

# Towards air shower observations with SKA-Low

**ARENA 2026**

**Katie Mulrey for the SKA CR team**

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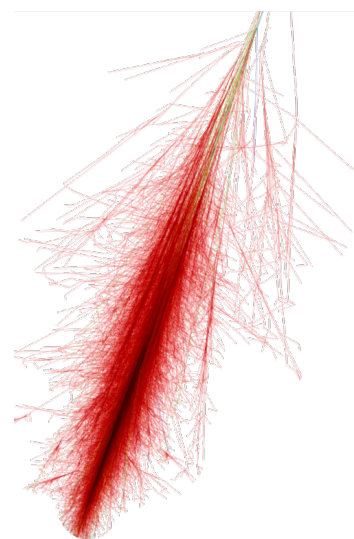
# Cosmic rays @ LOFAR

Low band (30-80 MHz)



~ 100s of antennas per event

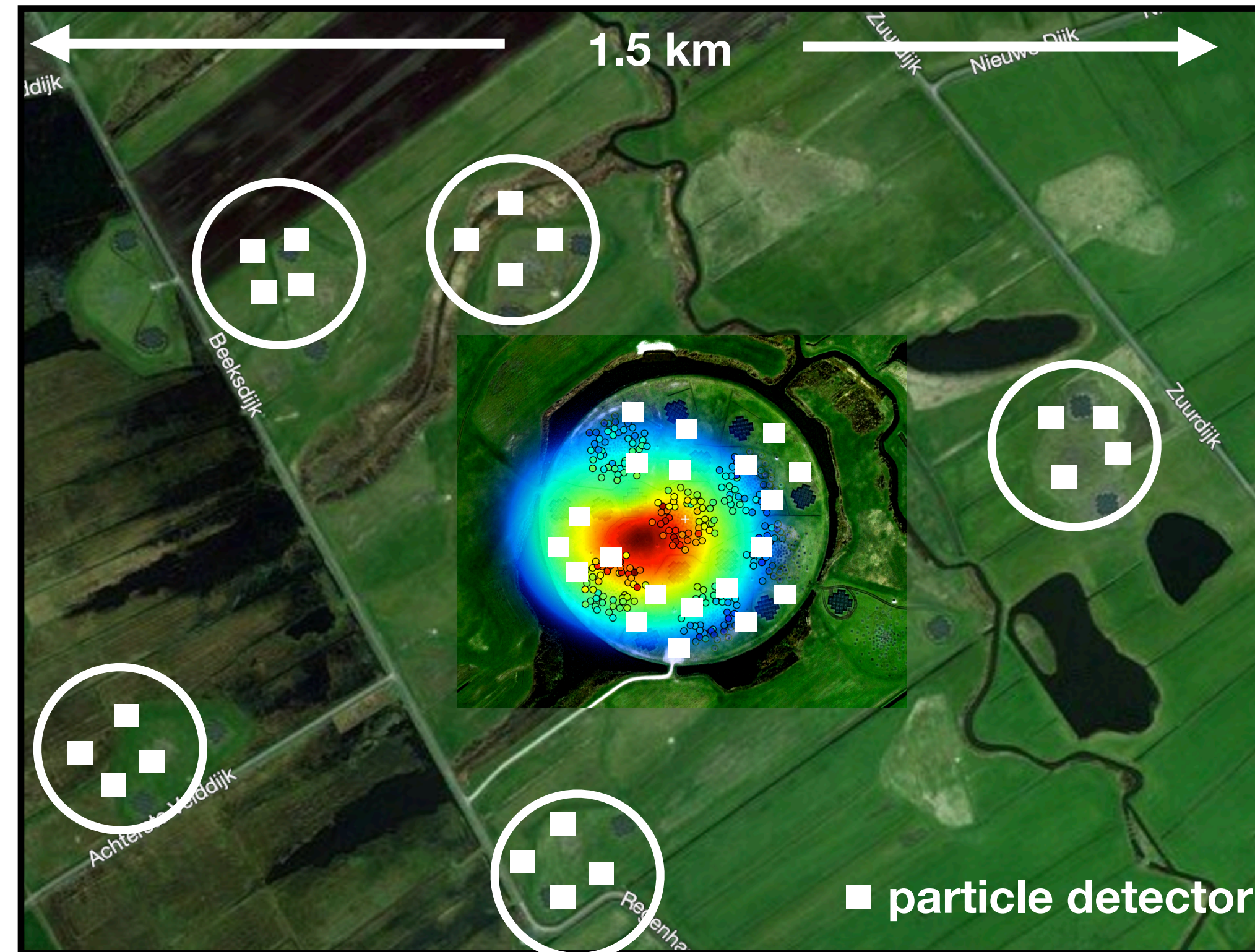
CR event



particle trigger

radio buffer readout

offline analysis



Particle detector for triggering



P. Schellart et al., A&A 560, 98 (2013)



# Cosmic rays @ LOFAR

Low band (30-80 MHz)



High band (120-240 MHz)

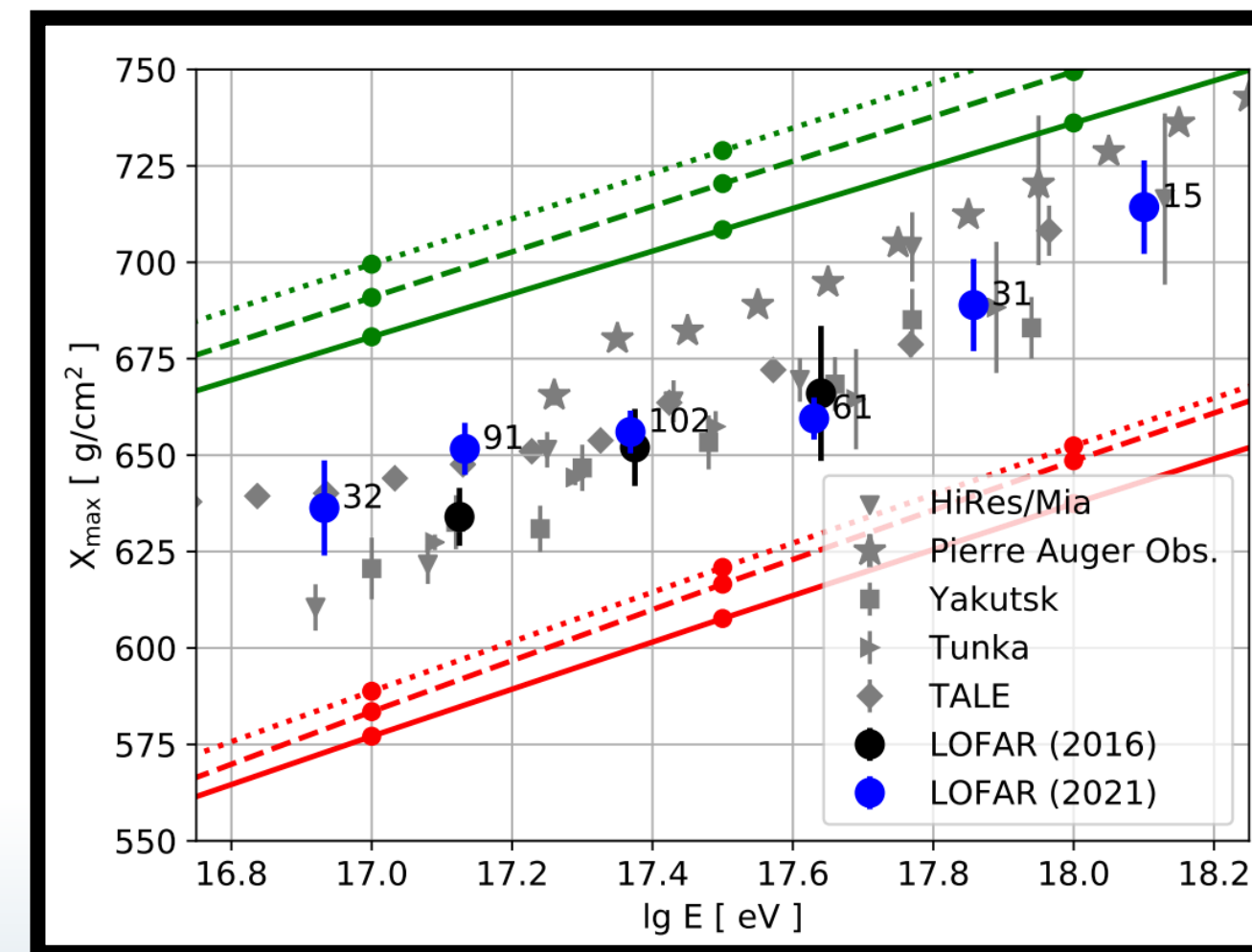
## Continued analysis of LOFAR 1 data

- New approaches to reach low energy
- Interferometry
- Information Field Theory

Talk from Karen Trever  
Thursday 9:45

## Preparation for LOFAR 2 (2026)

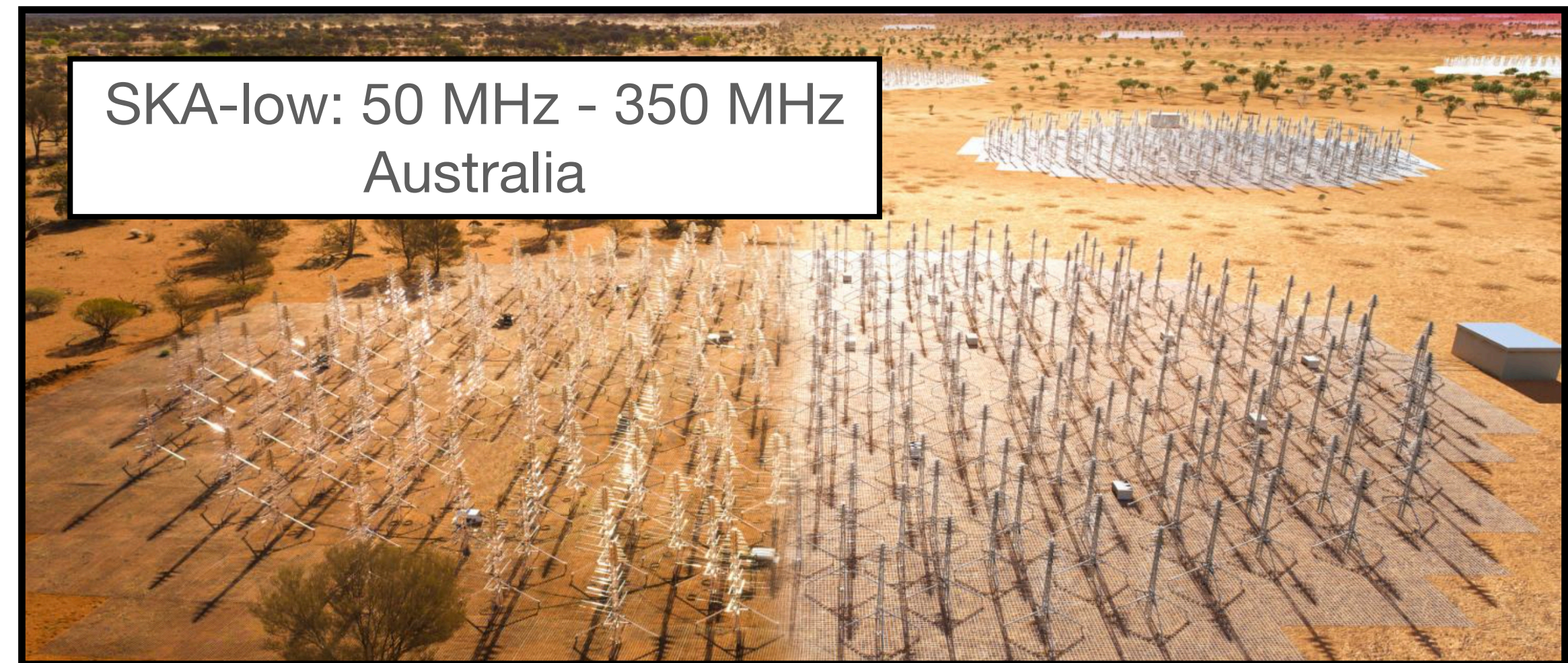
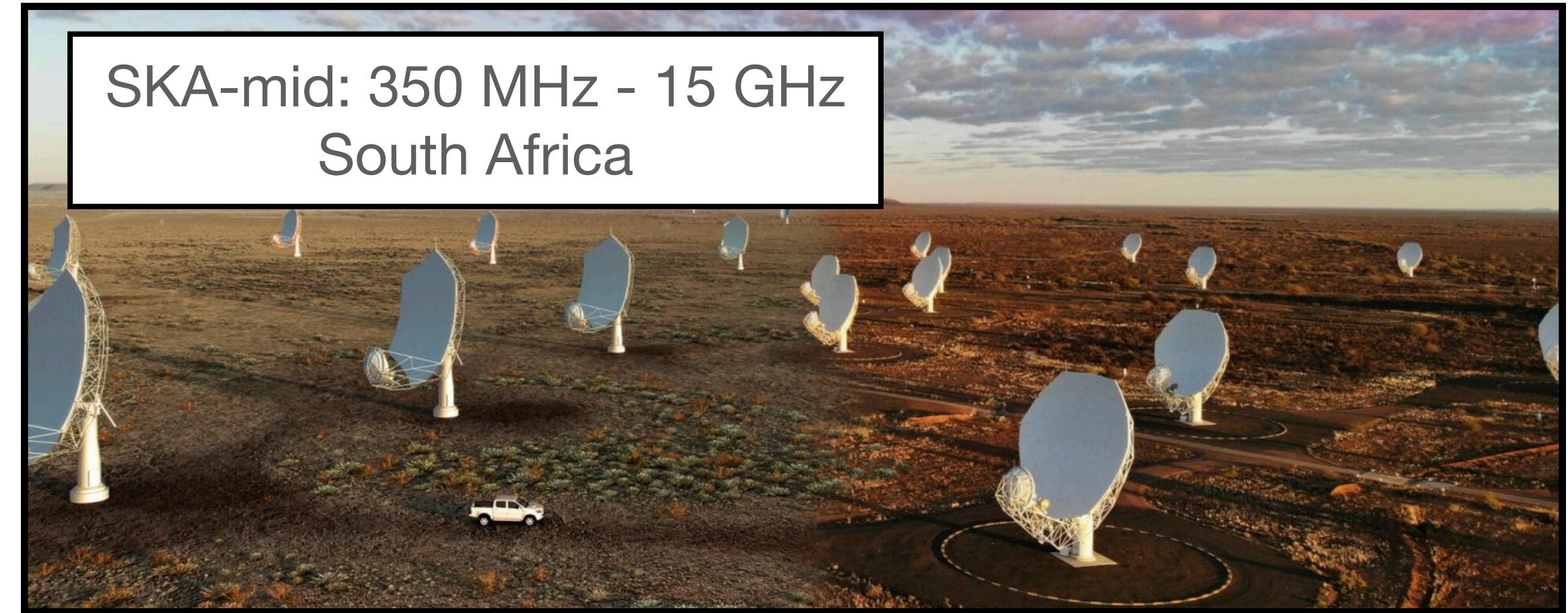
- New pipeline based on NuRadioReco
- Continuous observations for all antenna sets
- Usable data from LBA + HBA antennas
- Increased network speed



Buitink et al. Nature, 2016.  
Corstanje et al. Phys. Rev. D., 2021.



