Capturing the shape and variations of beam patterns with holography

K. Asad, J. N. Girard, M. De Villier, T. Ansah-Narh, K. Iheanetu, O. Smirnov, M. Santos, et al.

10.1093/mnras/stab104

LESIA/Observatoire de Paris, Université de Paris Cité

Capturing the shape and variations of beam patterns with holography

Why ?

What ?

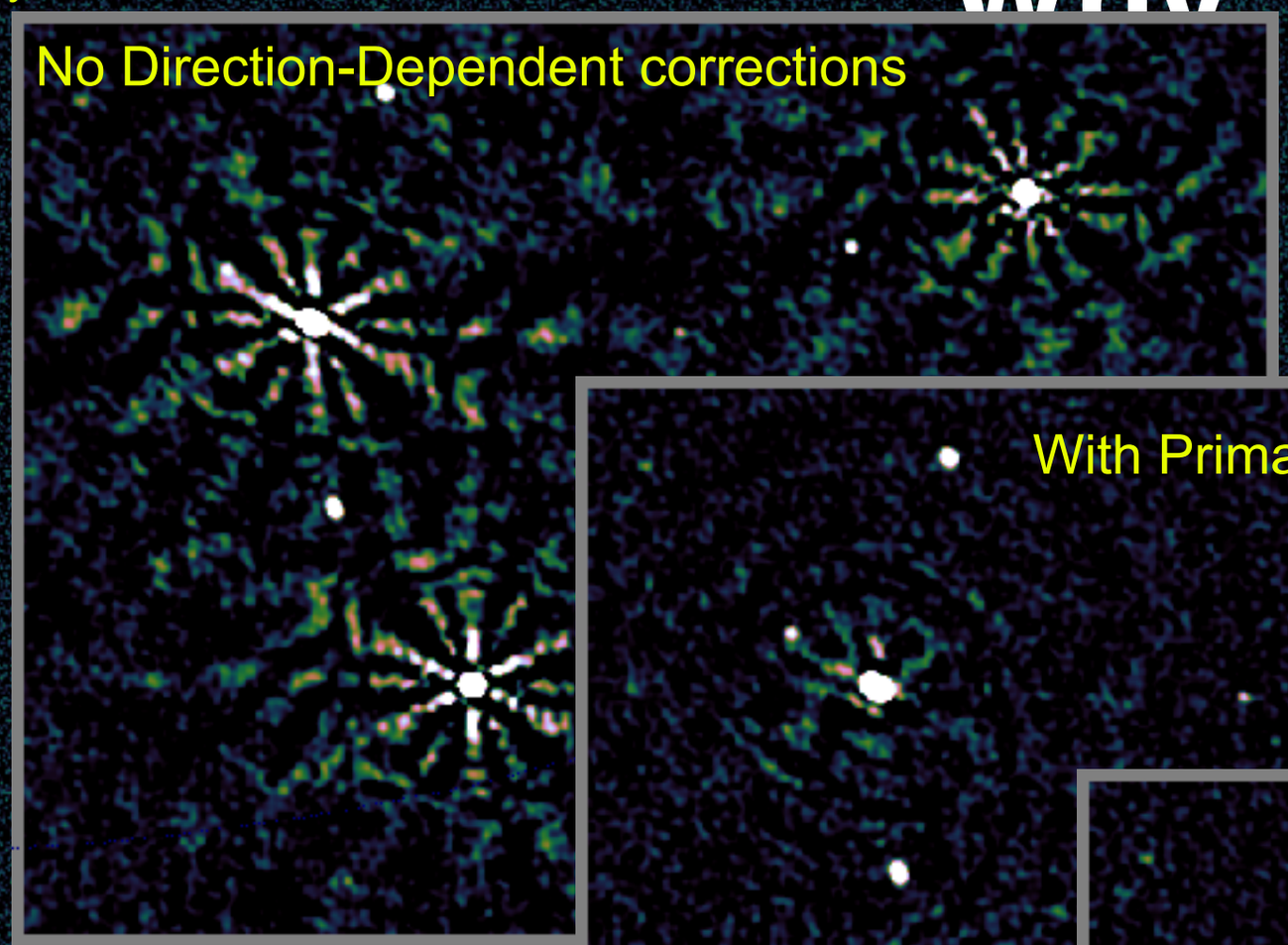
How ?

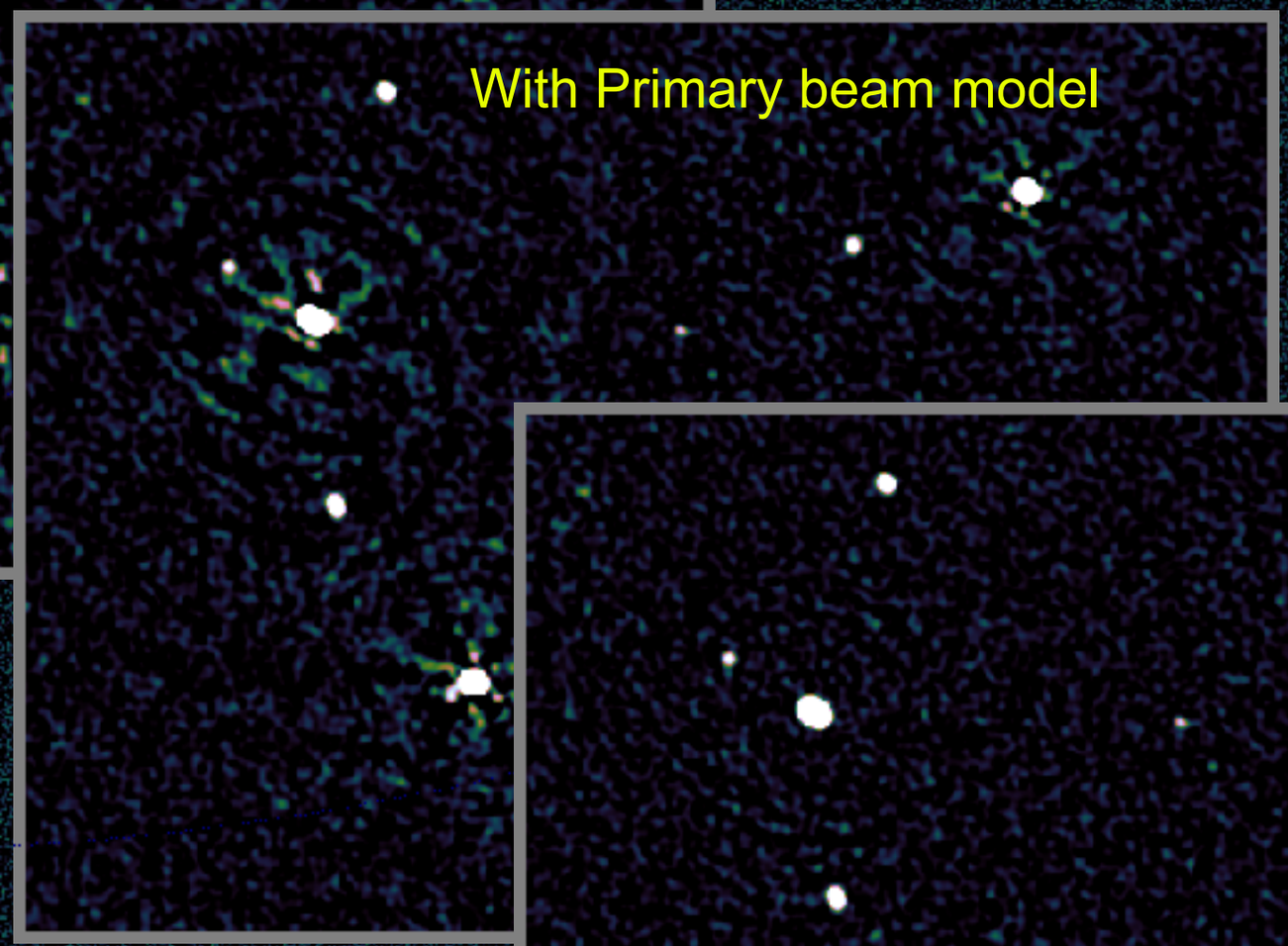
What results?

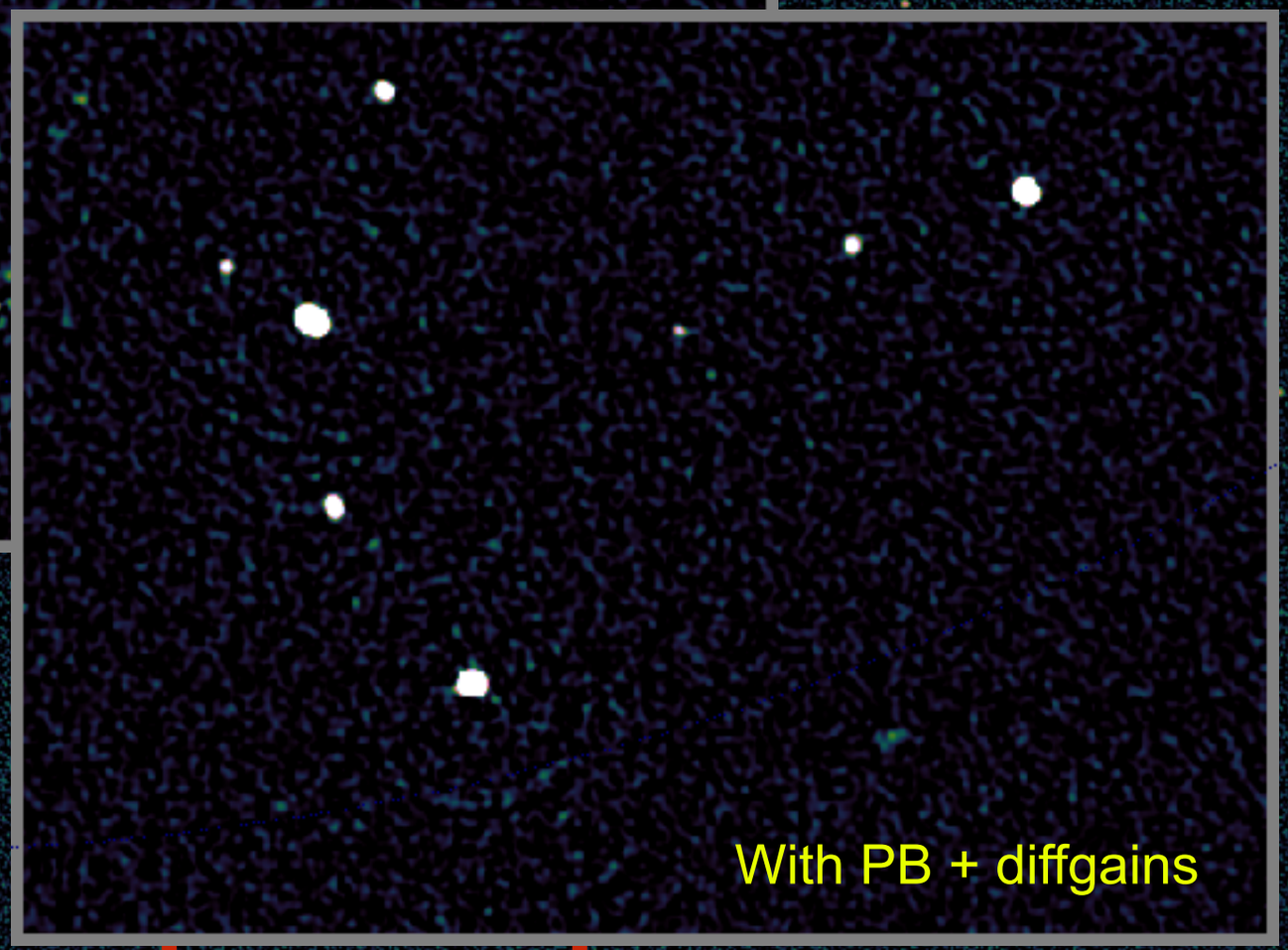
JVLA 5 million DR - 3C147
Perley & RATT 2014

Why ?

