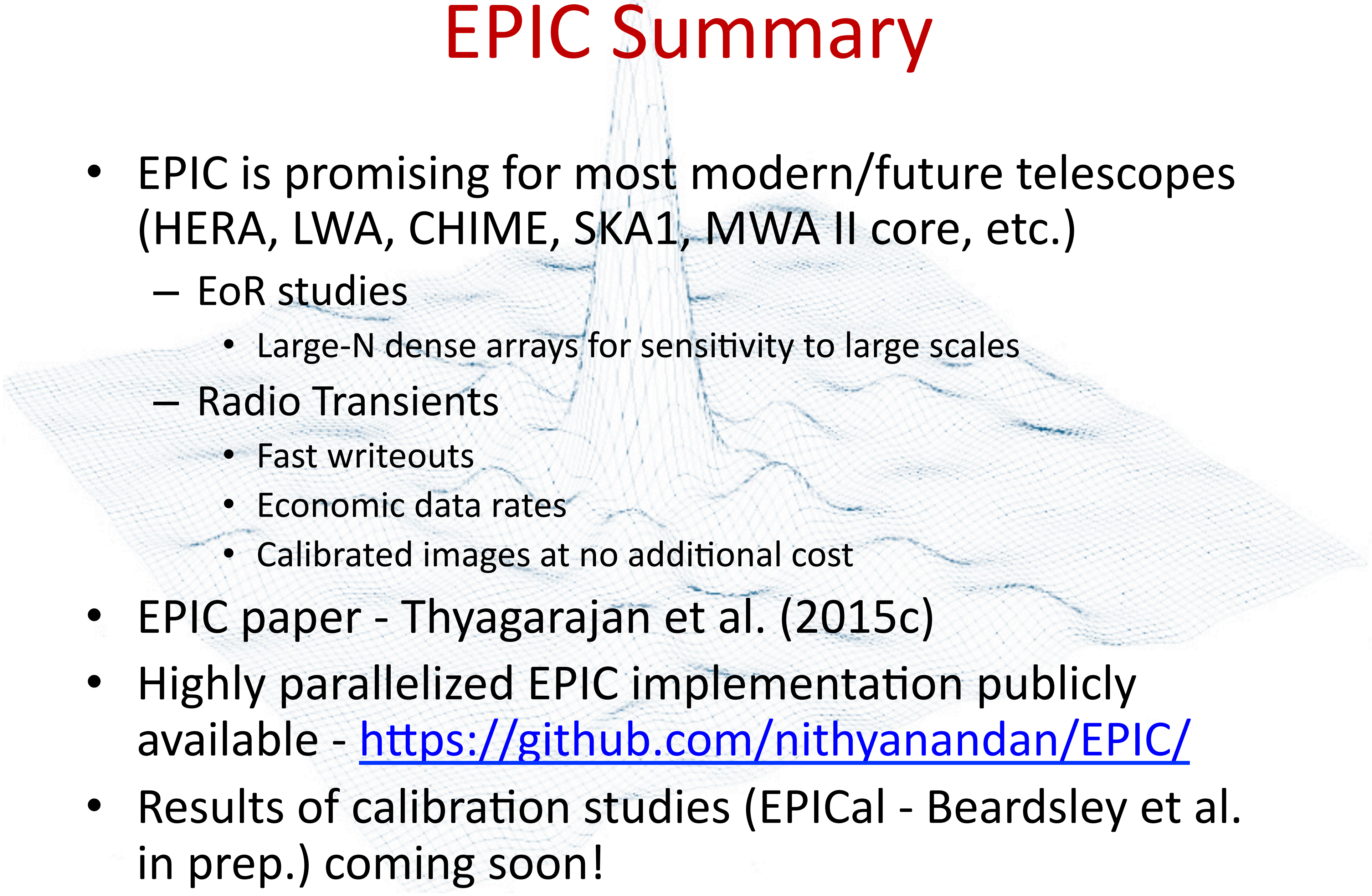
Proposed EPIC demonstration on HERA

- HERA (Hydrogen Epoch of Reionization Array)
  - B = 100MHz
  - 1024 channels
  - ~100 kHz channels
  - FoV ~ 10 deg. At 150 MHz
  - Compact hexagonal array
  - 14m dishes



- Use HERA GPU-backend as test bed
- HERA will use current PAPER F-engine & GPUs that comprise the X-engine
- Design a GPU-based transient search backend
- NSF-ATI proposal submitted

EPIC Summary



- EPIC is promising for most modern/future telescopes (HERA, LWA, CHIME, SKA1, MWA II core, etc.)
  - EoR studies
    - Large-N dense arrays for sensitivity to large scales
  - Radio Transients
    - Fast writeouts
    - Economic data rates
    - Calibrated images at no additional cost
- EPIC paper - Thyagarajan et al. (2015c)
- Highly parallelized EPIC implementation publicly available - https://github.com/nithyanandan/EPIC/
- Results of calibration studies (EPICal - Beardsley et al. in prep.) coming soon!