# Square Kilometer Array

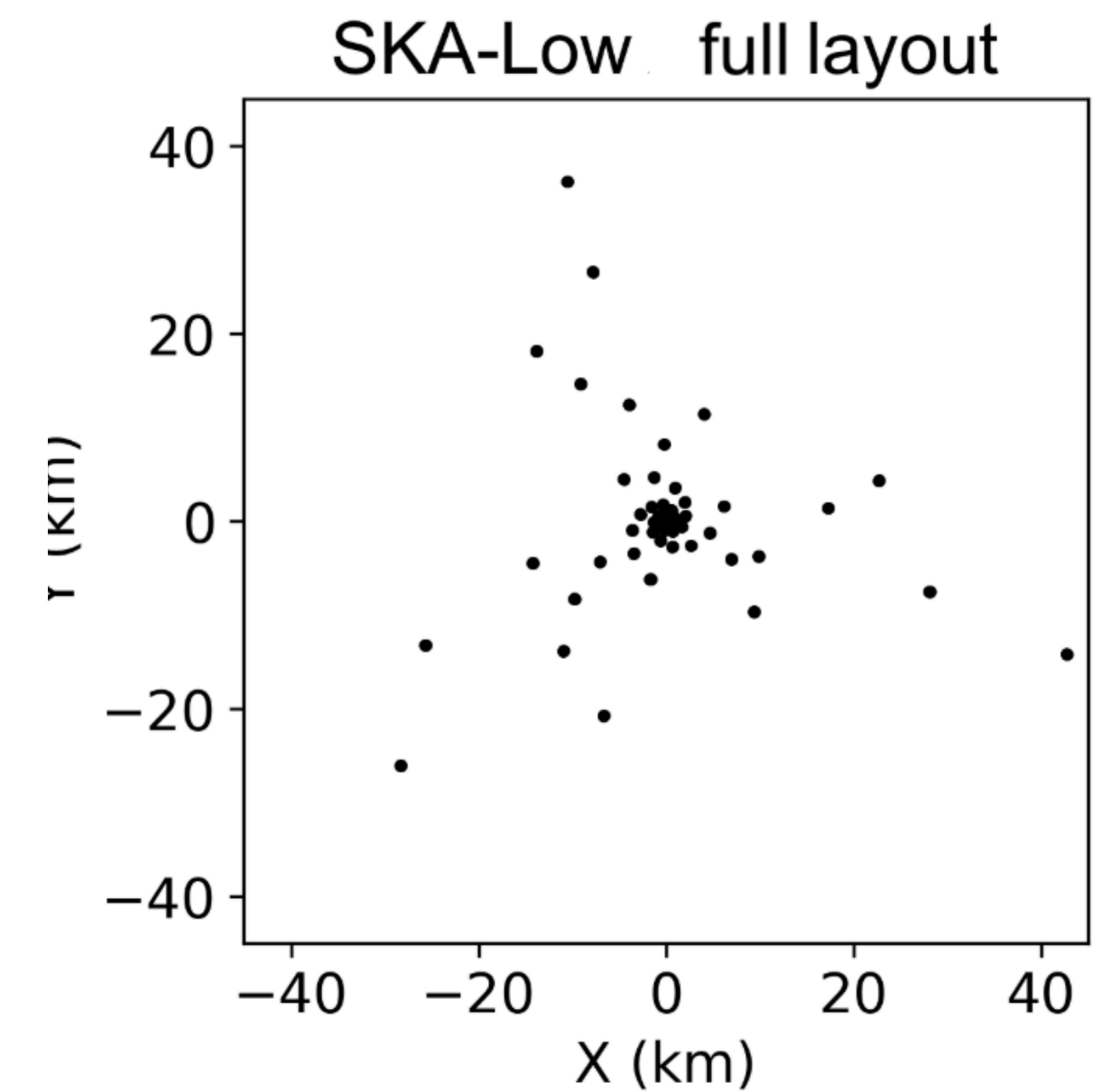
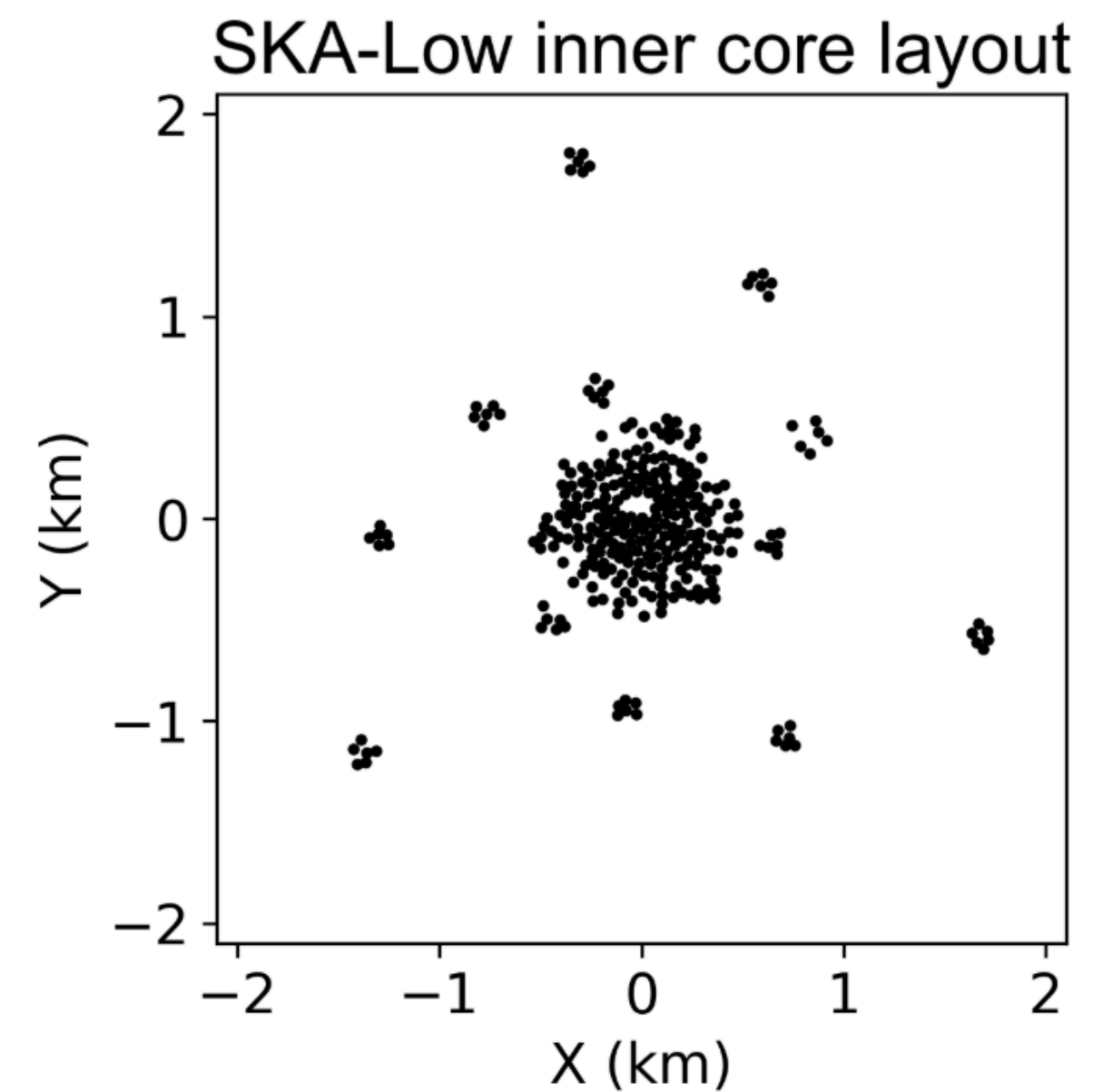




# Square Kilometer Array



- Core region:  $\sim 60,000$  antennas within  $1 \text{ km}^2$
- SKALA4 LPDA: 30 - 350 MHz
- 10,000 antennas currently deployed
- Commissioning happening now

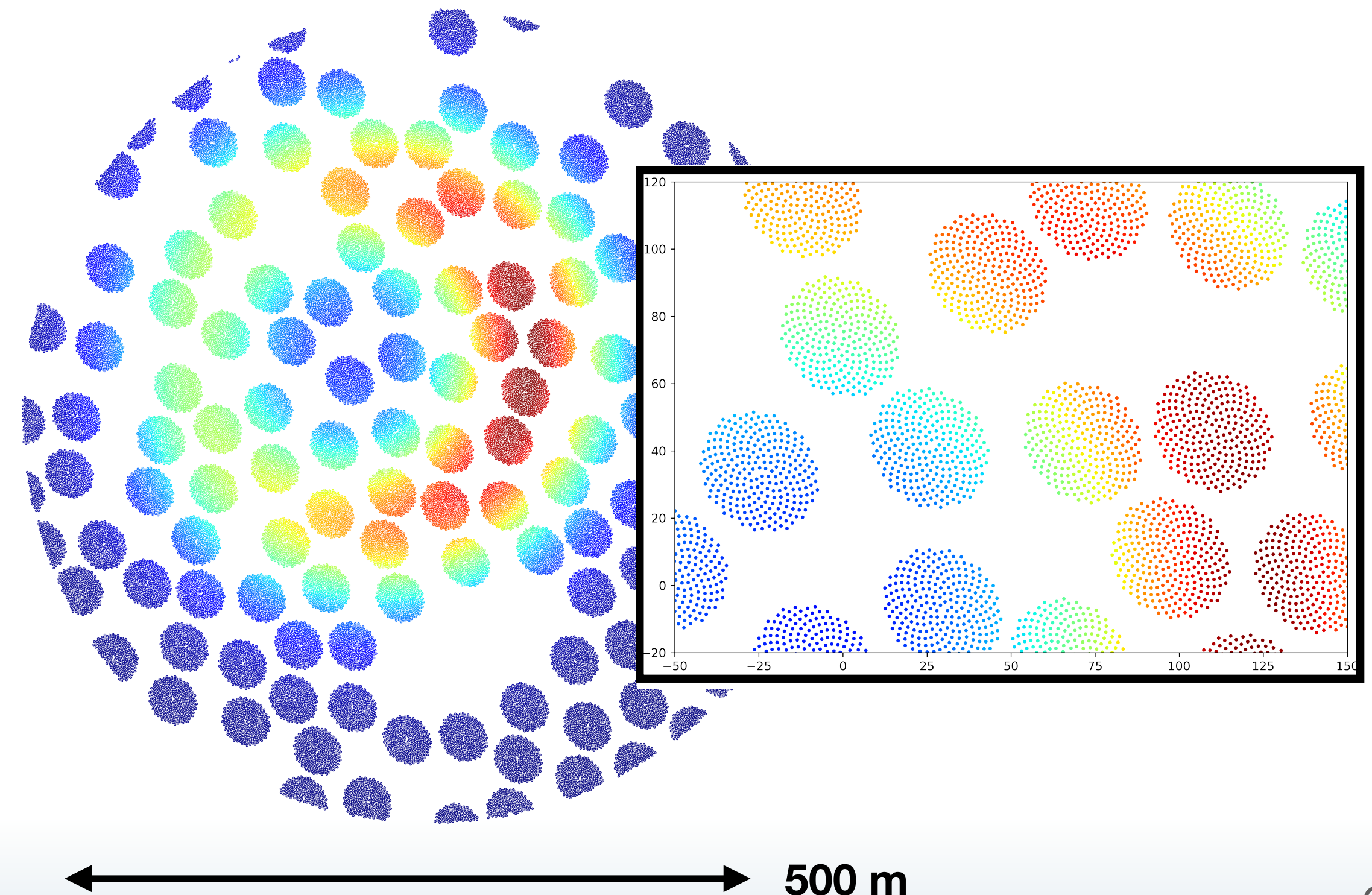




# Square Kilometer Array

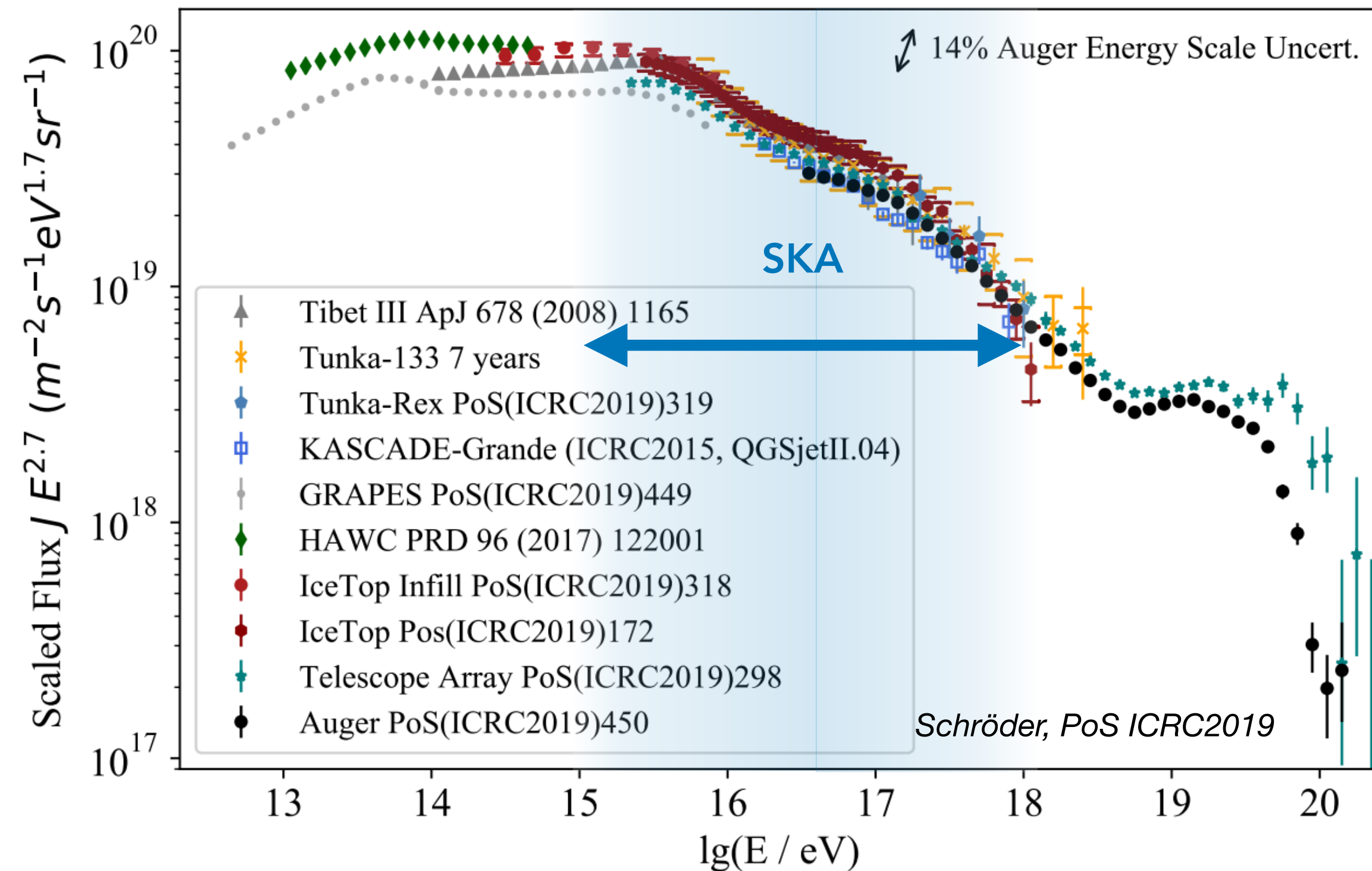


- CR observations run in the background of astronomical observations
- Particle detector array for triggering
- Few  $\mu$ s of buffered raw voltage data read out
- Observe air showers with  $\sim 10$ k antennas per event