22.82 Jy peak
4.5 uJy noise
5 million DR
confusion limited



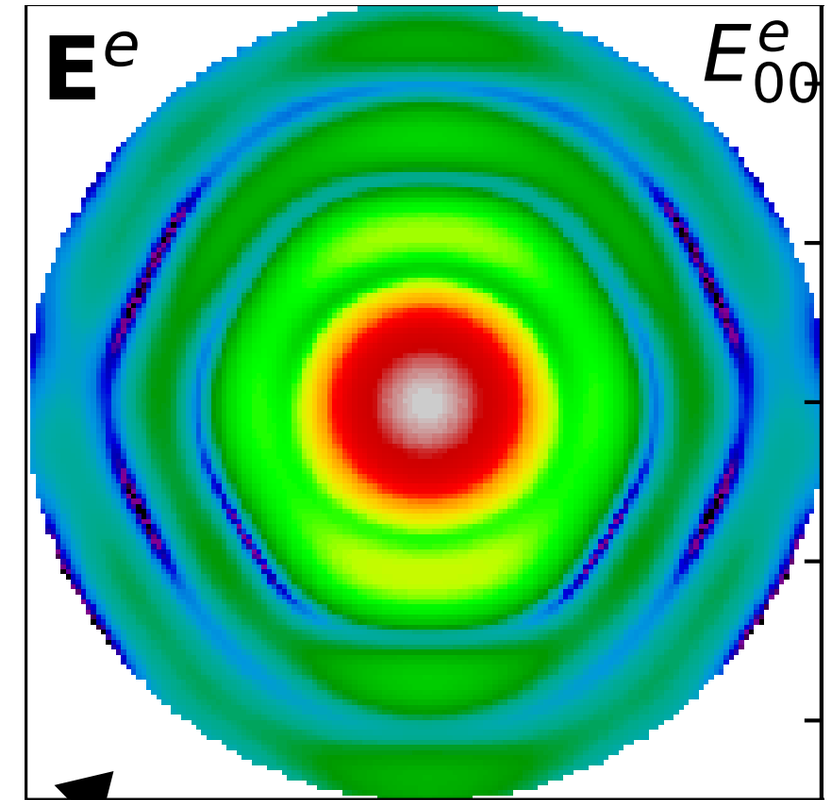




Credits: Oleg Smirnov

~640 MHz bandwidth

What ?



Modeling

EM simulation (MoM, FDTD…)

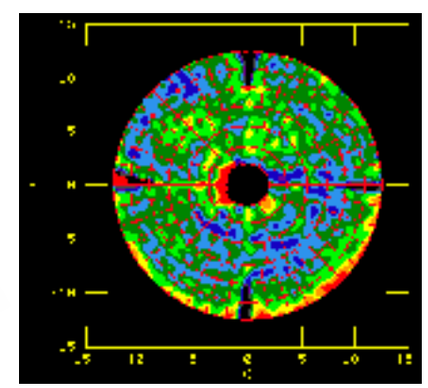
Ray-tracing (e.g. **`Cassbeam`**, Brisken 2003)

Analytic (e.g. **`Katbeam`**, Mauch et al. 2020)

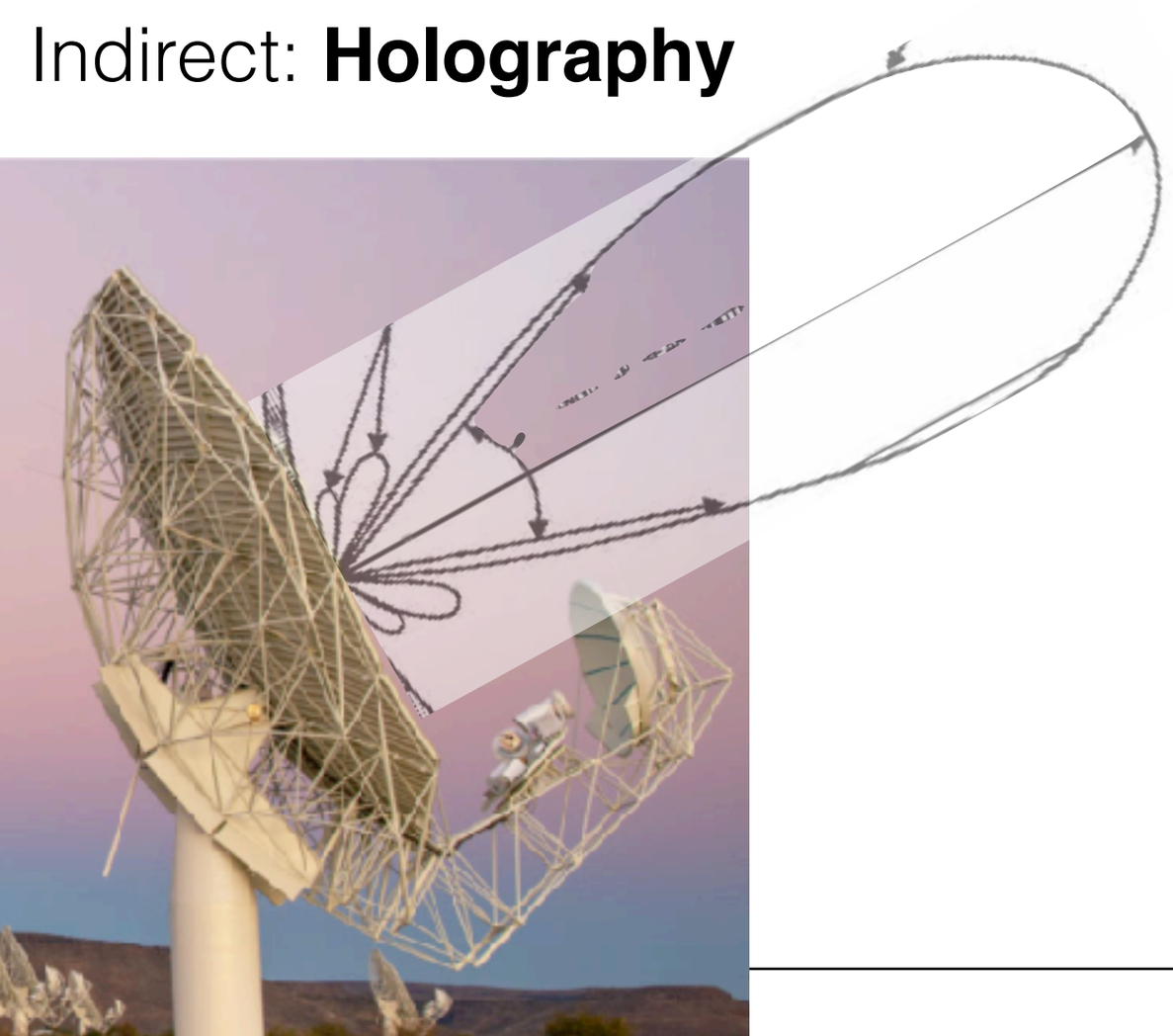
Measurements

Direct: e.g. Anechoic test chambers

Indirect: **Holography**

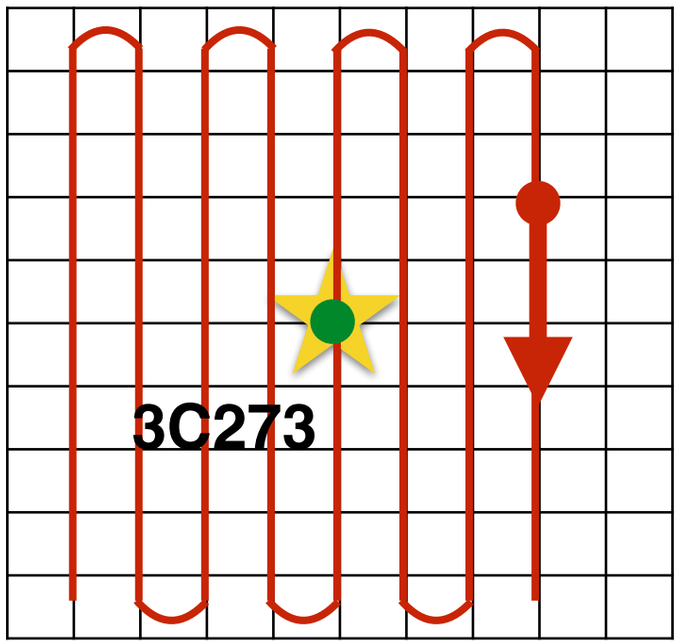


FT



All beams are ≠

How ? (1/2)



Reference antennas (x36)

"Target" antennas (x18)

Beam-modulated Visibilities

$$V_{pq}$$

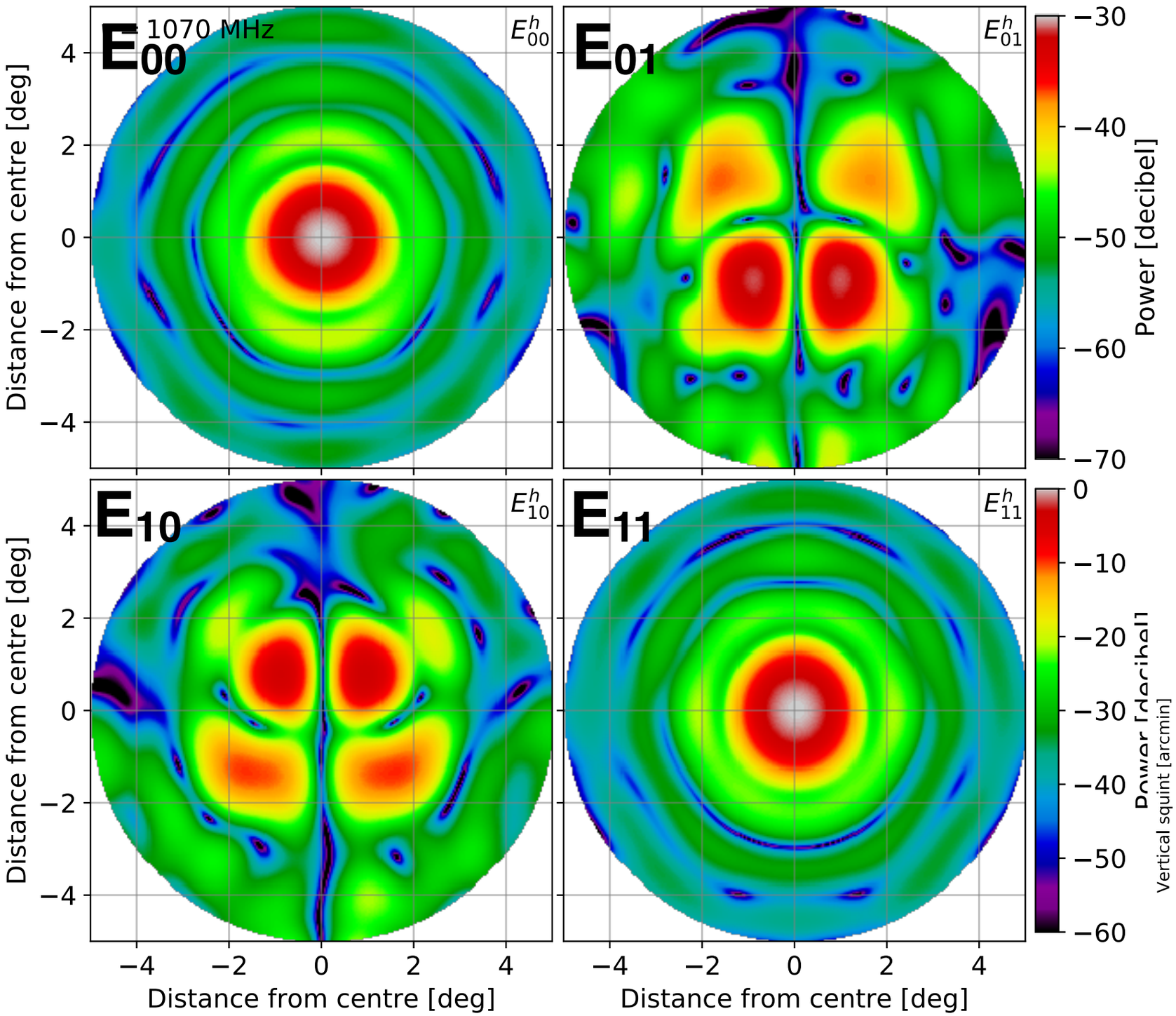
EVLA Memo 195

Perley, 2016

How ? (1/2)

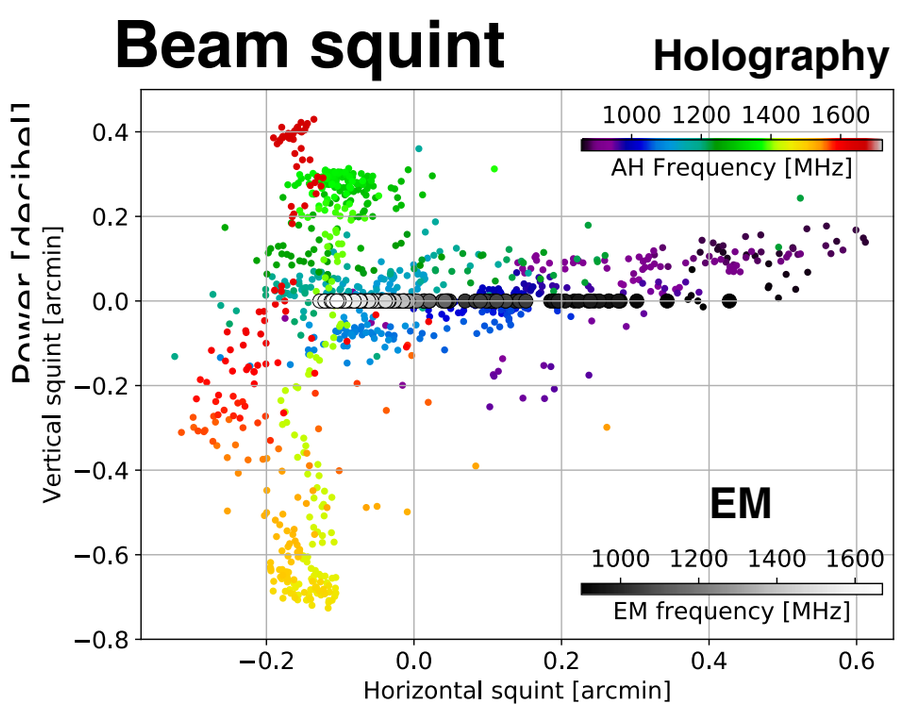
Holographic Observation of MeerKAT Primary beam

`https://github.com/ska-sa/katholog` M. De Villiers (in prep)

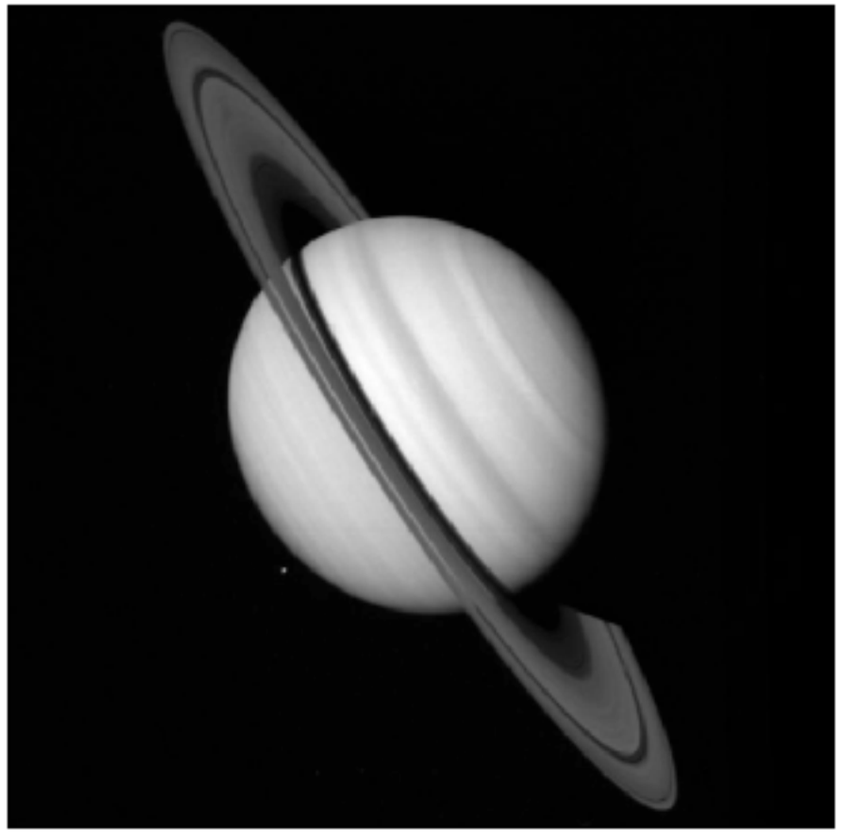


F = 1070 MHz

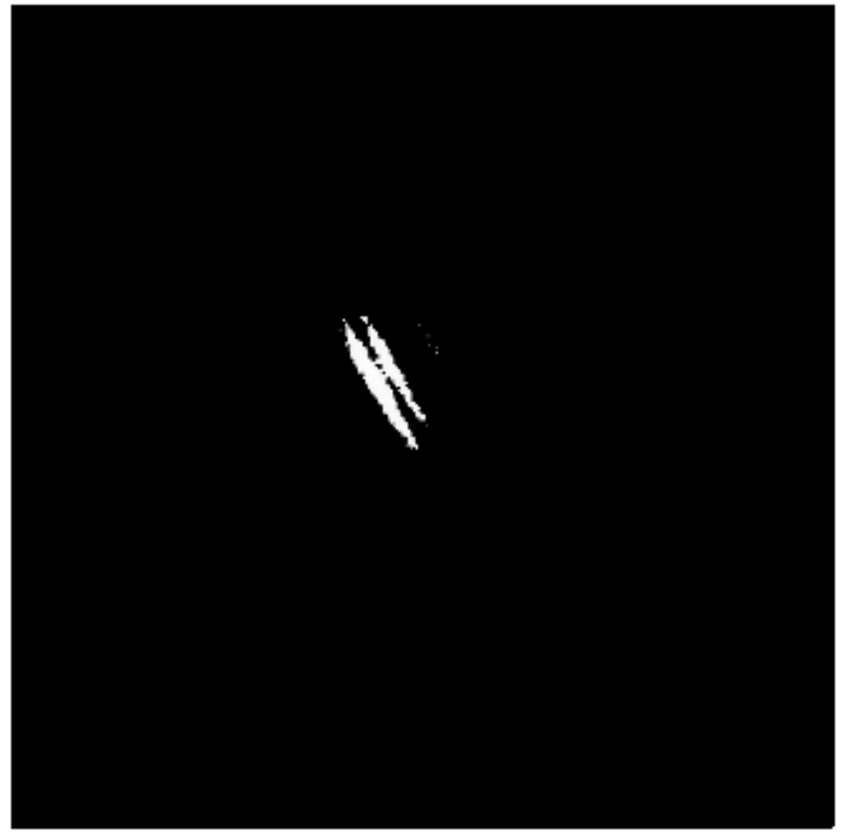
M009, M012, M015



About signal sparsity and space of representation



Original image

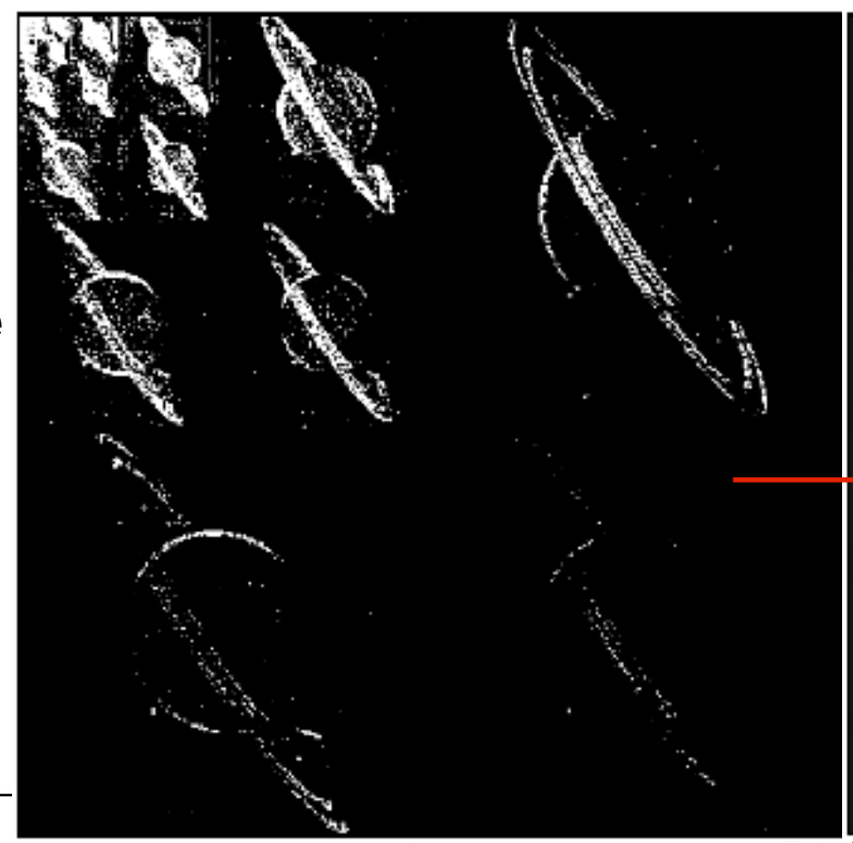


Direct space

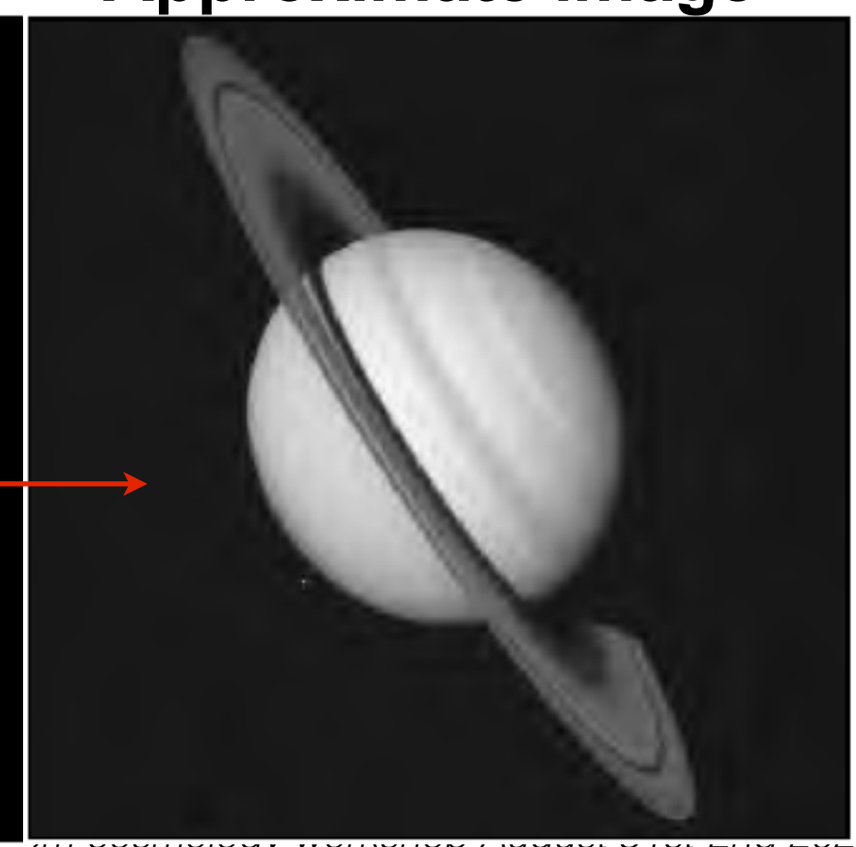
5% of the brigthest pixels

Wavelet space

0,5% of the highest coeff



Approximate image

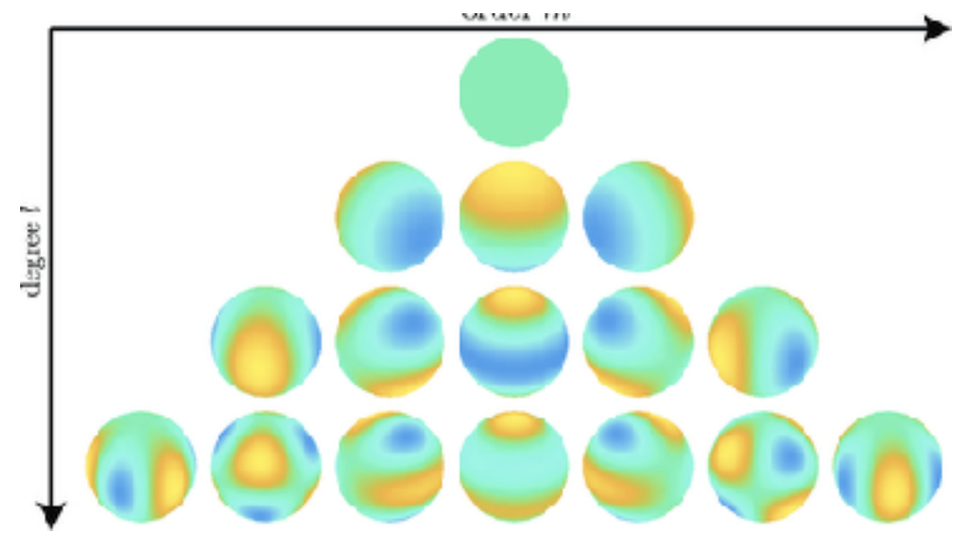


How ? (2/2)