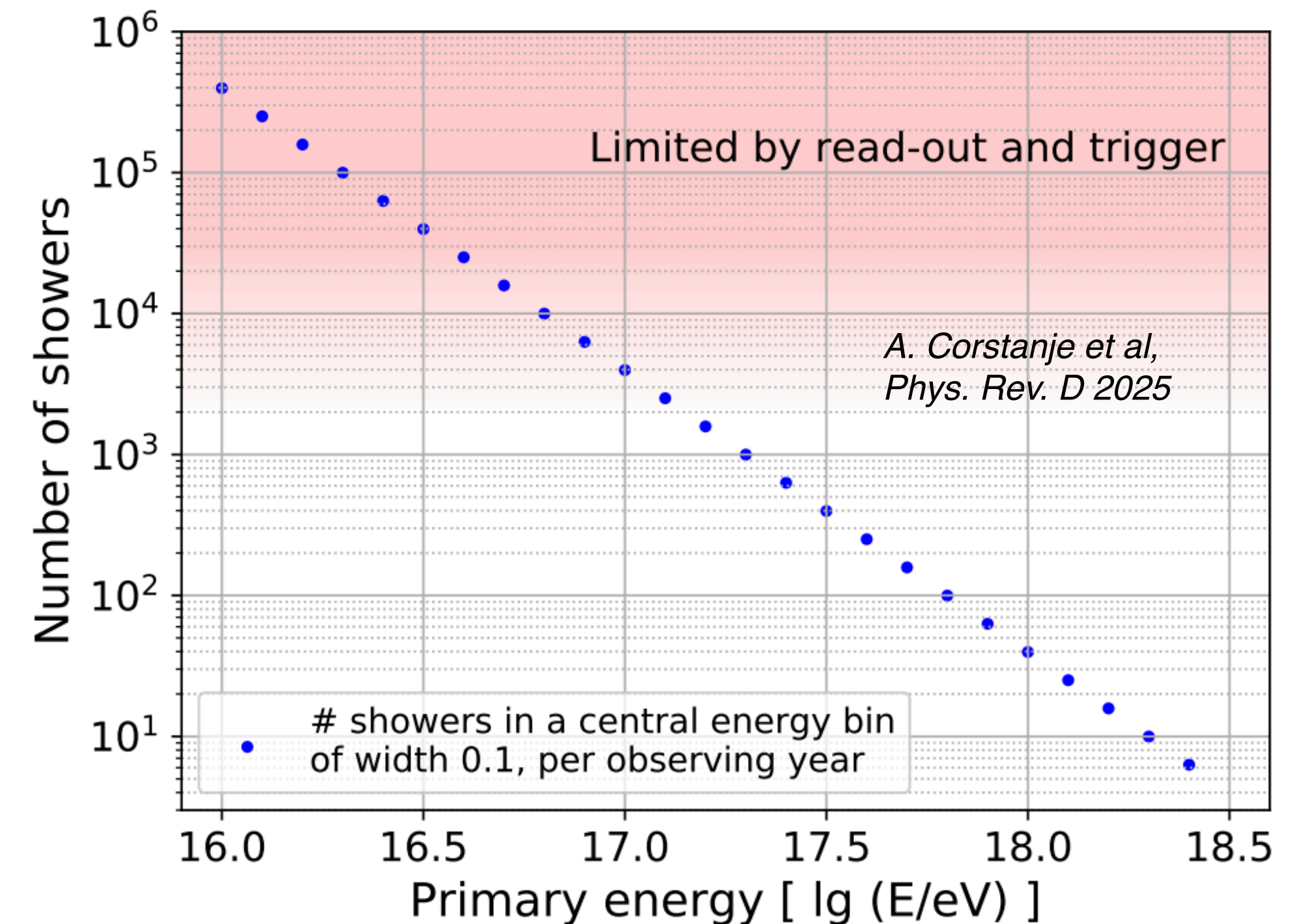


# Square Kilometer Array



## Target Science

- High resolution mass composition in transition region
- Hadronic physics
- Low energy air showers, gamma rays?



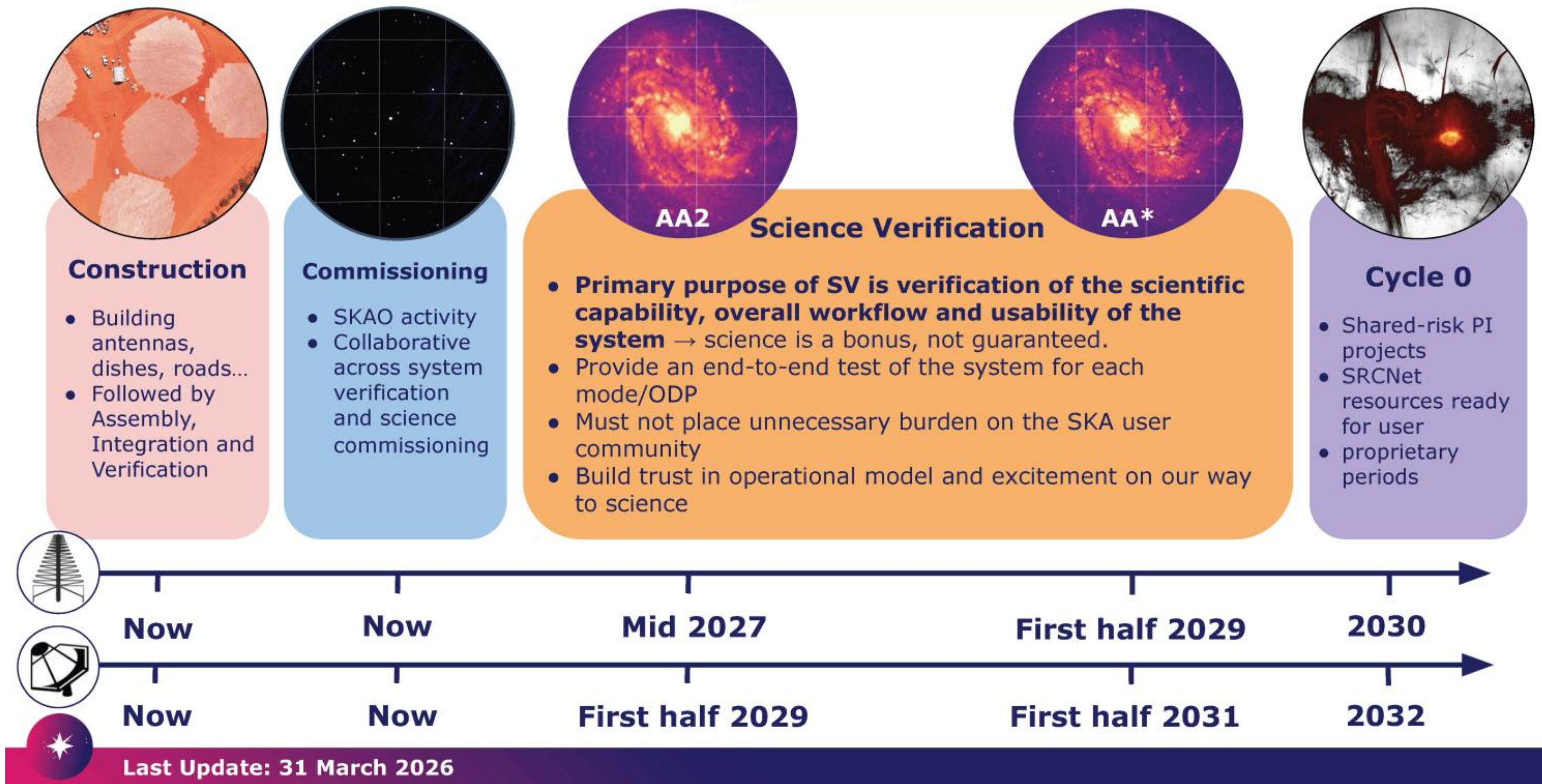


# Square Kilometer Array

## SKAO milestones

Community involvement starts

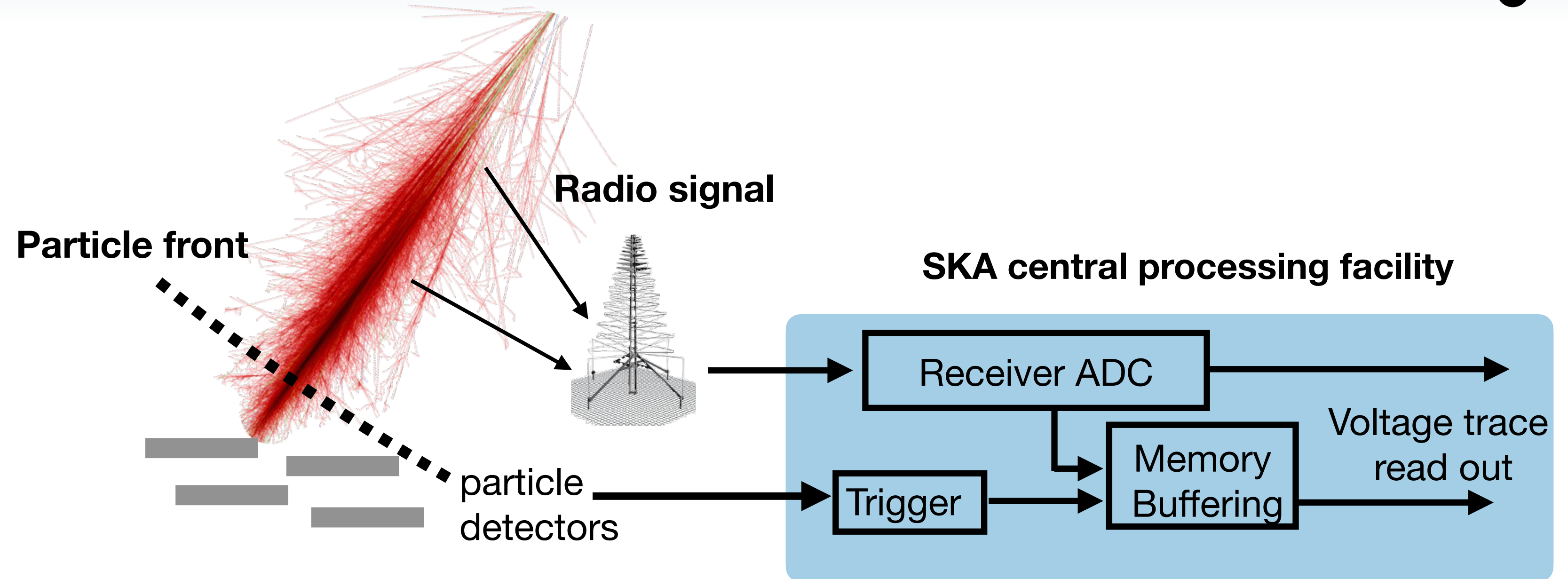
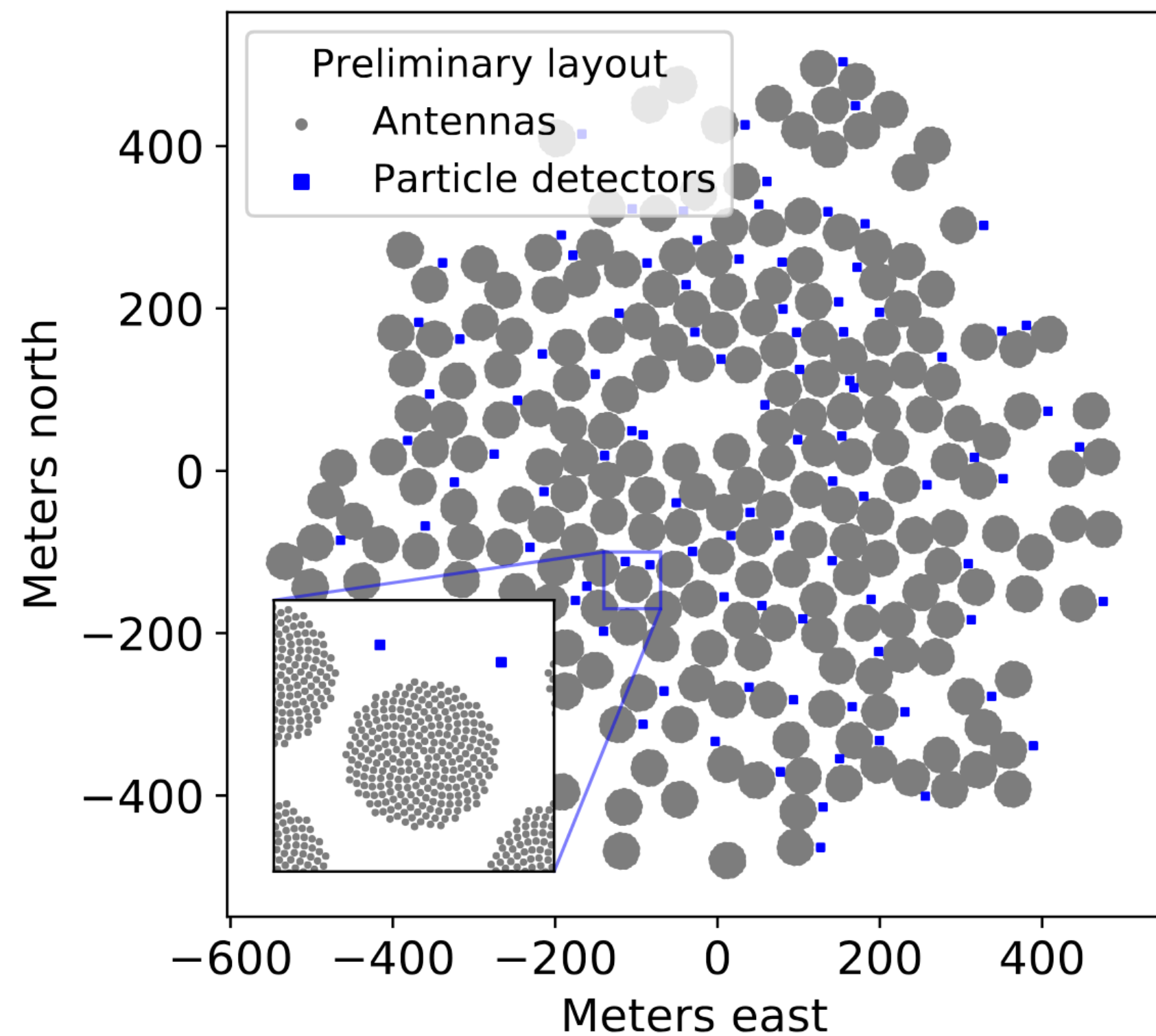
Credit: I. Heywood, SARAO



- Cosmic ray detection in the process of becoming an SKA “custom experiment”
- Development of particle detector and triggering strategy happening in parallel
- SKA CR pipeline following the LOFAR NuRadioReco approach
- Developing analyses



# Particle detector array

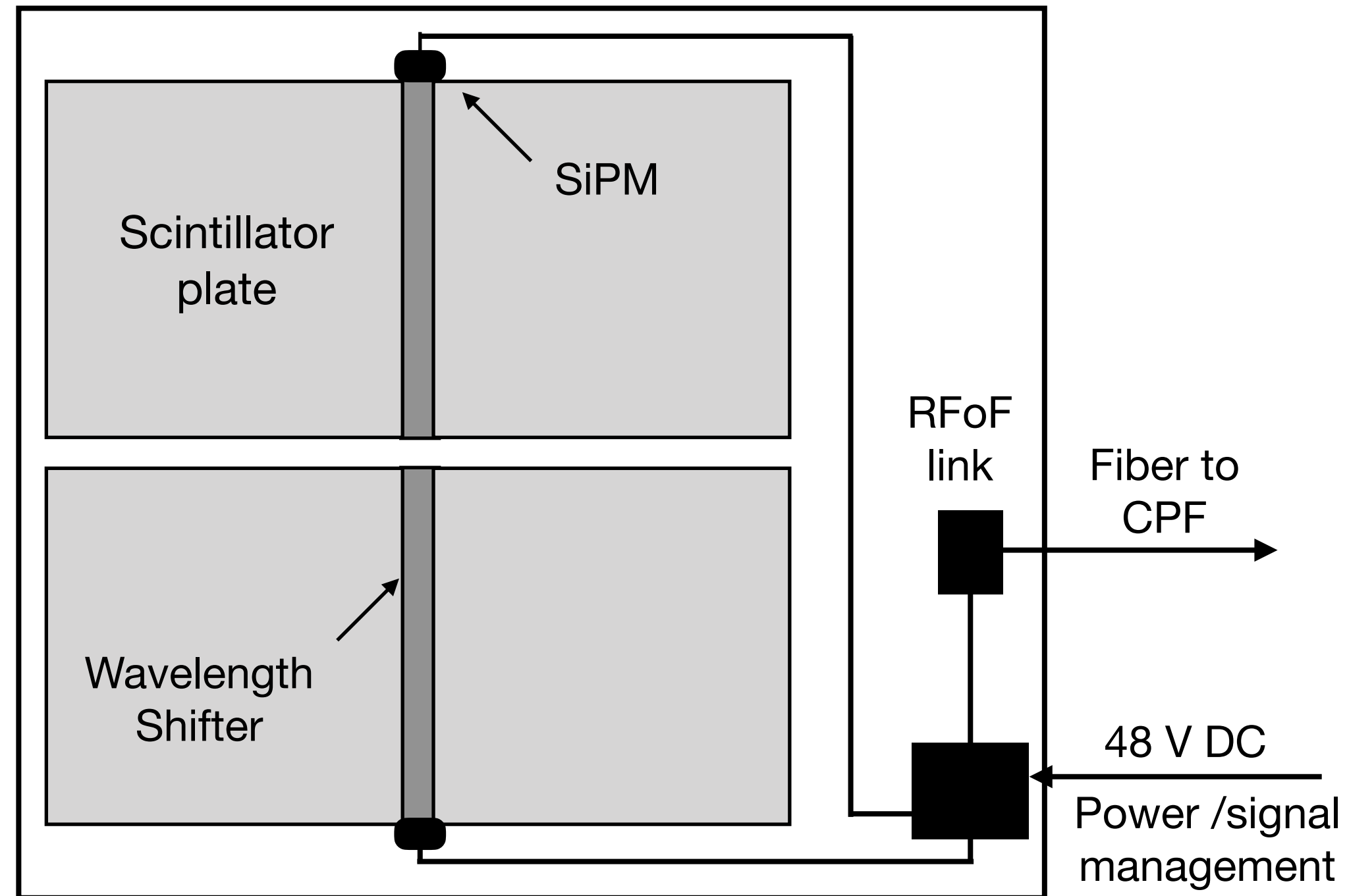


Prototype detector installed at Murchison Widefield Array

*J. Bray et al., NIMPA, 2020.  
arXiv:2603.00414*

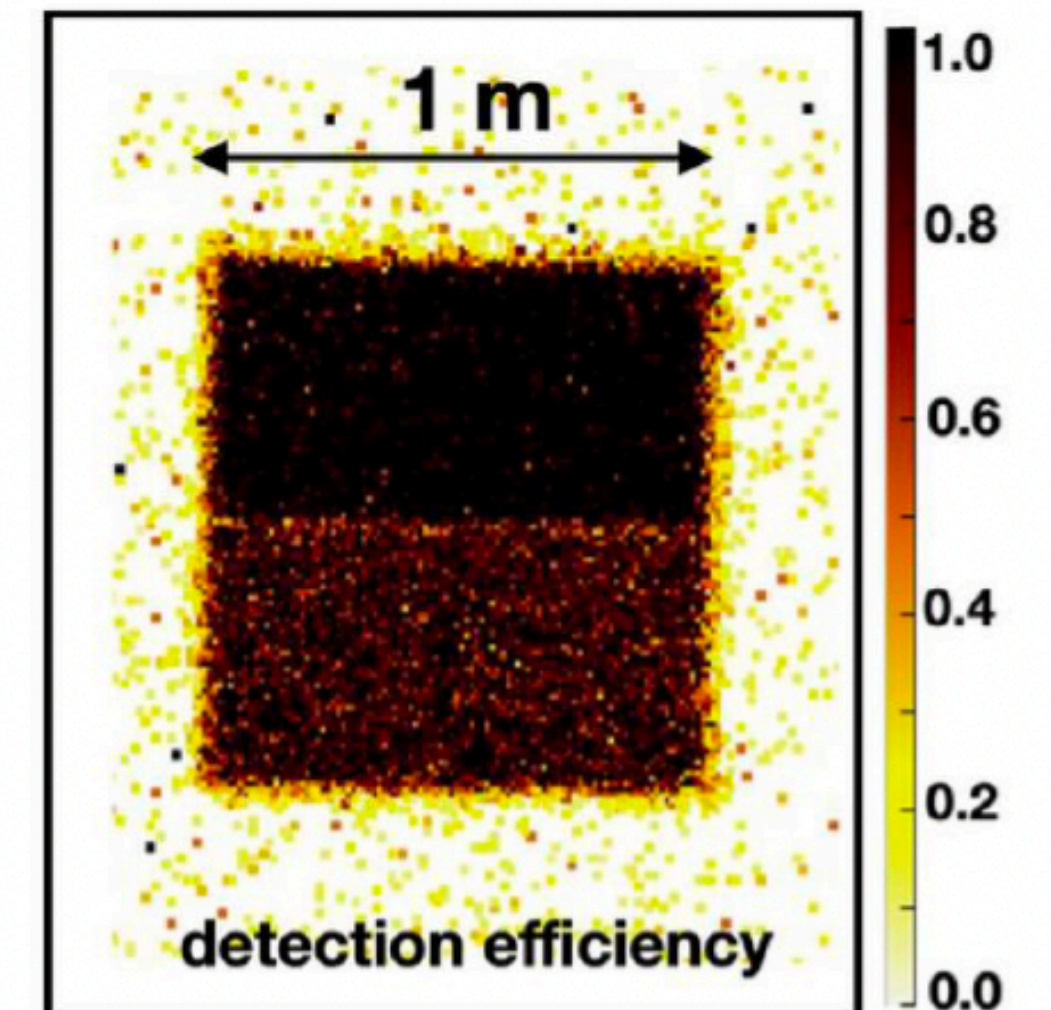
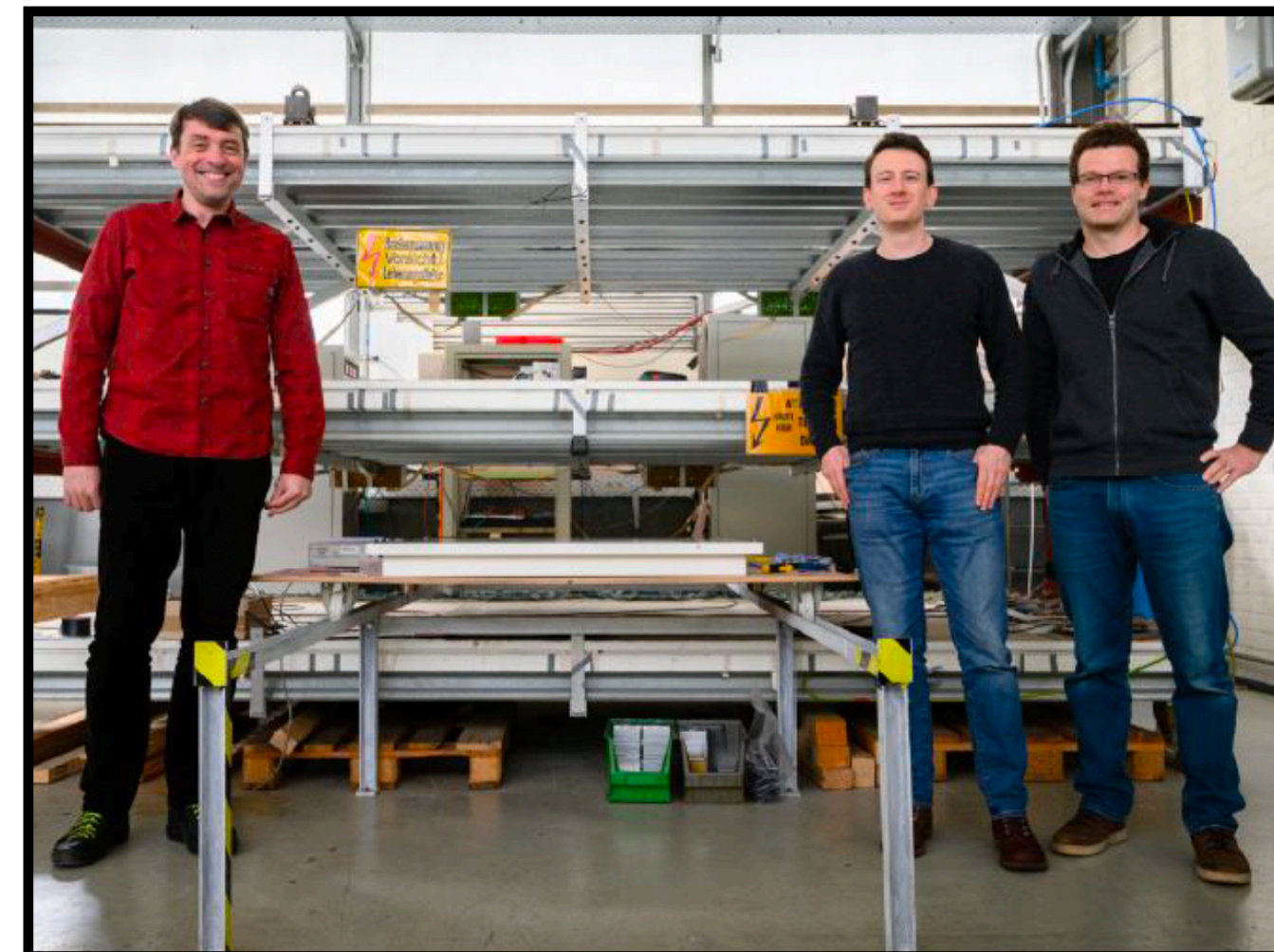