EM simulations with FEKO

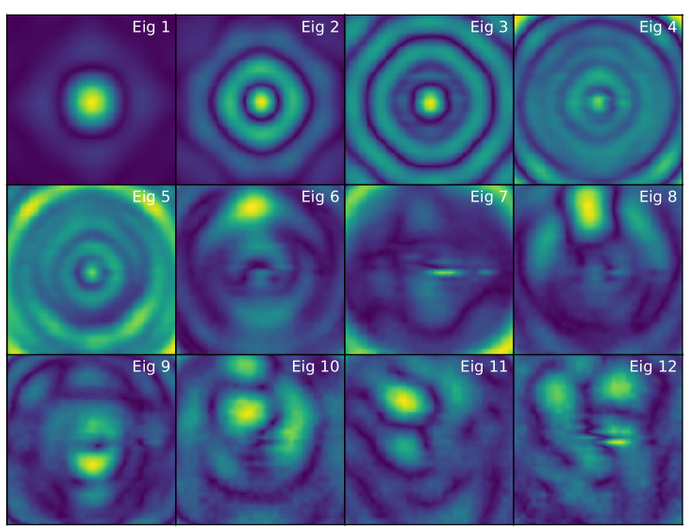
Stellenbosch University

Spherical harmonics



PCA / SVD

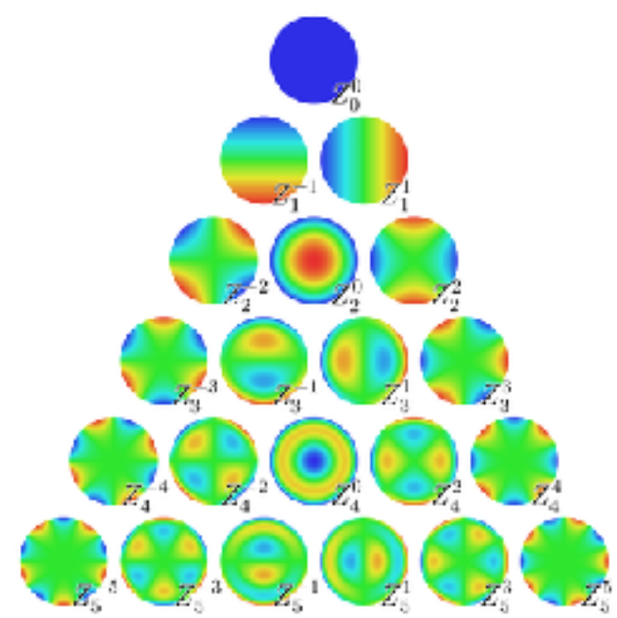
Eigenfaces



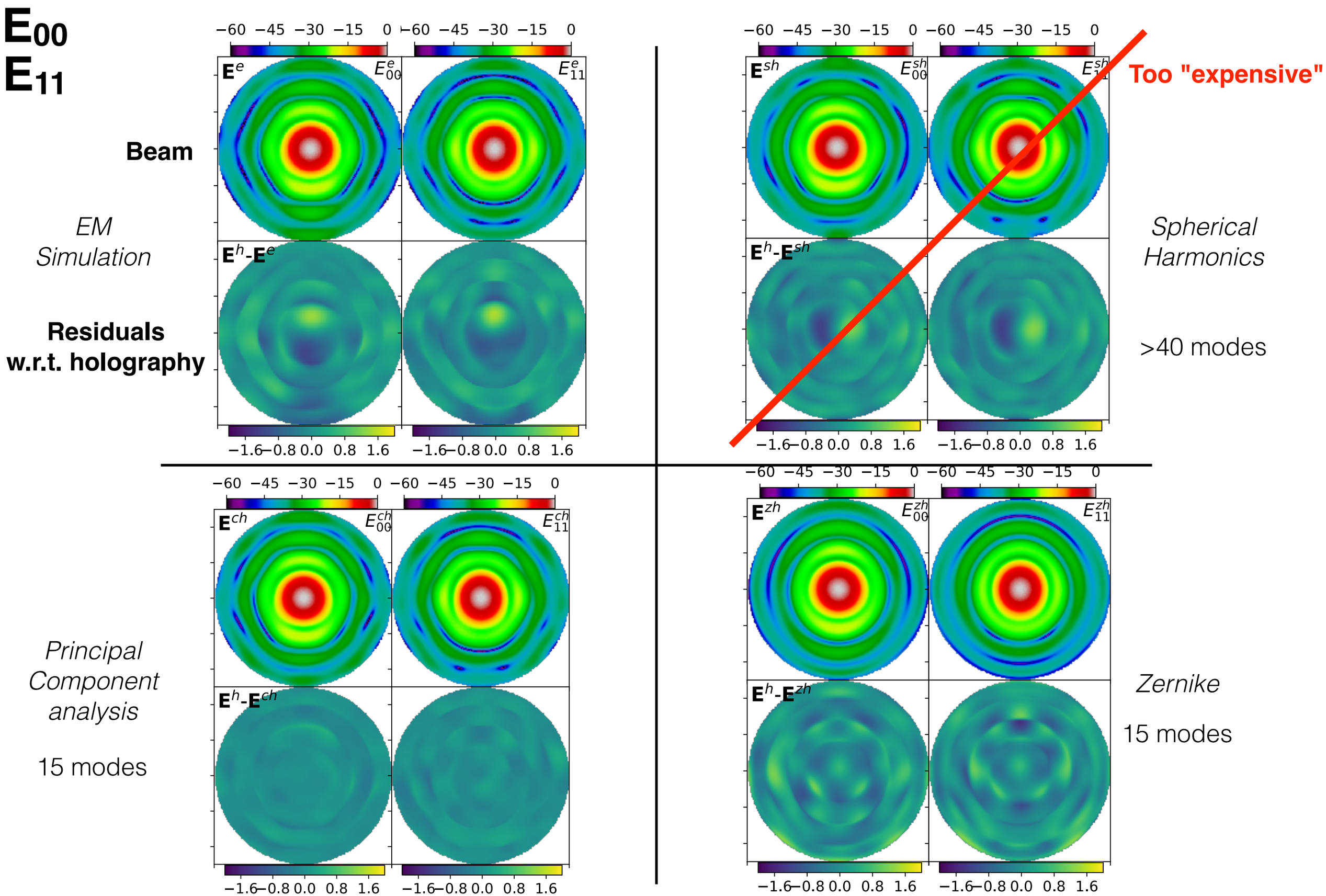
Eigenbeams

$$A = U\Sigma V^T$$

Zernike polynomials



What results ?

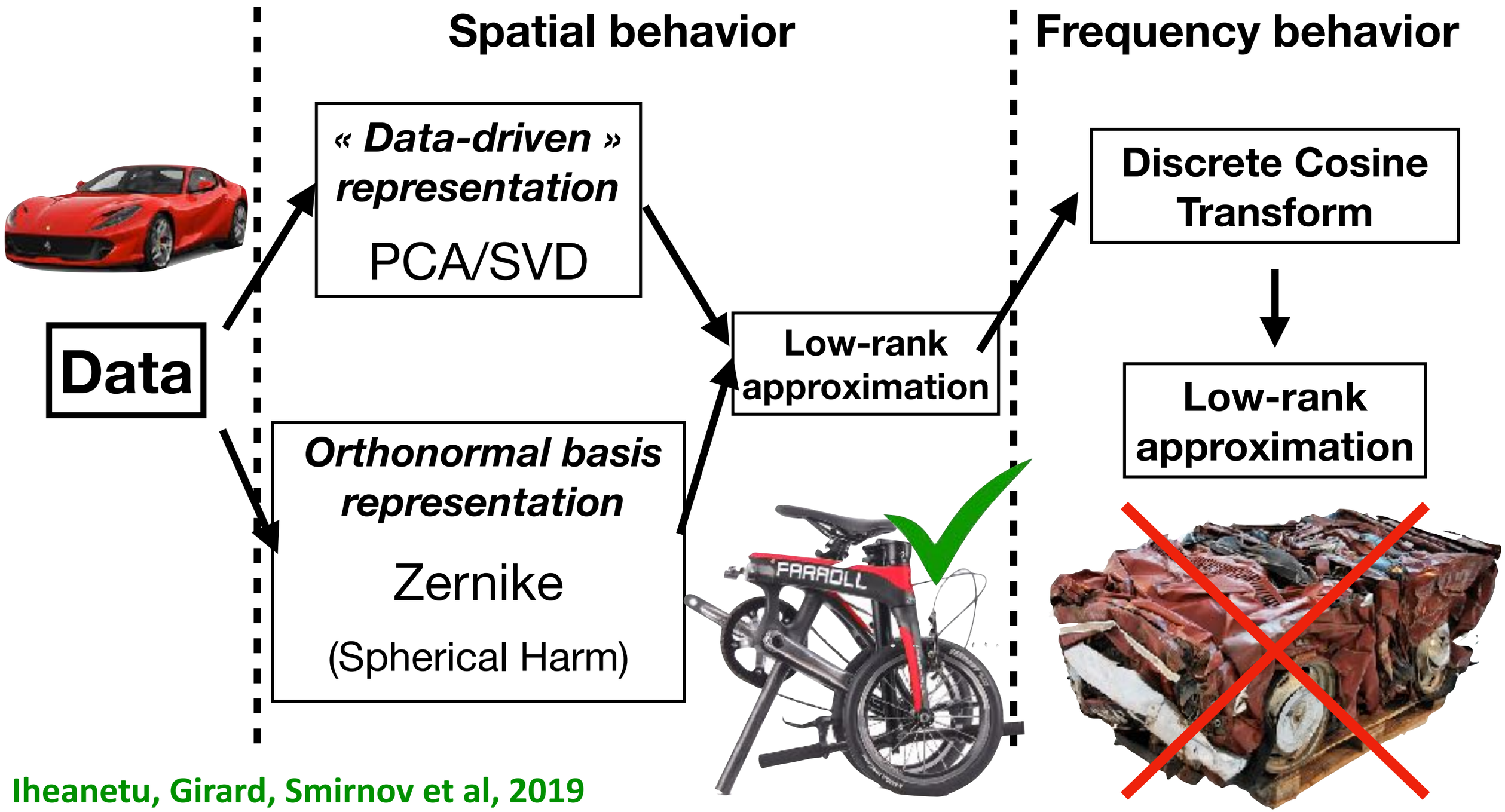


Modeling

Holography data are 3D (2 for space, 1 for frequency)

How to find the relevant space to have sparse representations ?