# Particle detector array



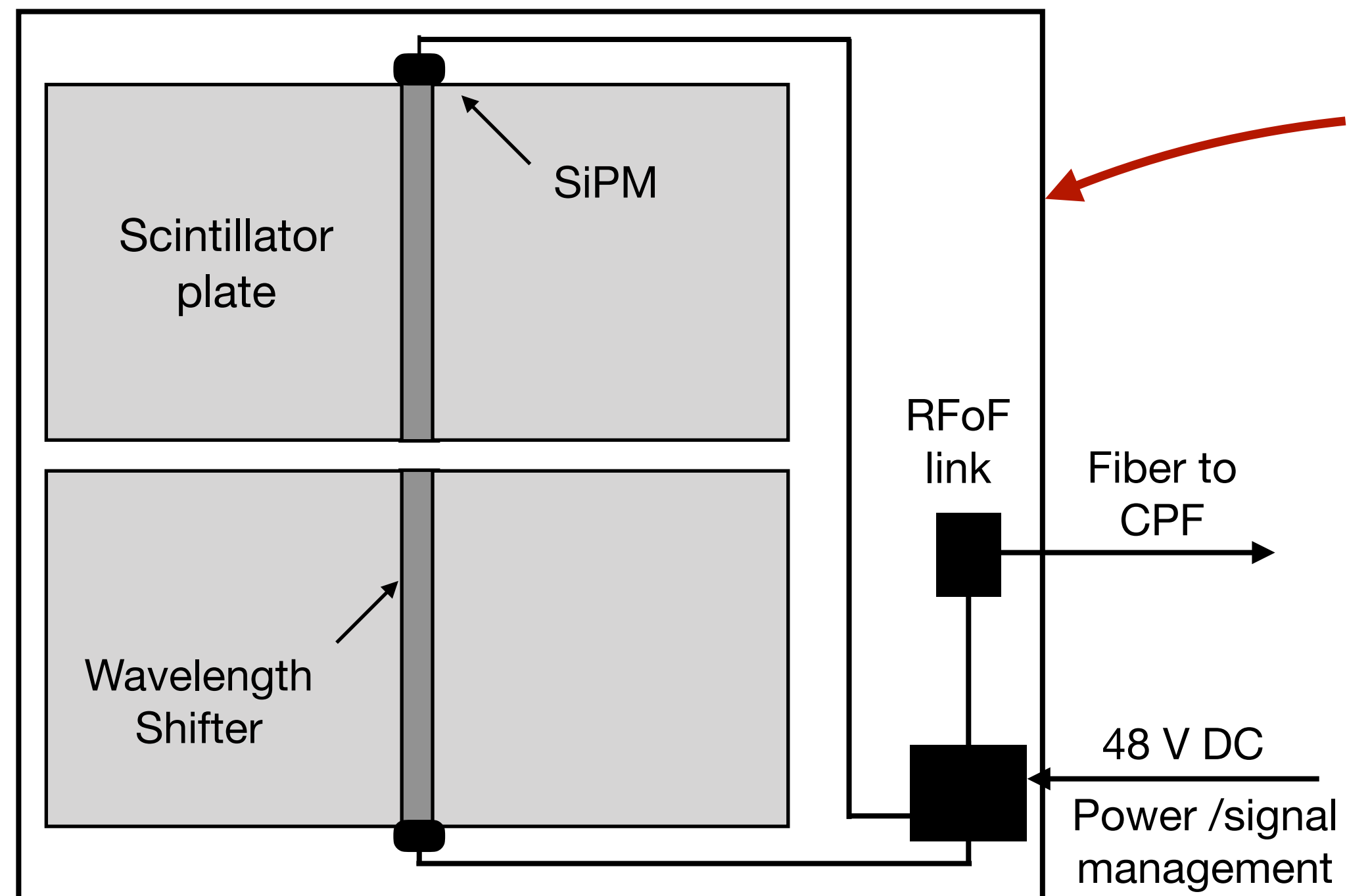
- Fully funded 120 detector array by FWO Belgium, NOVA Netherlands + in-kind contributions KIT
- Currently under development at KIT and the Radboud Radio Lab
- Very strict regulations on radio quietness
- *First field deployment in the next 12 months*

**Muon tower at KIT**



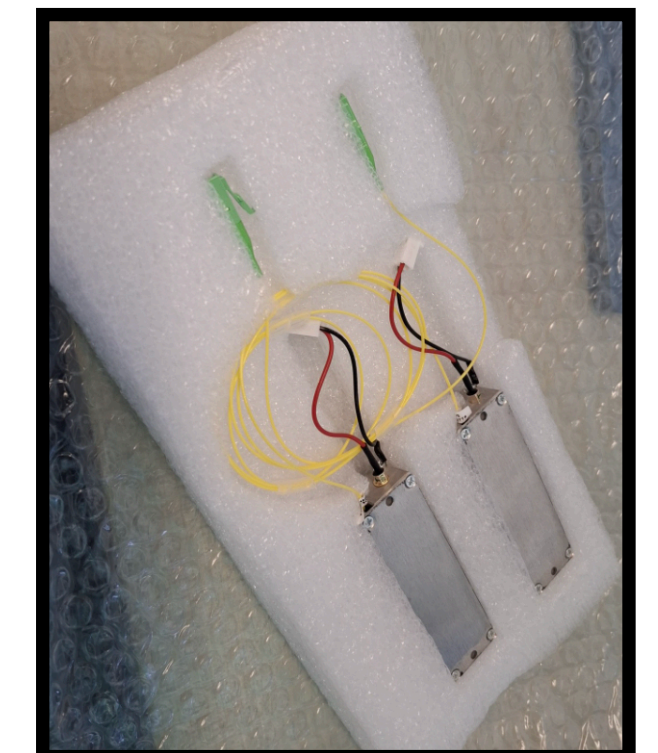


# Particle detector array

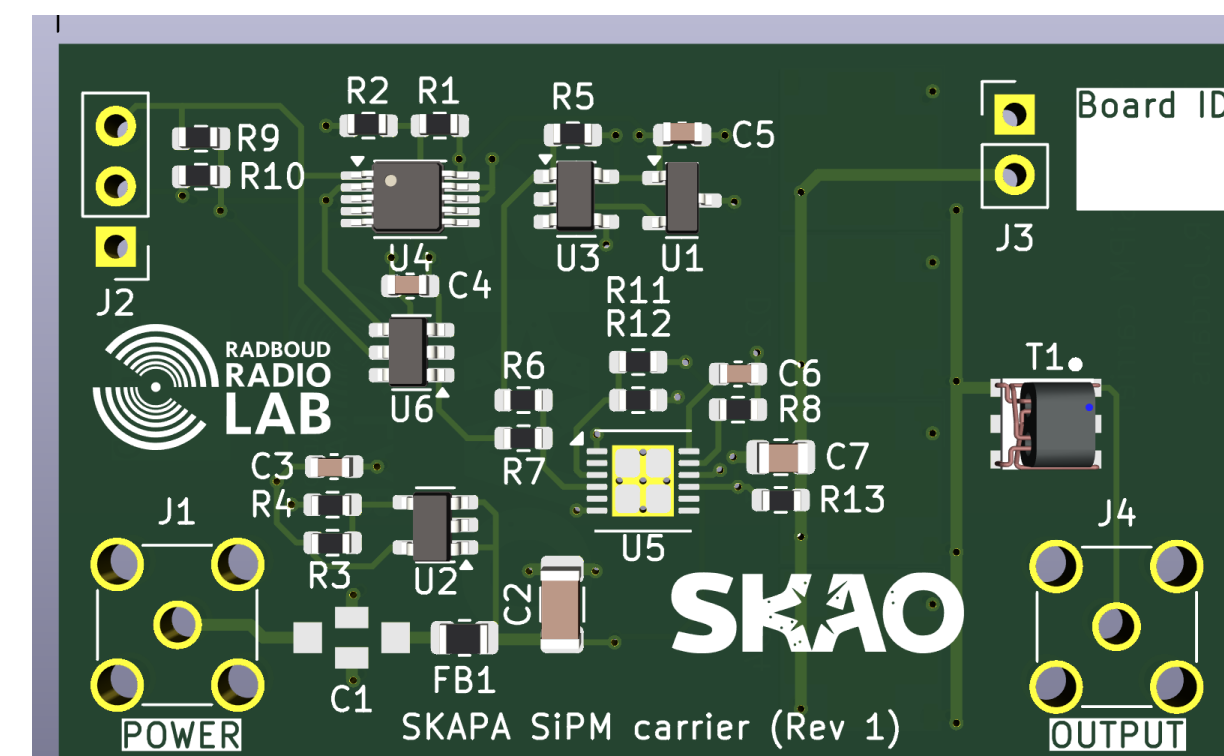


**Reused scintillator material and housing from KASCADE**

**Same power cables, RFoF links, digitizing electronics as antennas (*fast! 800 MSPS*)**

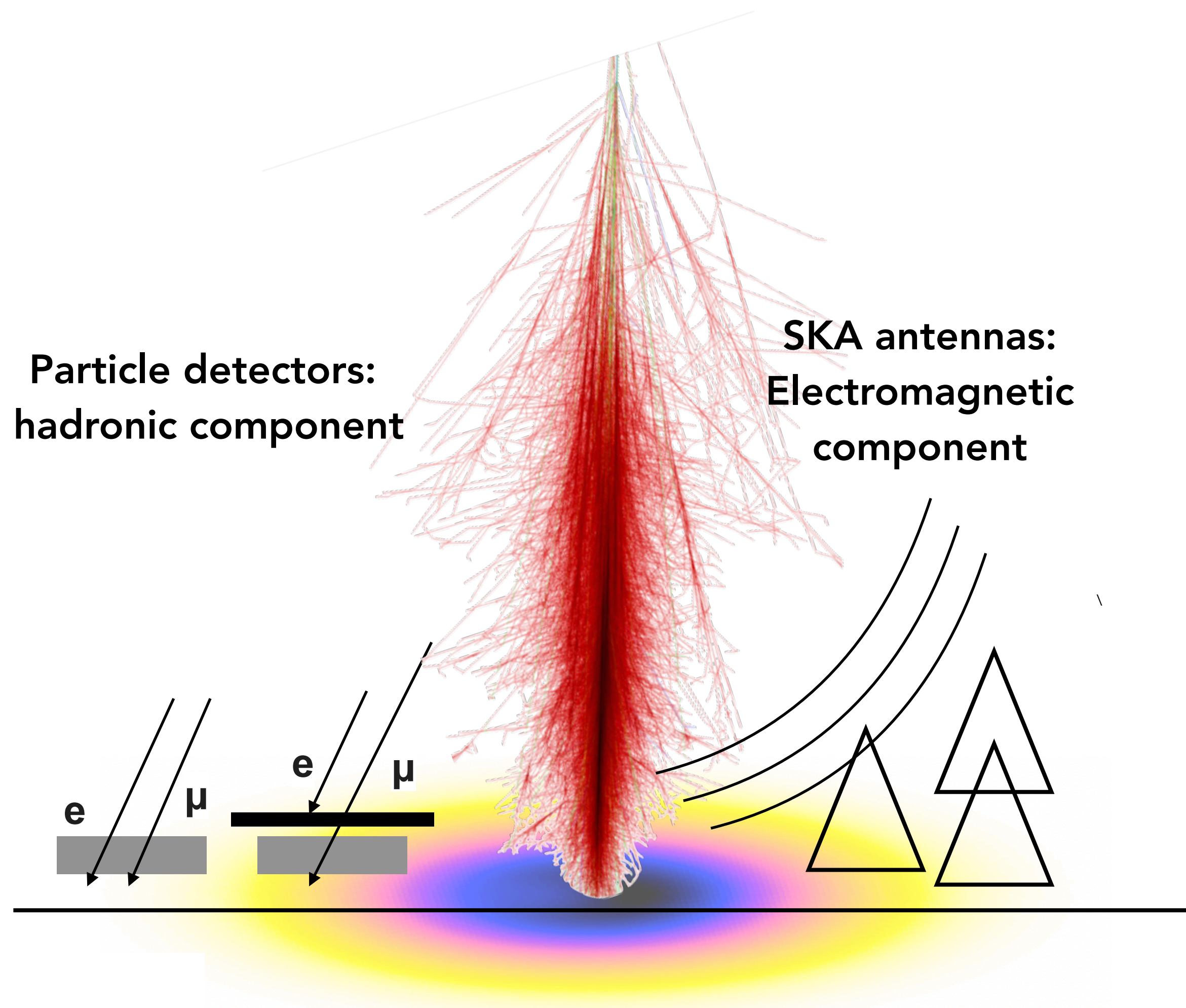


**PMT replaced with SiPM**





# Particle detector array



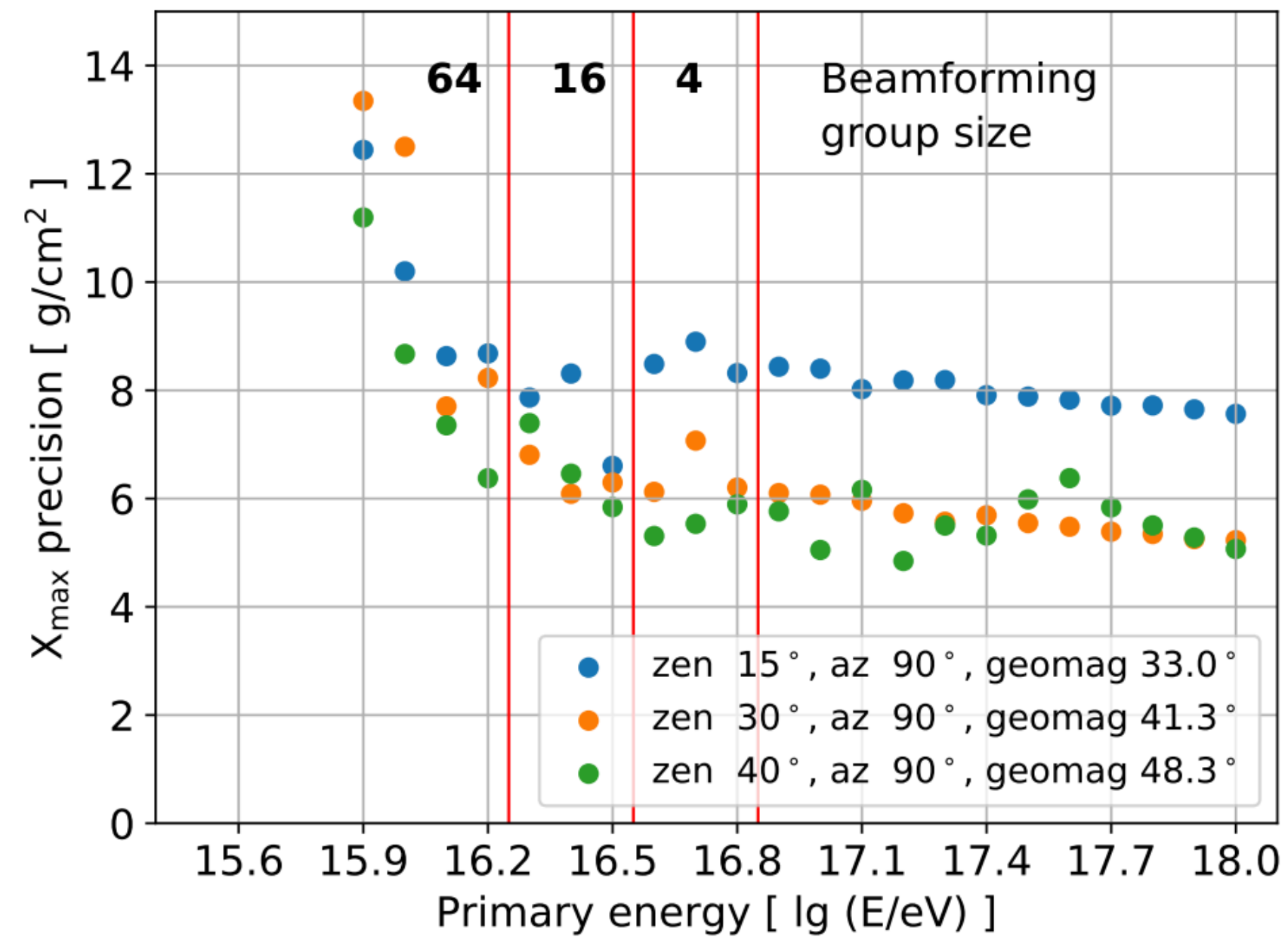
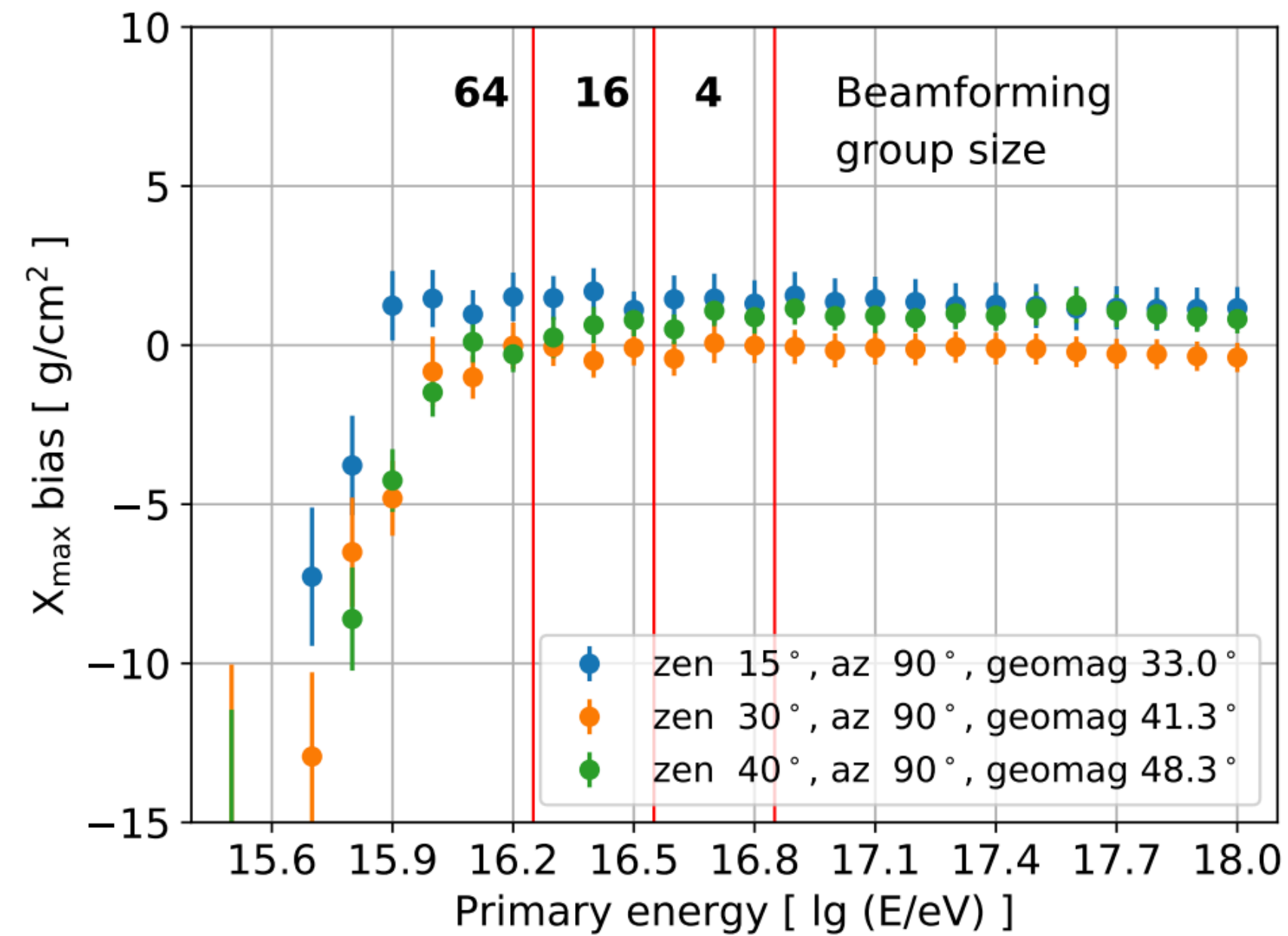
- Additional funding to develop muon separation capabilities
- Radio data will constrain the geometry of the shower, muon information allows for better understanding of shower development, primary mass, hadronic model testing



European Research Council  
Established by the European Commission



# Standard “LOFAR-style” reconstruction

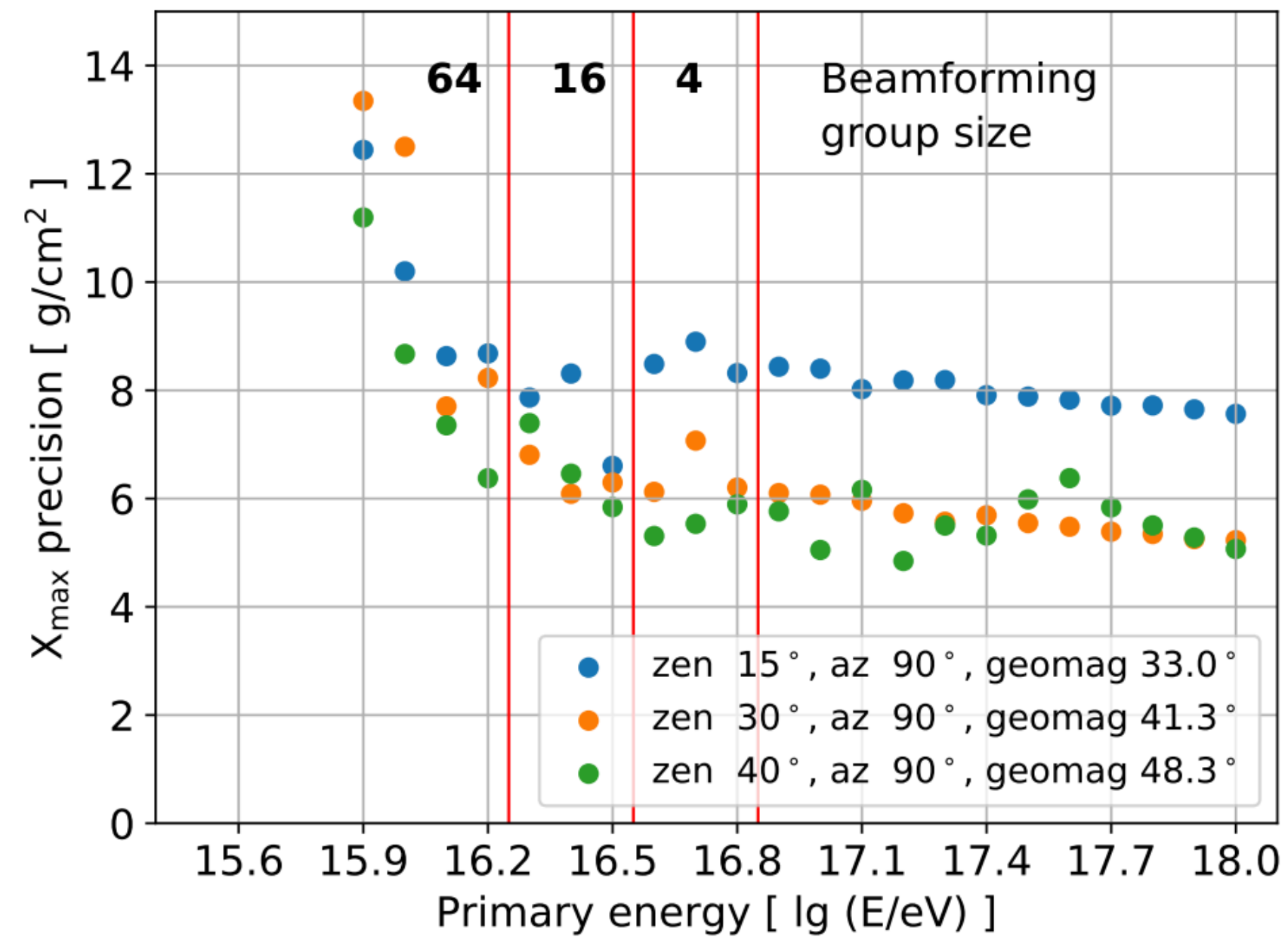
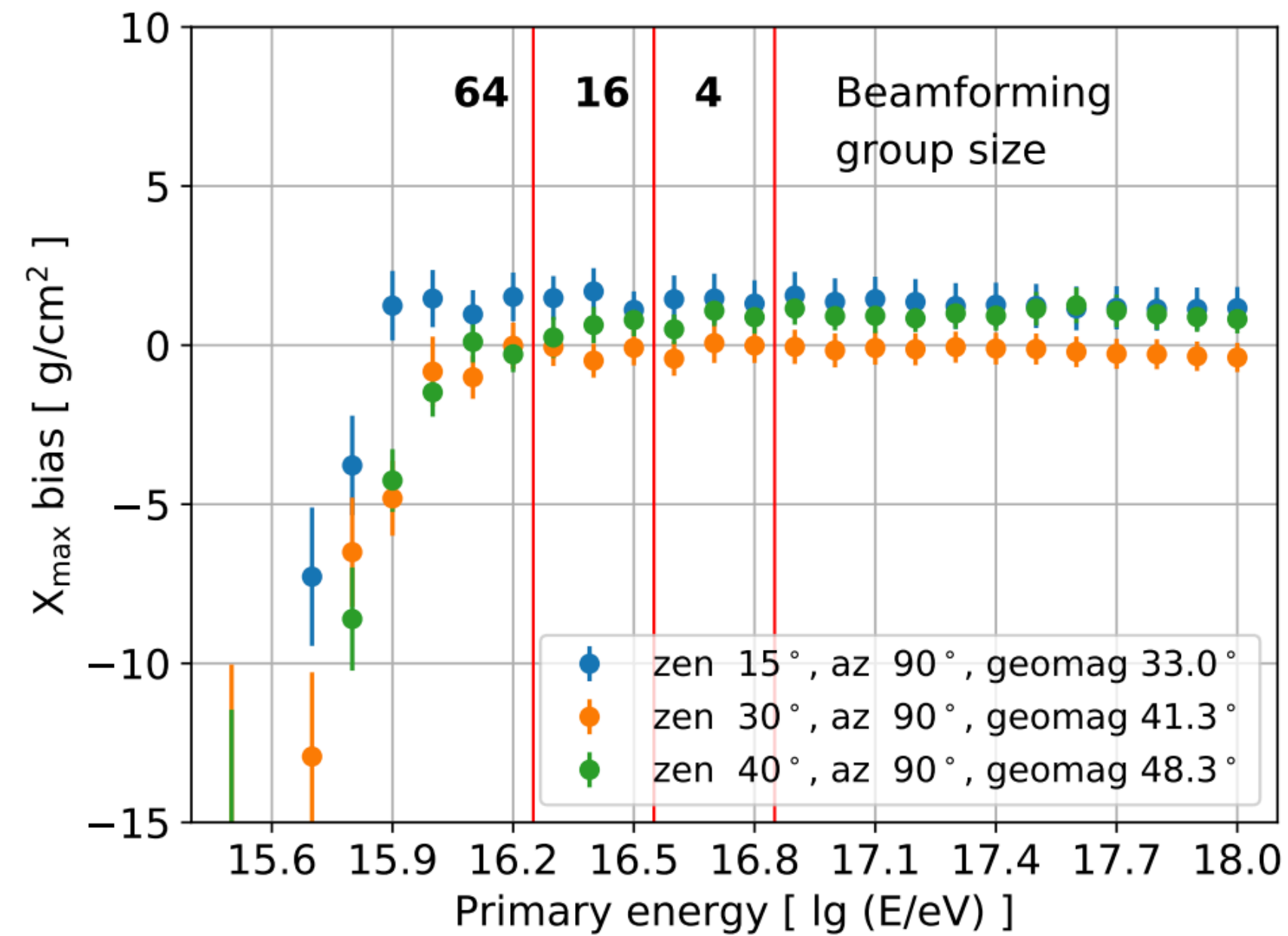


*A. Corstanje et al,  
Phys. Rev. D 2025*

- LOFAR / AERA - style reconstruction based on CORSIKA / CoREAS + realistic Galactic & instrumental noise
- Precision: 6-8 g/cm<sup>2</sup> , bias < 2 g/cm<sup>2</sup>