We need to compress the information while insuring fidelity



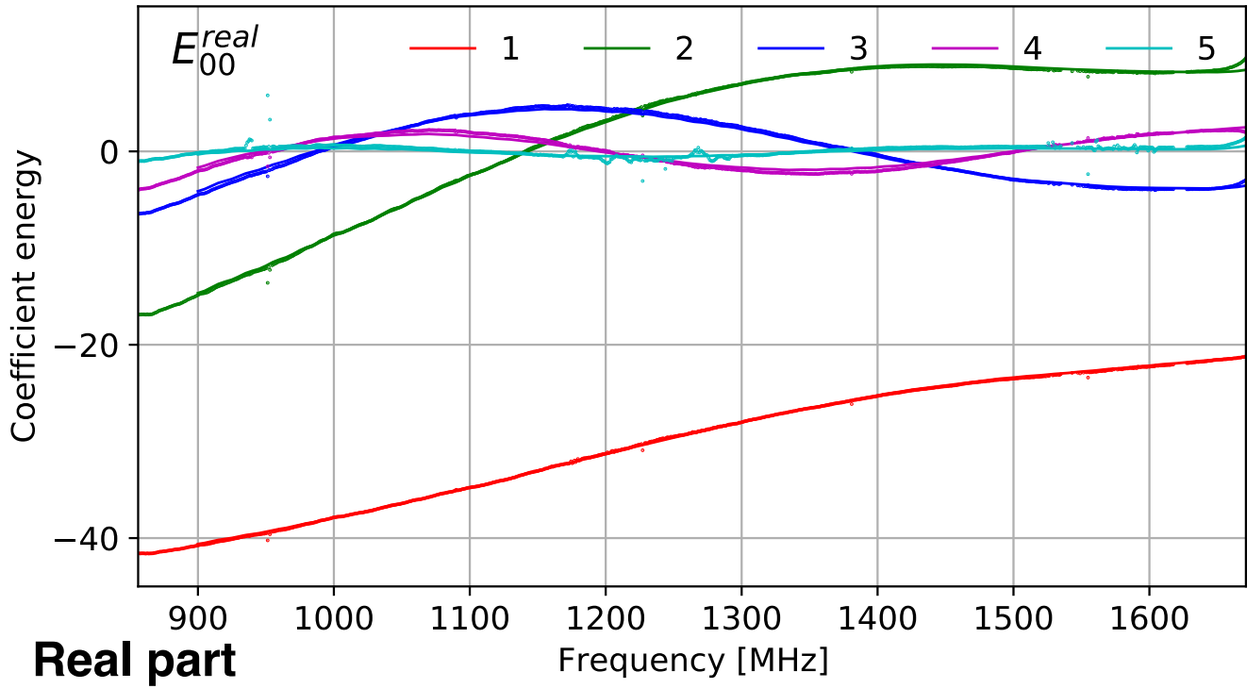
Iheanetu, Girard, Smirnov et al, 2019

PCA

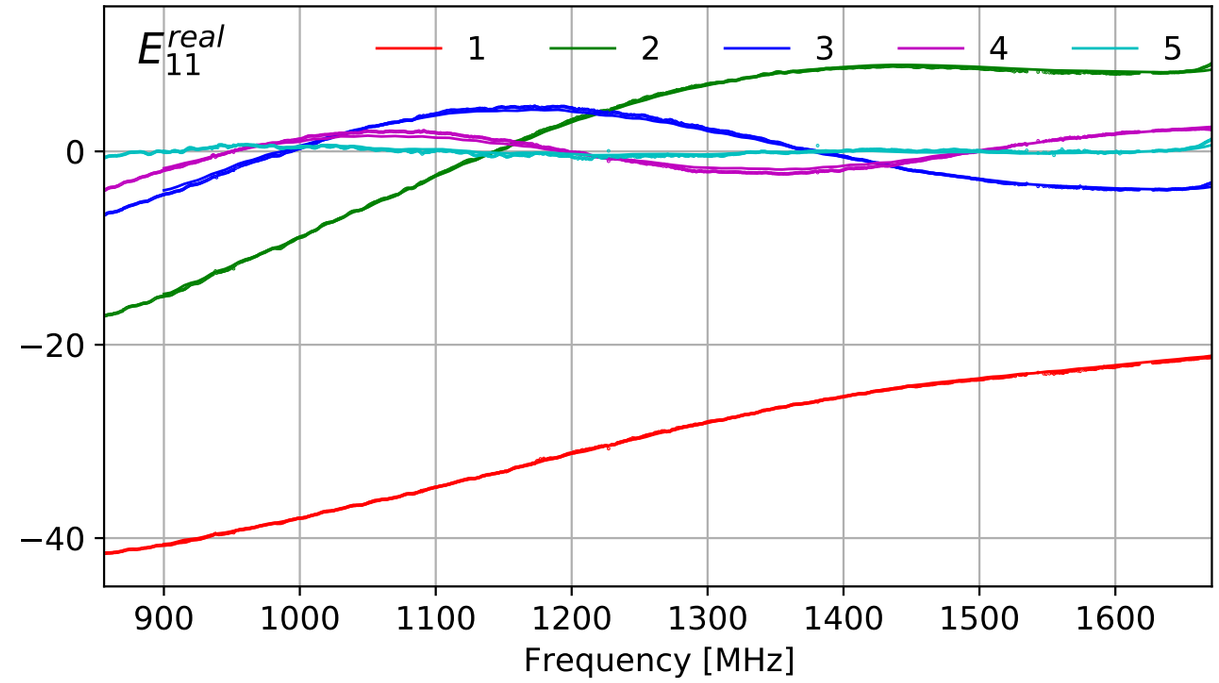
What results ?

5th dominant PC

E_{00}



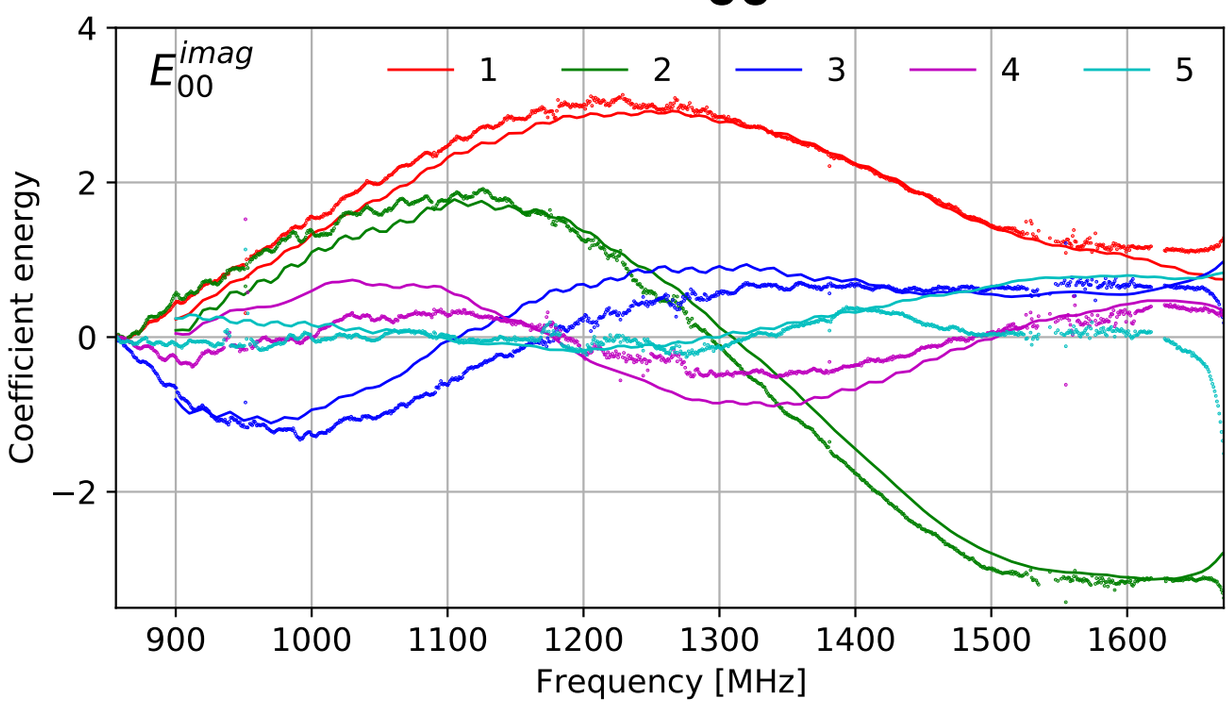
E_{11}



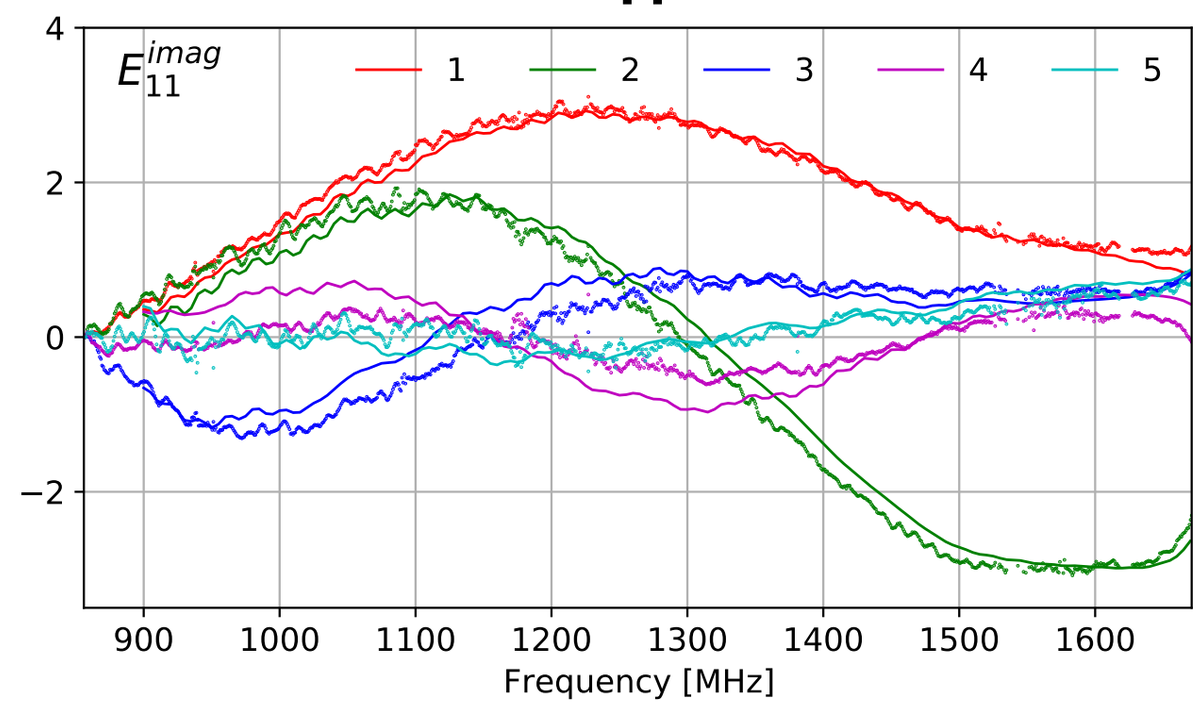
Real part

Imaginary part

E_{00}



E_{11}



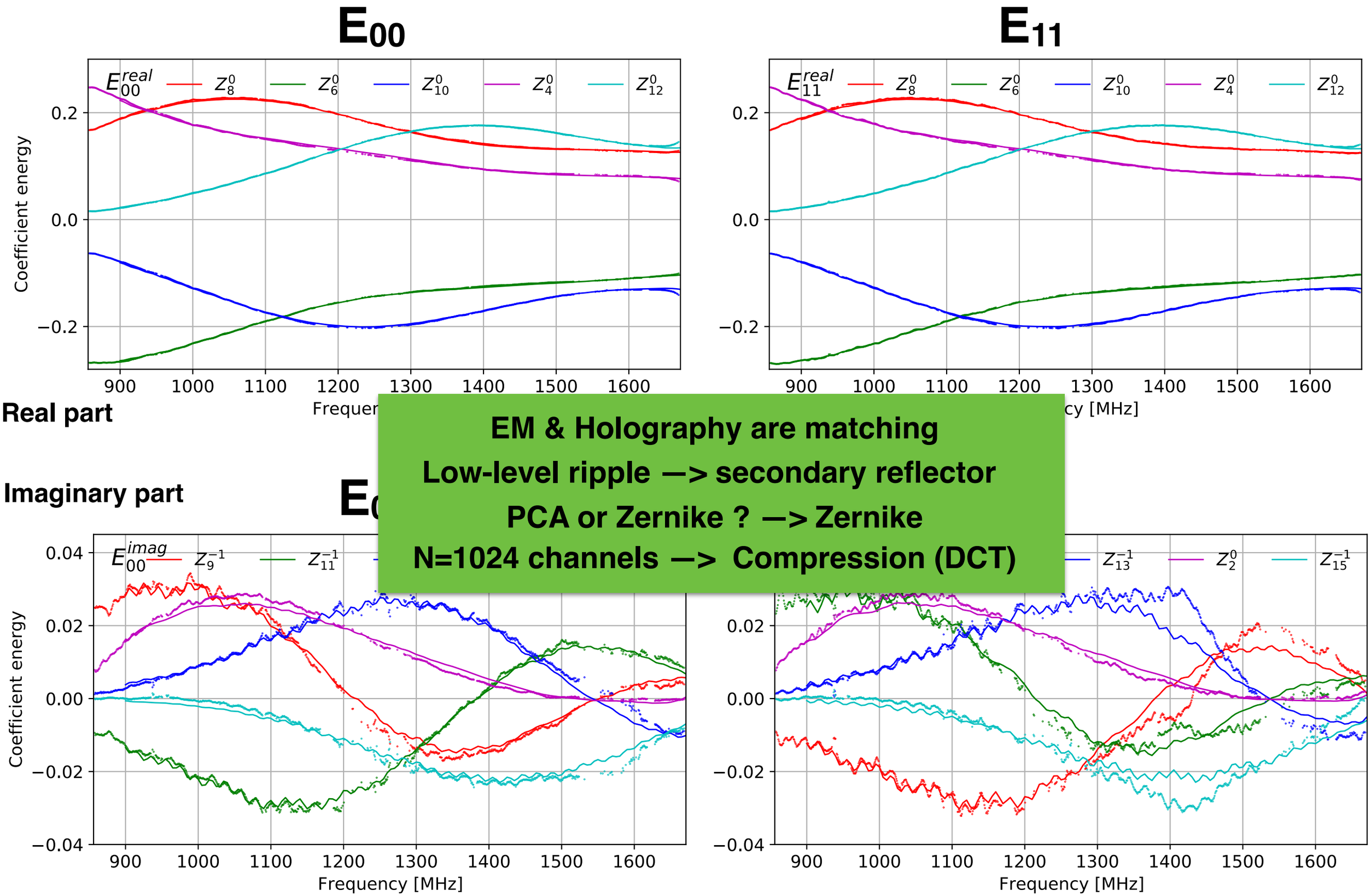
What results ?