# Standard “LOFAR-style” reconstruction



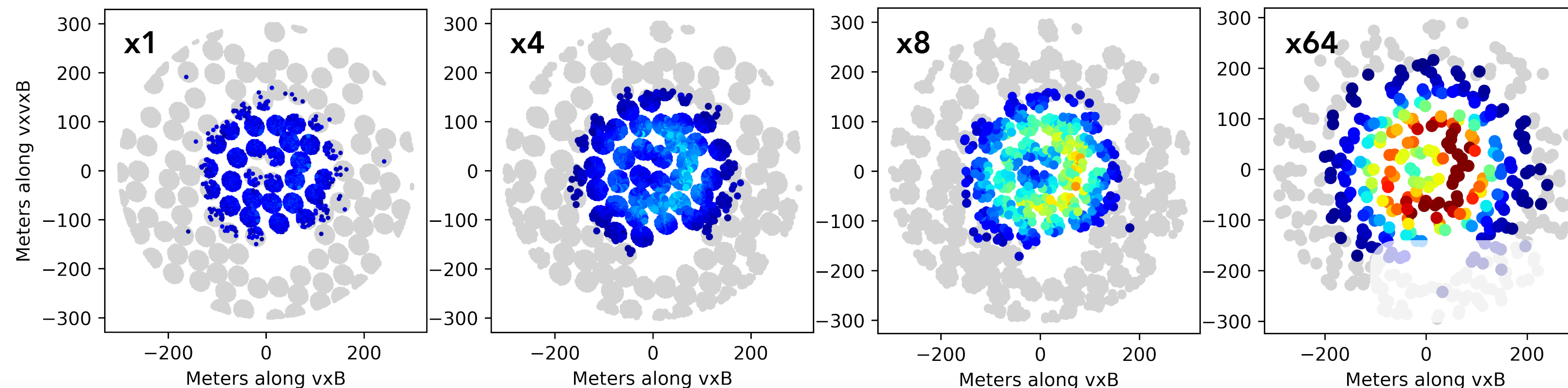
## Low energies reconstruction

- beam forming
- Interferometry

Talk from Subhadip Saha  
Thursday 9:45

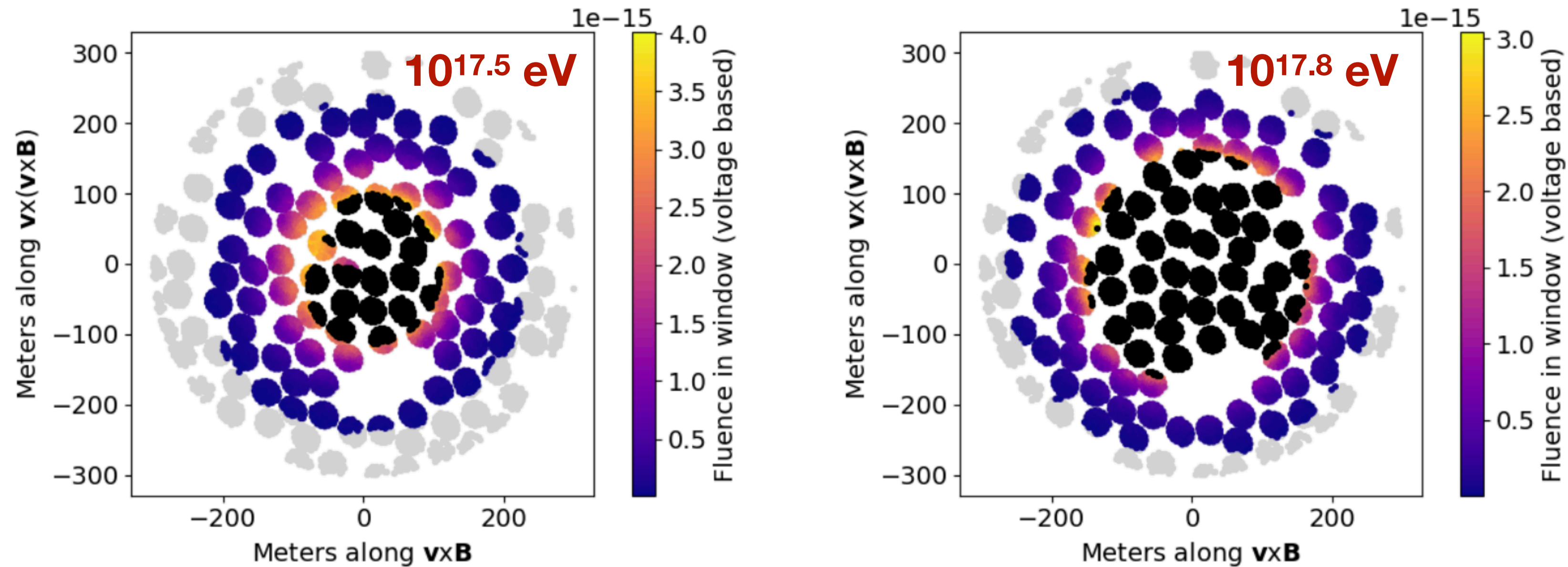
- matched filtering

Talk from Arthur Corstanje  
Thursday 11:30



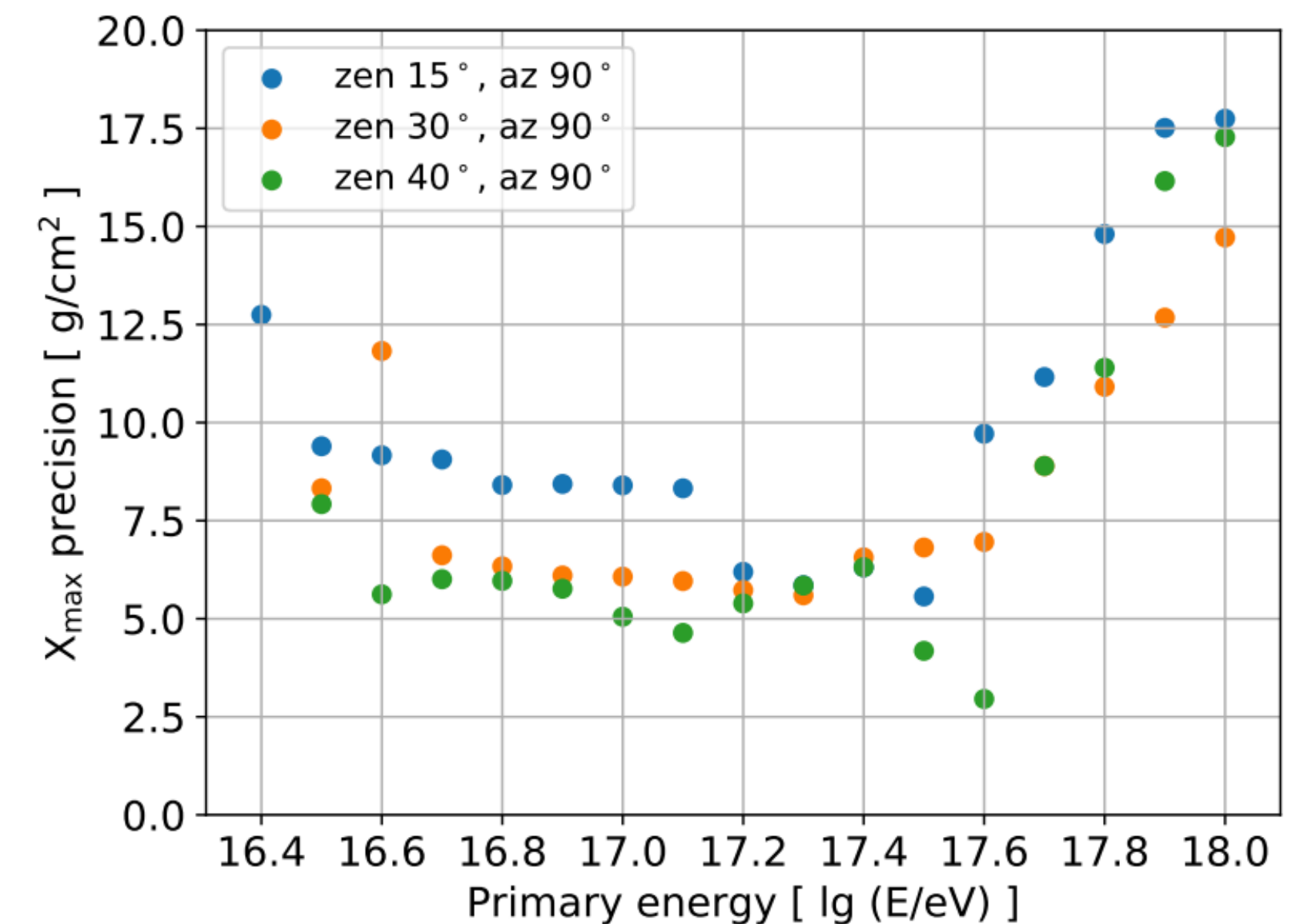


# Standard “LOFAR-style” reconstruction



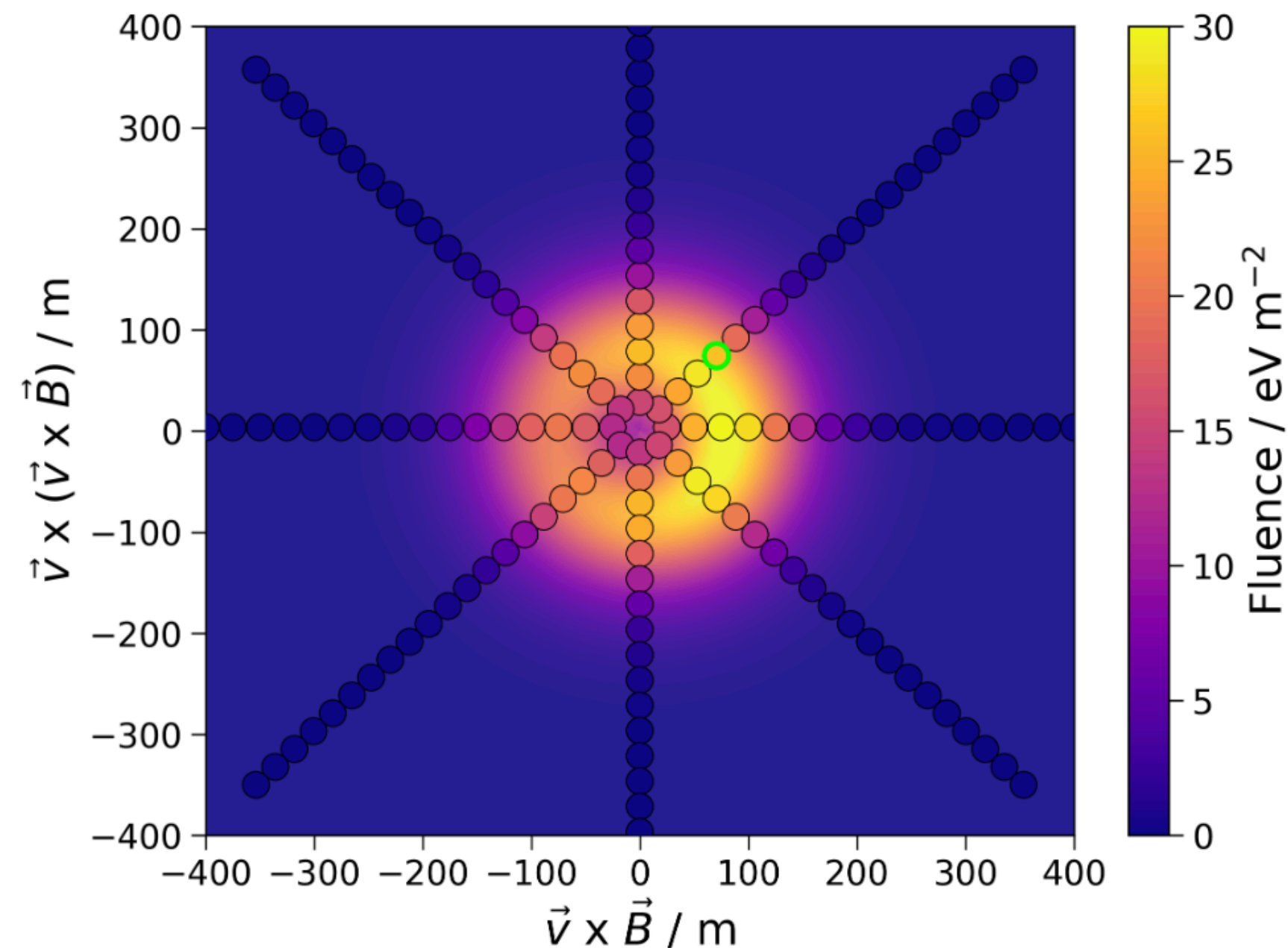
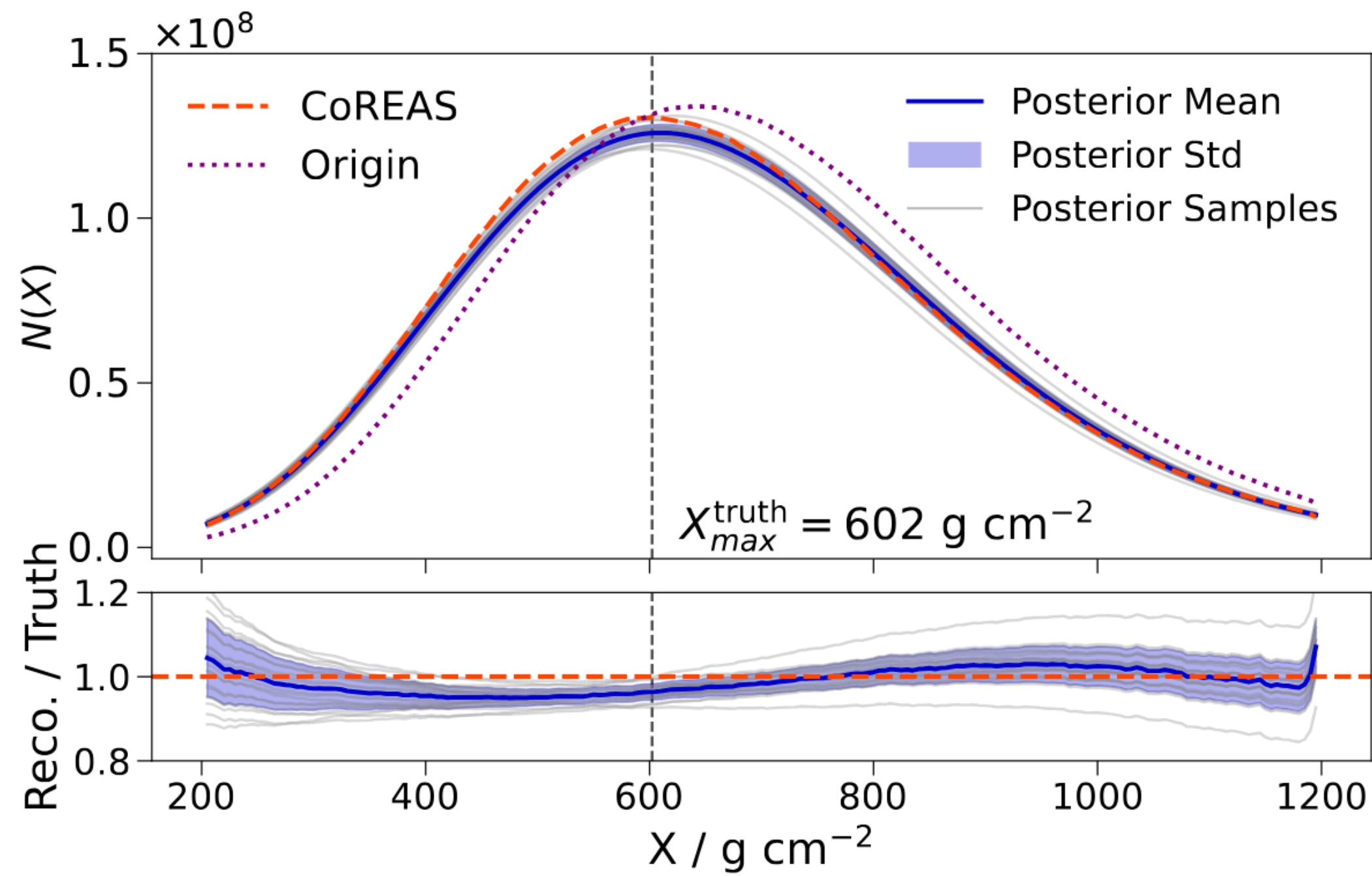
## Dynamic range limitations?