Zernike

5th dominent Zernike modes

Real part

Imaginary part



EM & Holography are matching

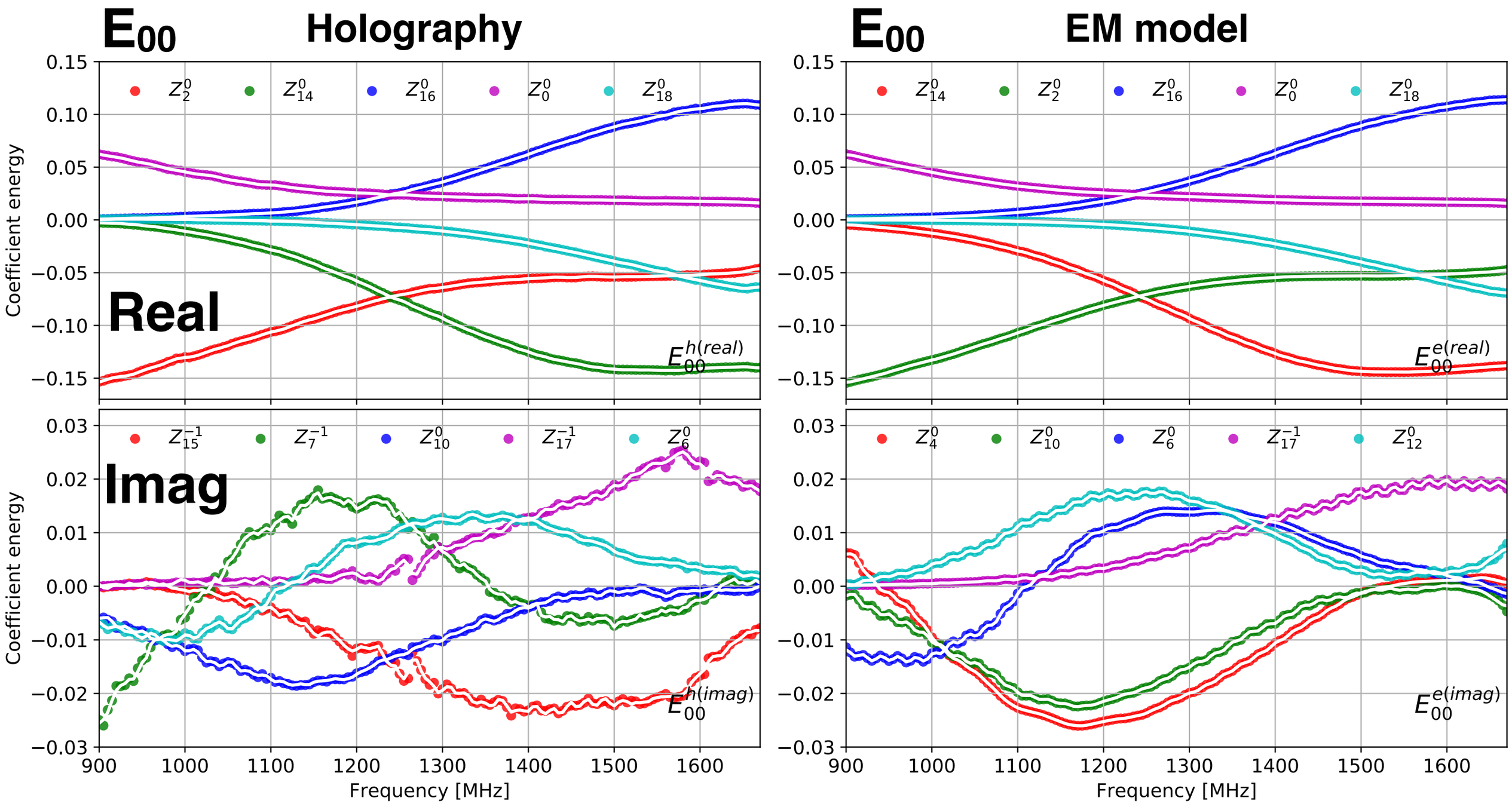
Low-level ripple —> secondary reflector

PCA or Zernike ? —> Zernike

N=1024 channels —> Compression (DCT)

Zernike + DCT compression What results ?

5th next dominent Zernike modes



At the end

20 Zernike modes are necessary to model the beam spatially in the L-band (N_{pix})

40 DCT coefficients are necessary to model the beam spectrally over 1024 channels

Summary

Why ? We need accurate beam models for calibration

For wide-field imaging beyond the primary beam first null

What ? Holography

Deduce the shape of the primary beam from observation

Historically used to monitor surface quality of dishes

How ?

1) Observe at and around a calibrator source
2) Decompose the measure

Spatially

Spectrally

on adapted spaces

What results?

Iheanetu, Girard et al., 2019 *Paper I (VLA)* *10.1093/mnras/stz702*

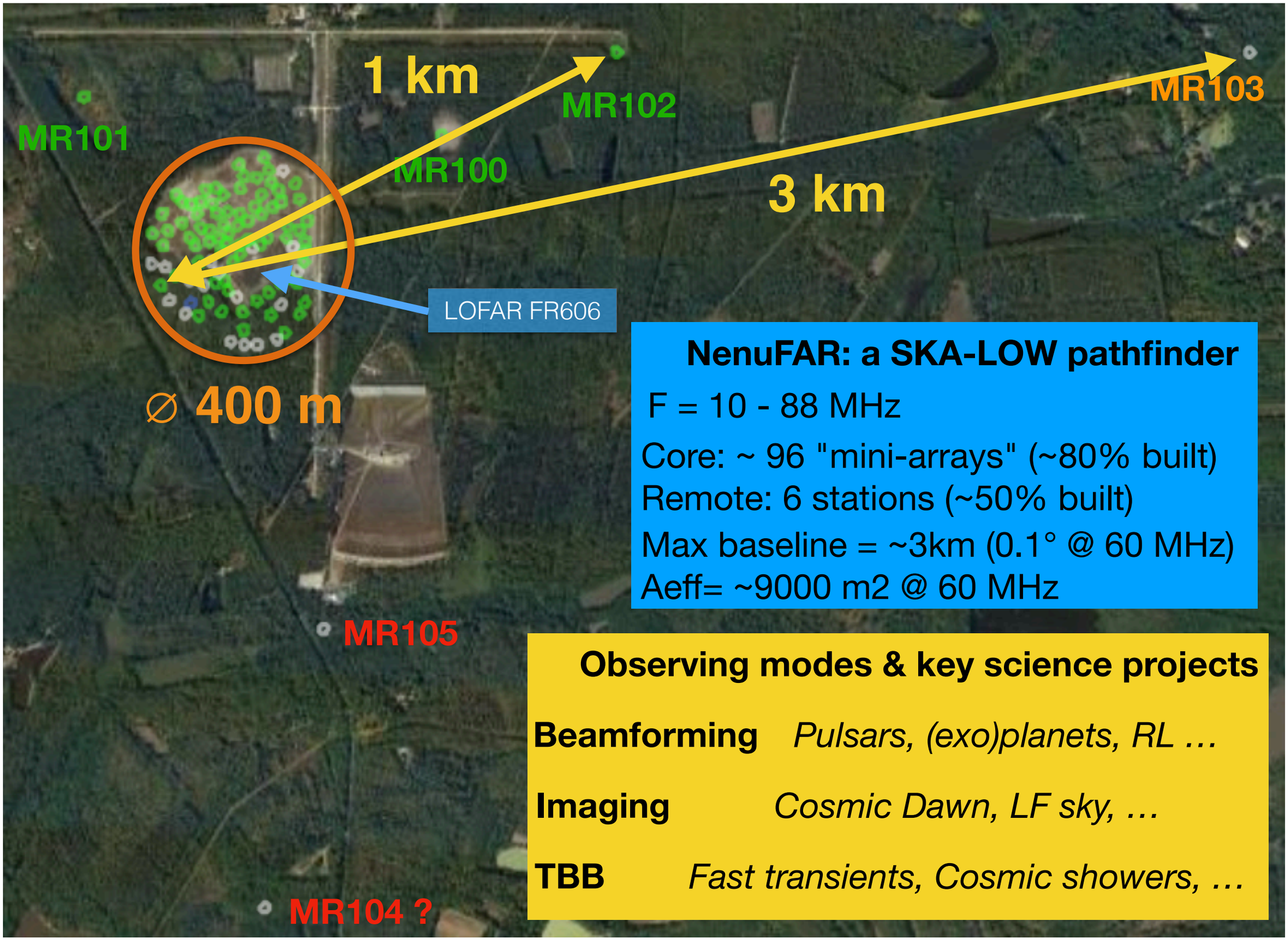
Asad, Girard et al., 2021 *Paper II (MeerKAT)* *10.1093/mnras/stab104*

Distribuable series of coefficients to generate MeerKAT beams

`https://github.com/ratt-ru/eidos`

The NenuFAR radio telescope

nenufar.obs-nancay.fr



NenuFAR: a SKA-LOW pathfinder

F = 10 - 88 MHz

Core: ~ 96 "mini-arrays" (~80% built)

Remote: 6 stations (~50% built)

Max baseline = ~3km (0.1° @ 60 MHz)

Aeff= ~9000 m2 @ 60 MHz

Observing modes & key science projects

Beamforming *Pulsars, (exo)planets, RL …*

Imaging *Cosmic Dawn, LF sky, …*

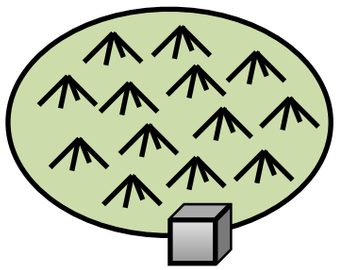
TBB *Fast transients, Cosmic showers, …*

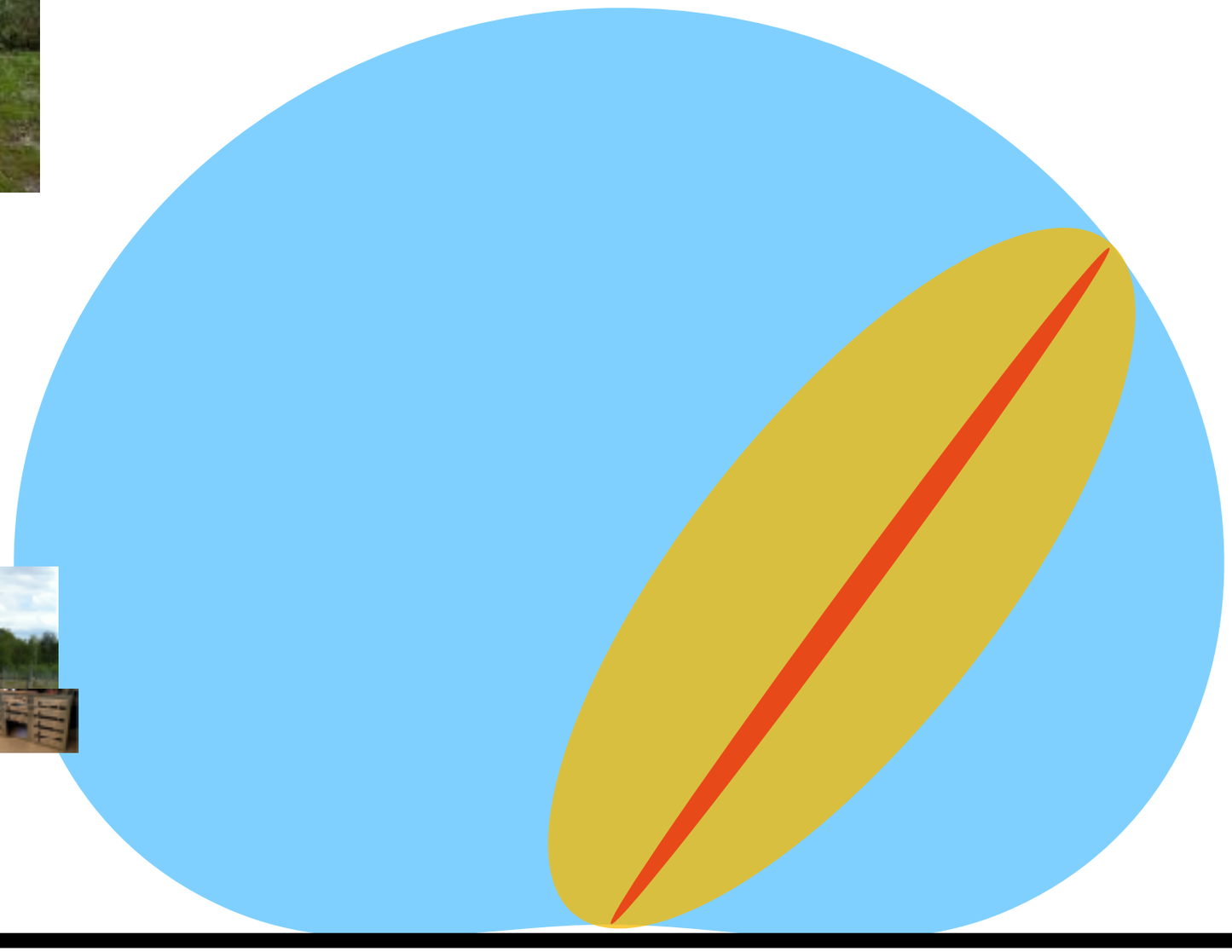
NenuFAR: a multiscale instrument

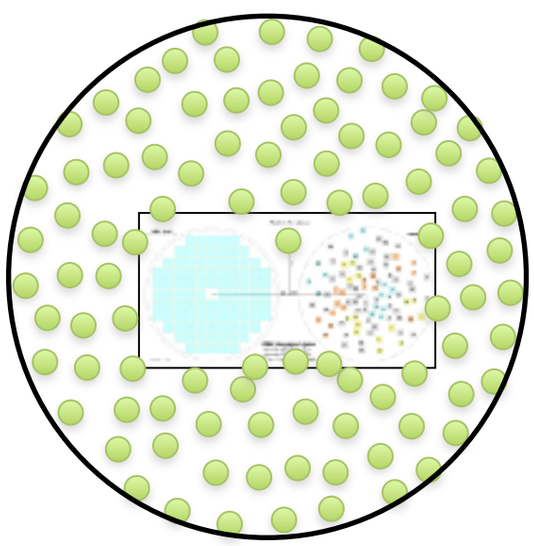
Element pattern

Analog beam

Digital beam

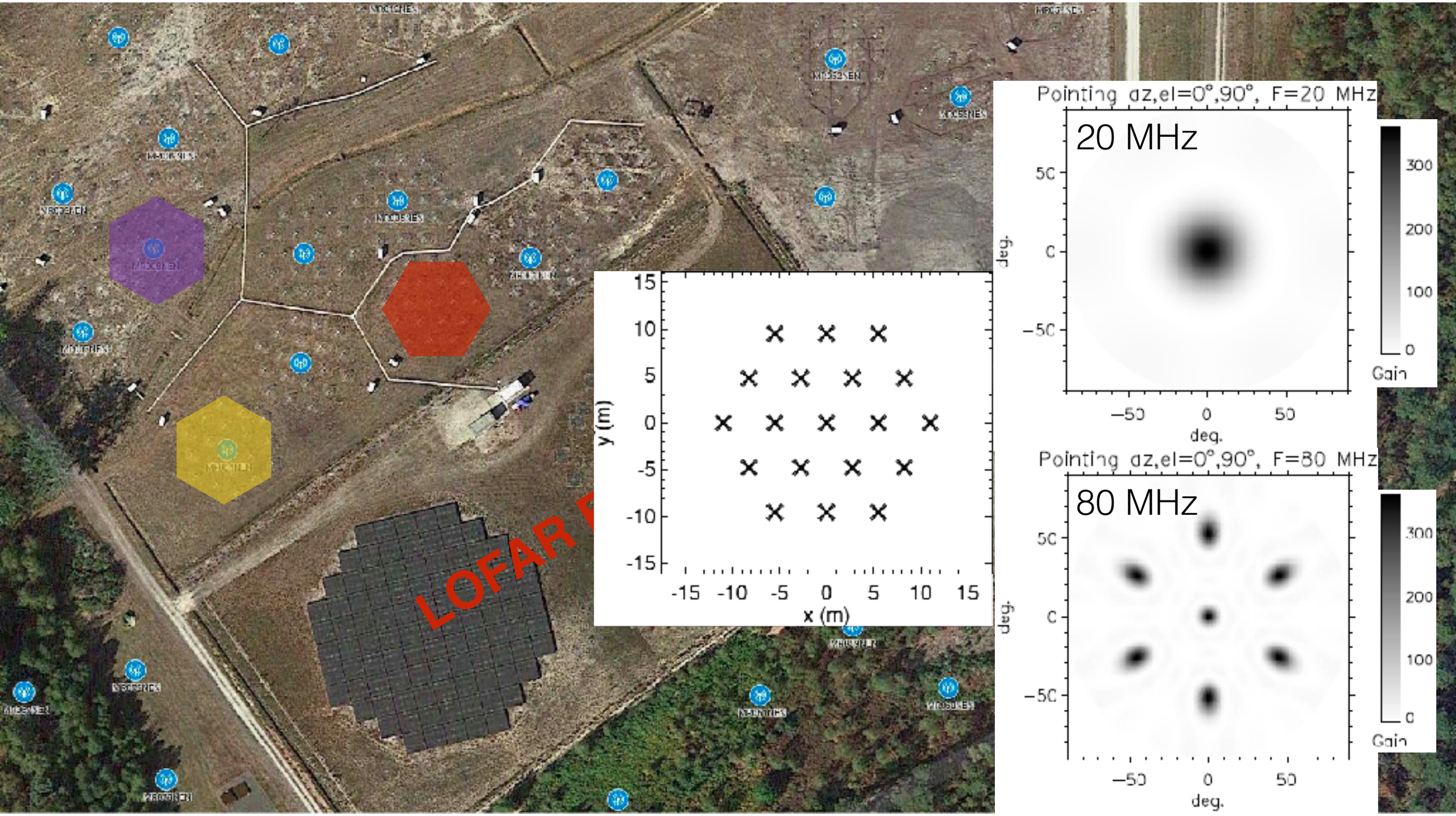






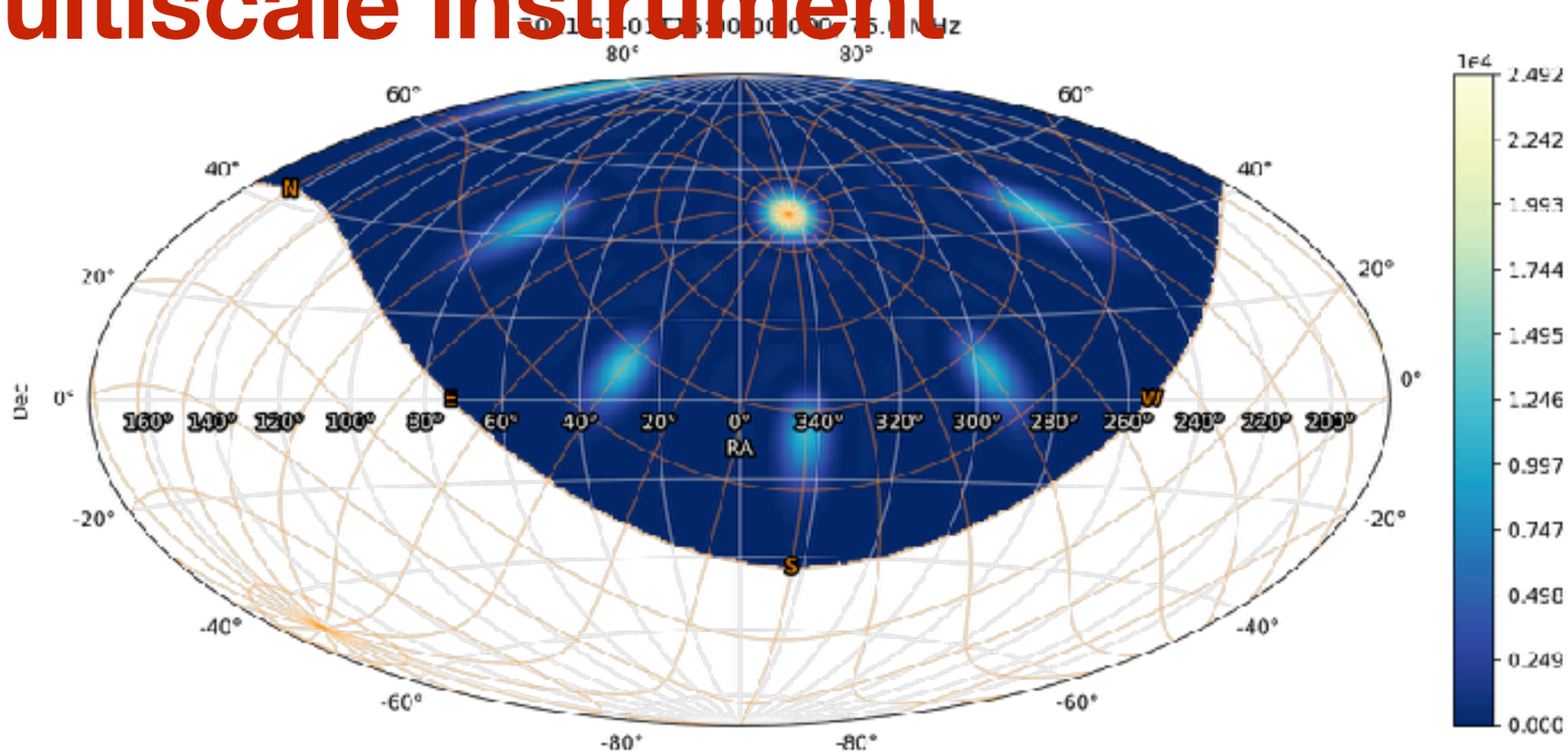
- Beam squint
- Direction-dependent beam pattern
- Challenging polarization response

NenuFAR: a multiscale instrument

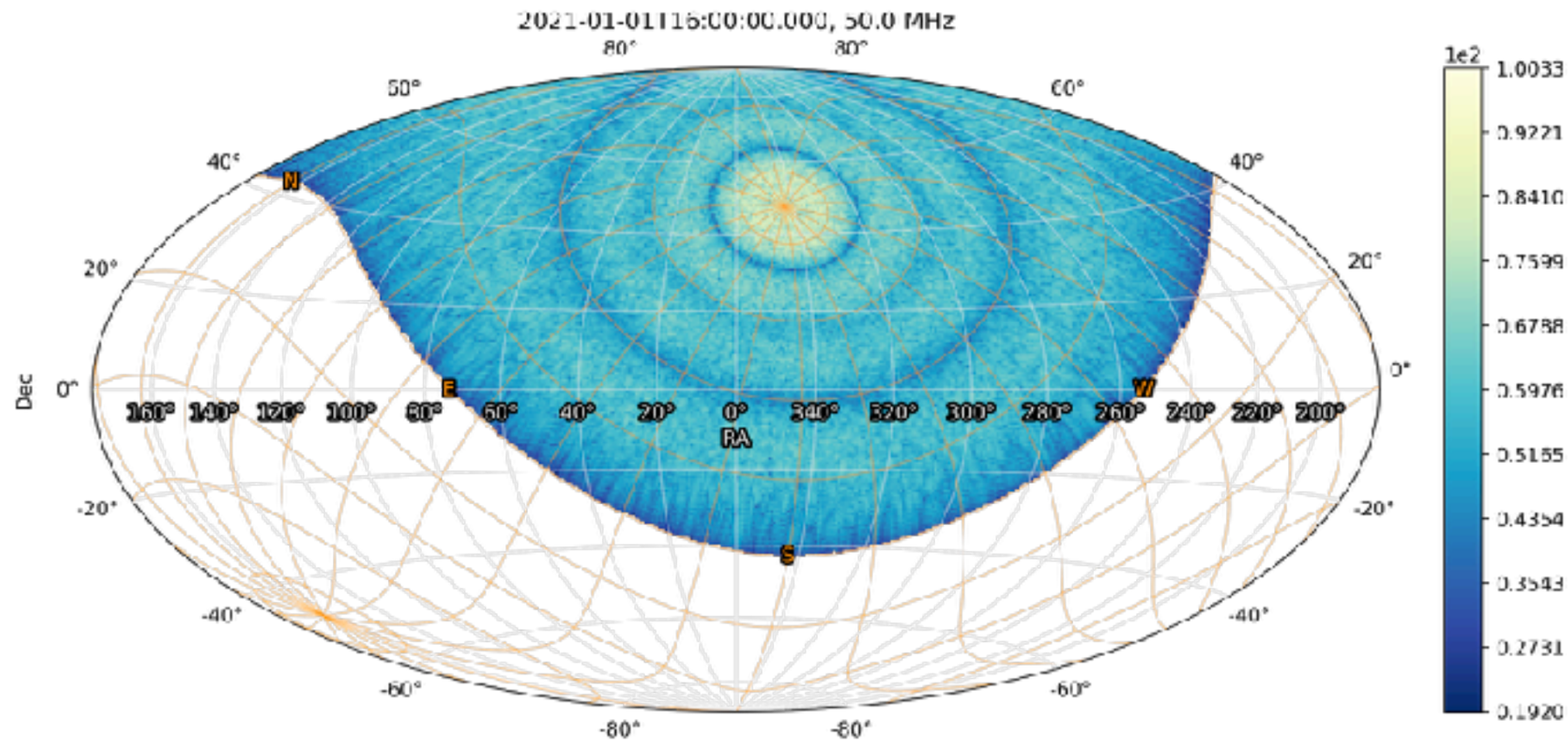


NenuFAR: a multiscale instrument

Single mini-array response (lin)



Rotated mini-arrays co-added (log)



Nenupy: https://nenupy.readthedocs.io

Credits: A. Loh

What's next: NenuFAR beam modeling

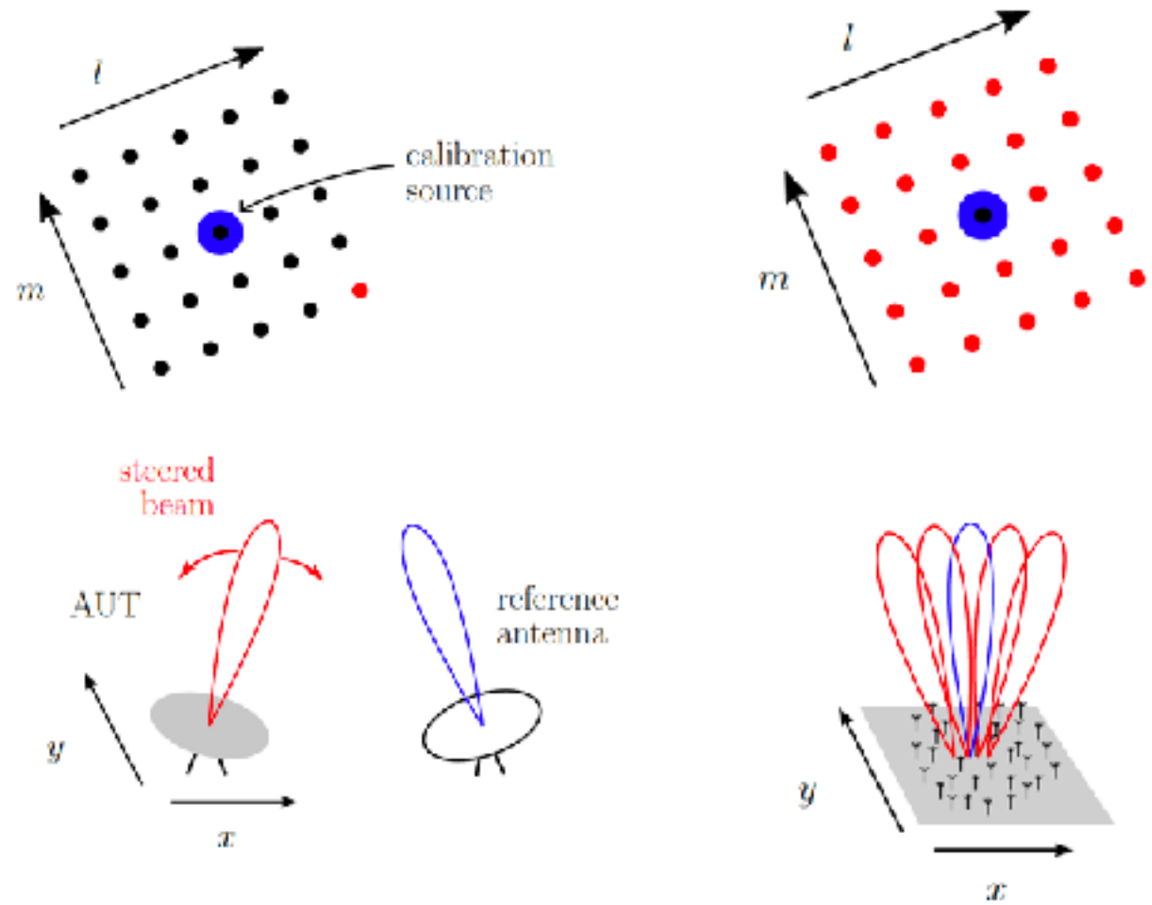
Kiefner et al., 2021

"Instantaneous" holography

possible with short, raw voltages

+

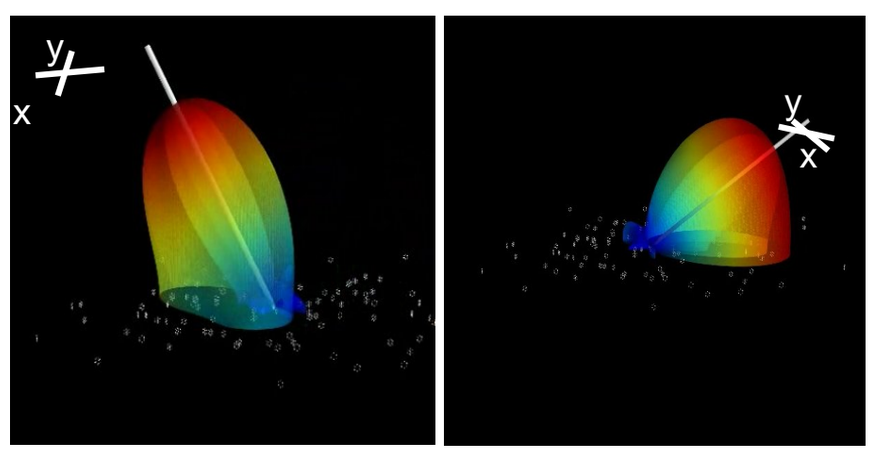
Post-processing to form all beams



"Ok" when: elements + array

e.g. EDA1, EDA2

But how to handle when: element + mini-array + array of mini-arrays ?

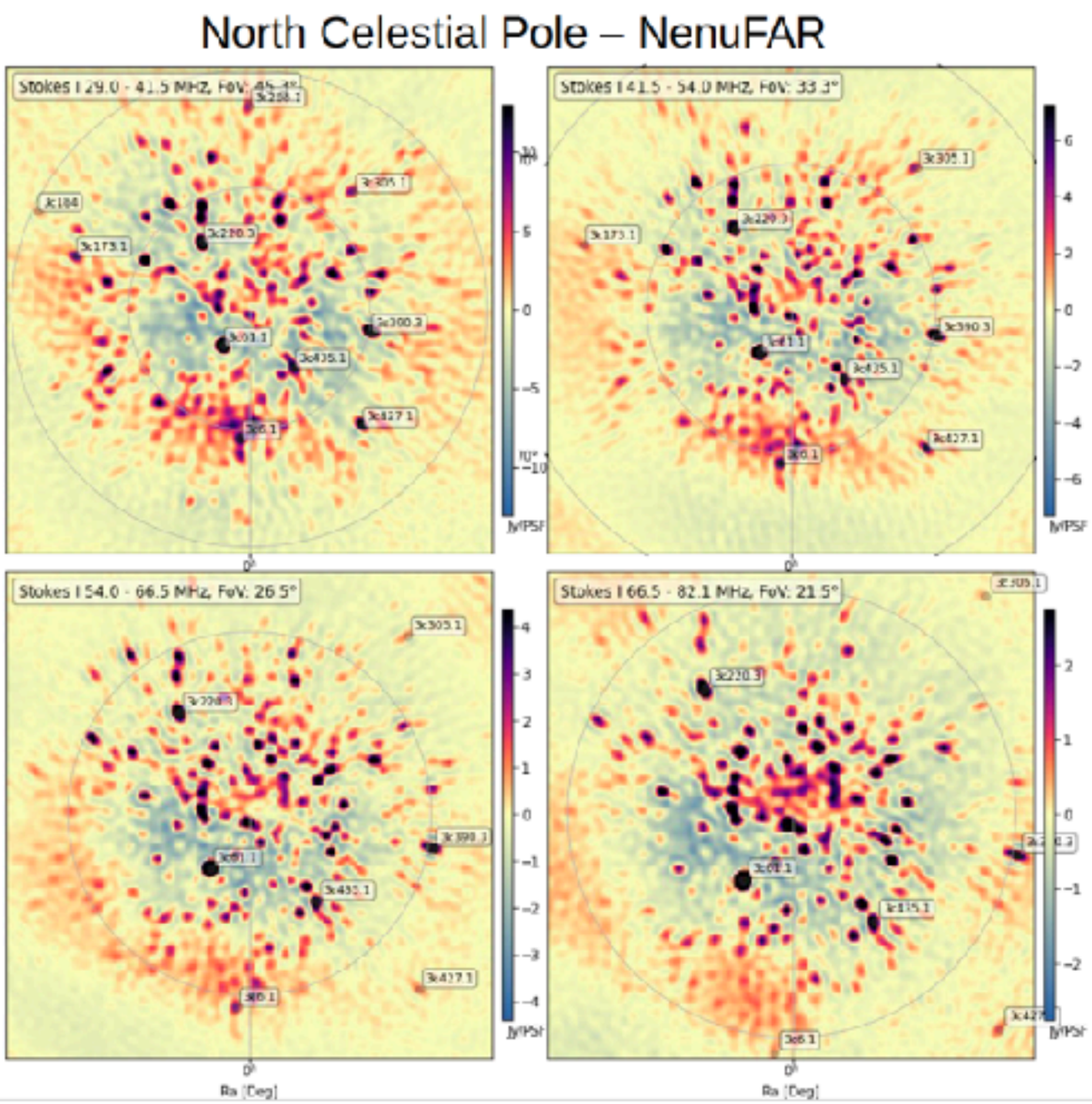


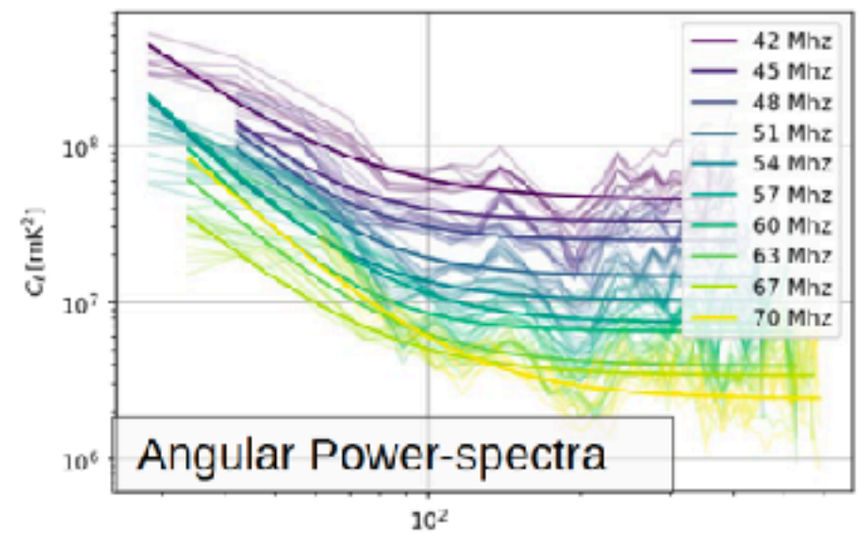
Direction 1 **Direction 2**

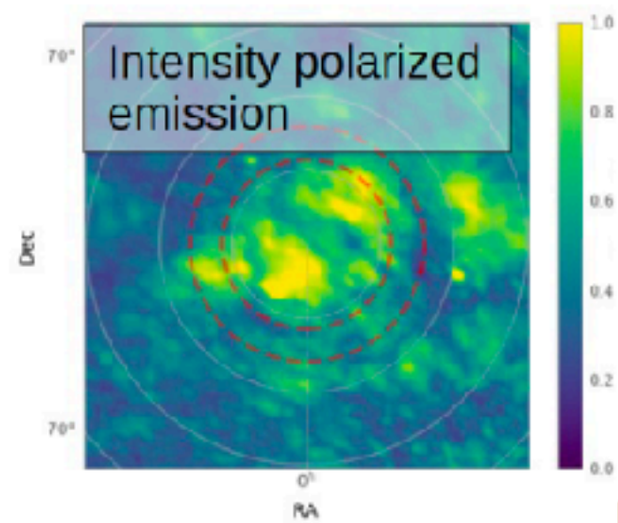
Impact on Cosmic Dawn observation programs

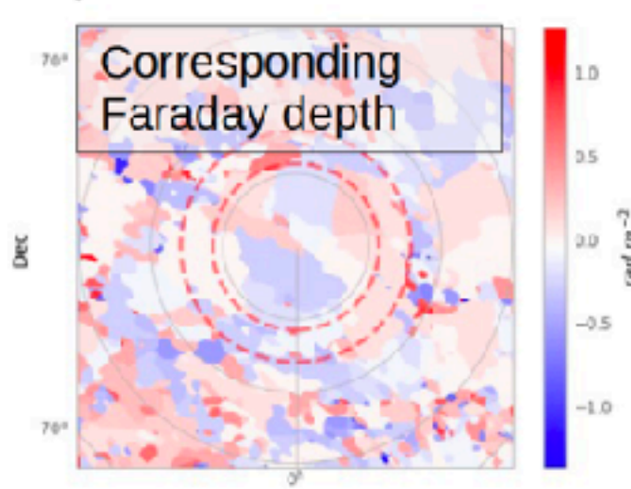
- "apparent" sky model, (DD calibration)
- foreground removal efficiency
- Polarization response corrections

Phase 1 results: diffuse emission









Bachelor thesis Krog + V. Jelic

+ results on the impact of RFIs and ionospheric disturbance to be published in Mertens et al. (in prep)

Credits: F. Mertens