- SKA may set the noise floor in a higher than optimal for CRs
- Example in the case that signals above  $32 \sigma$  saturate
- Strategies to mitigate this (one polarization, recover clipped signals, etc)



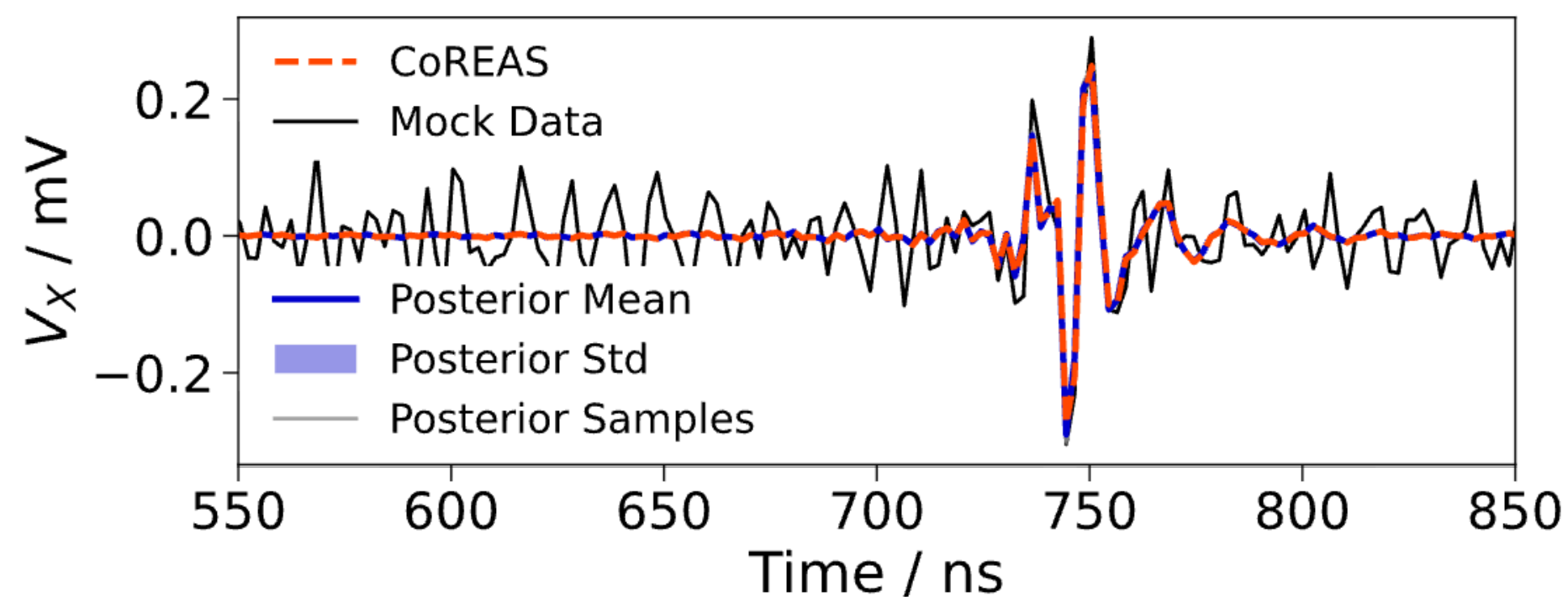
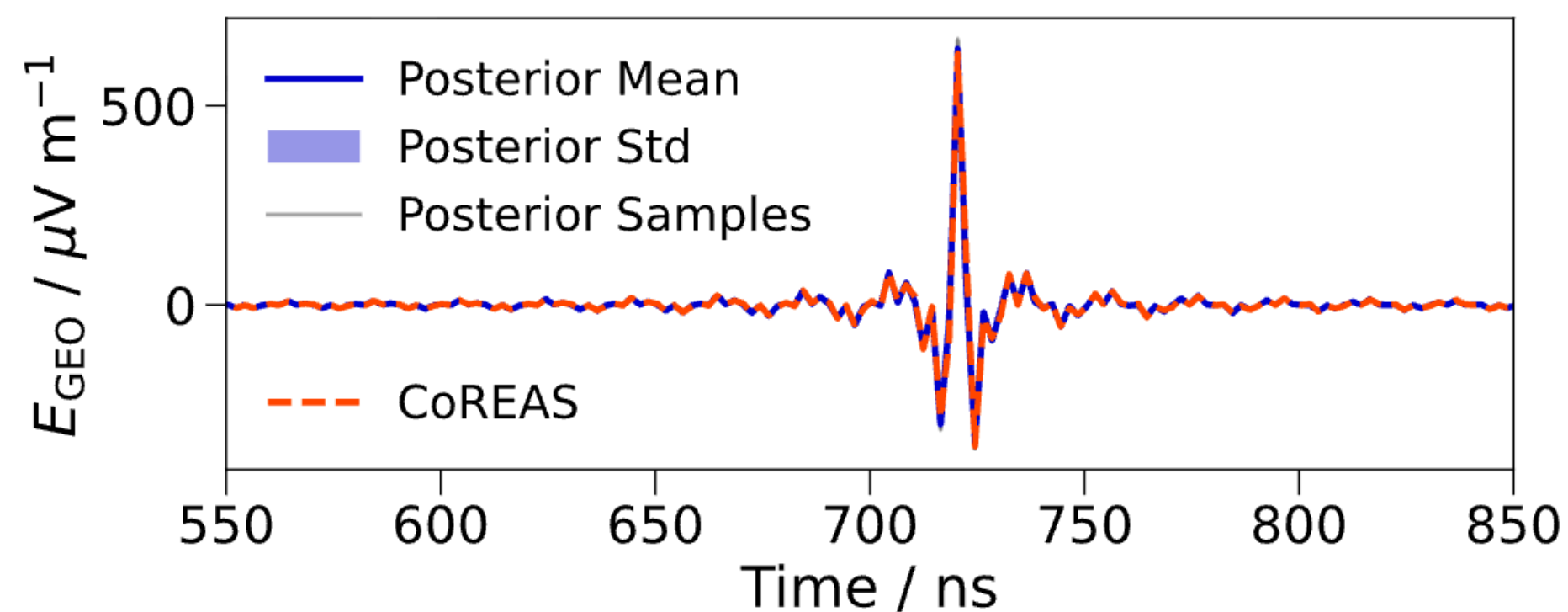


# Shower Profile Reconstruction with IFT



Using SMIET, Template Synthesis (Desmet et al., 2025) as a fast, and fully differentiable model for air shower development

**Talk from Keito Watanabe  
Thursday 10:15**

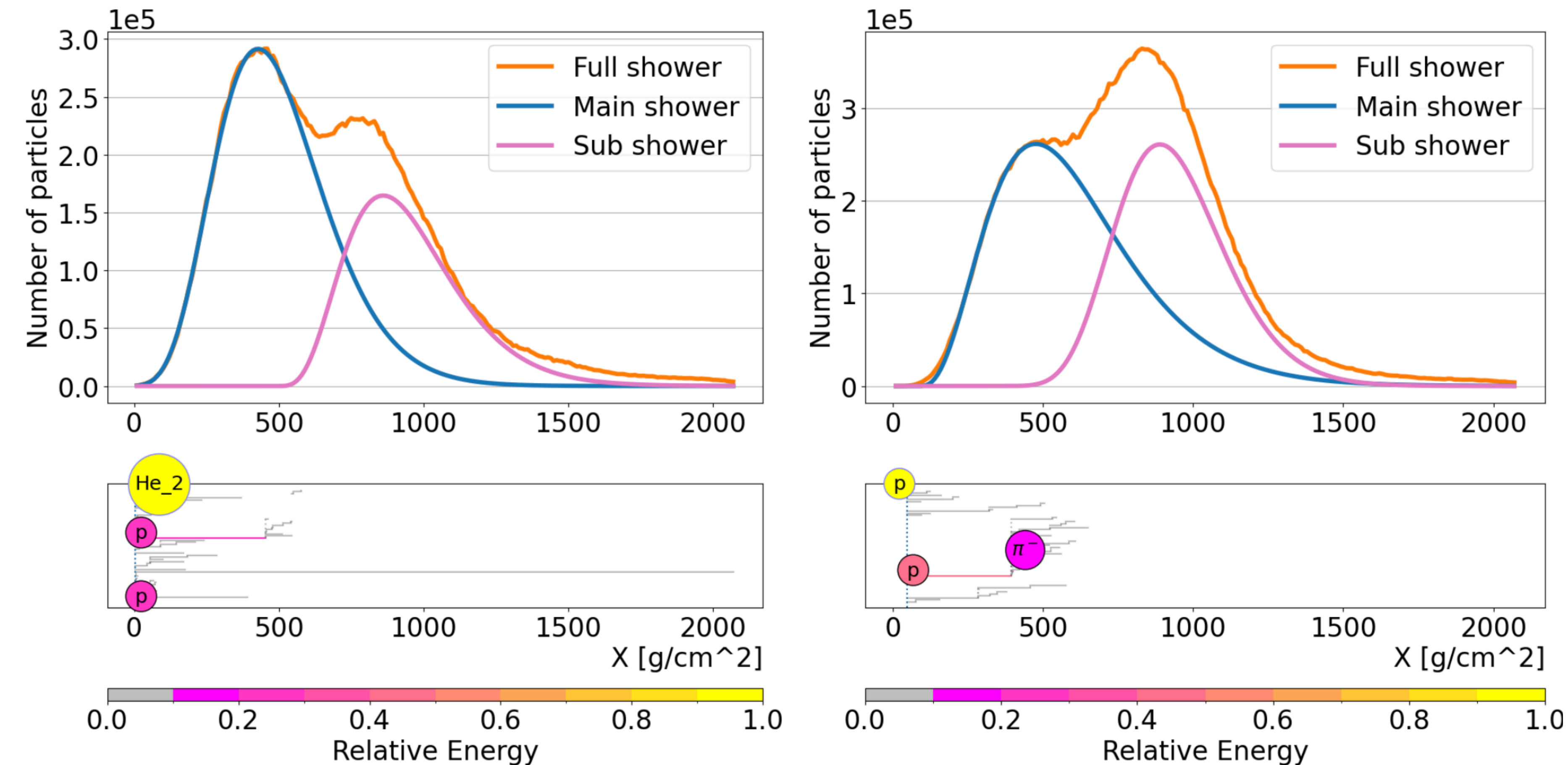


*K. Watanabe. ICRC 2025.*

*K. Watanabe, K. Terveer, SKA Science Book 2026.*



# Anomalous showers



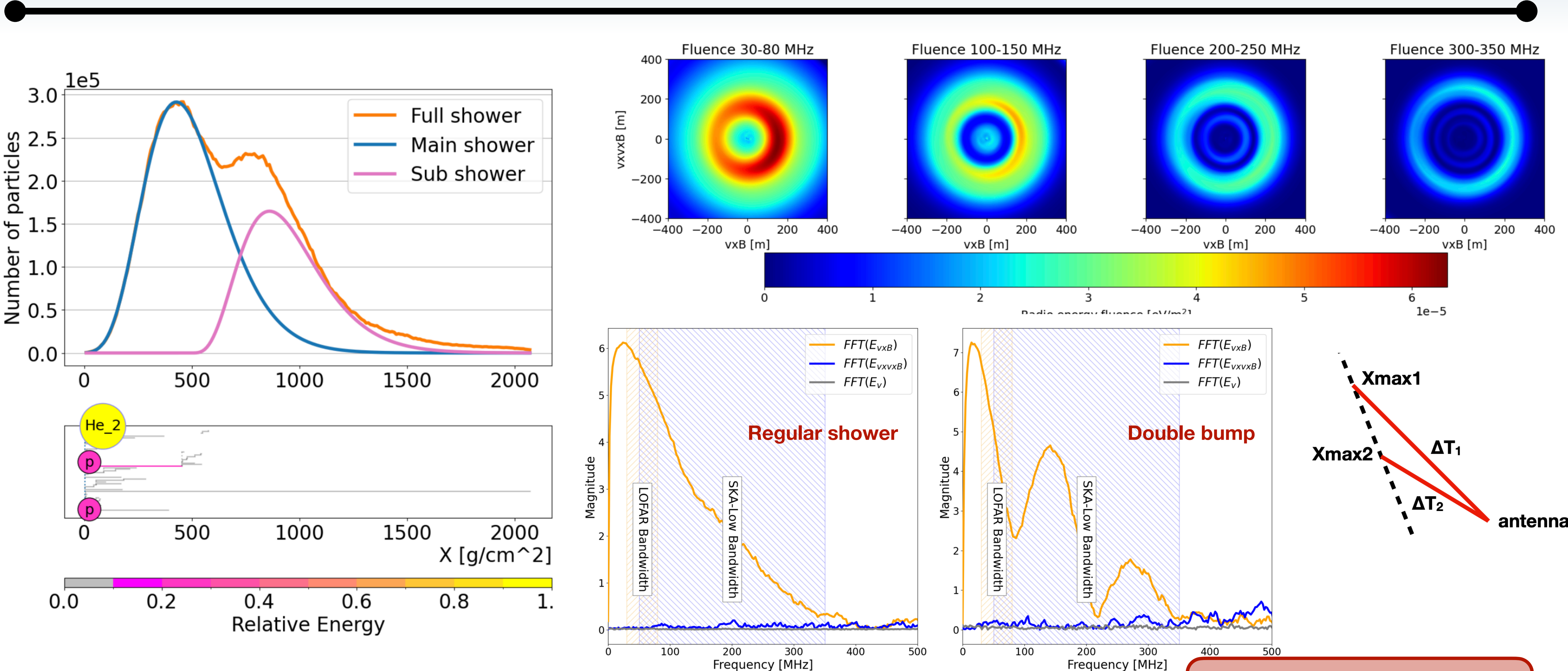
- Double bumps occur ~ 2% of the time for light primaries at 10 PeV, decreasing with energy
- Higher rate for lower masses
- Helium: second bump often 25% of energy
- Proton: second bump can be stronger than first

**Talk from Stijn Buitink  
Wednesday 9:30**

*S. Buitink, V. De Henau et al.  
SKA Science Book 2026*



# Anomalous showers

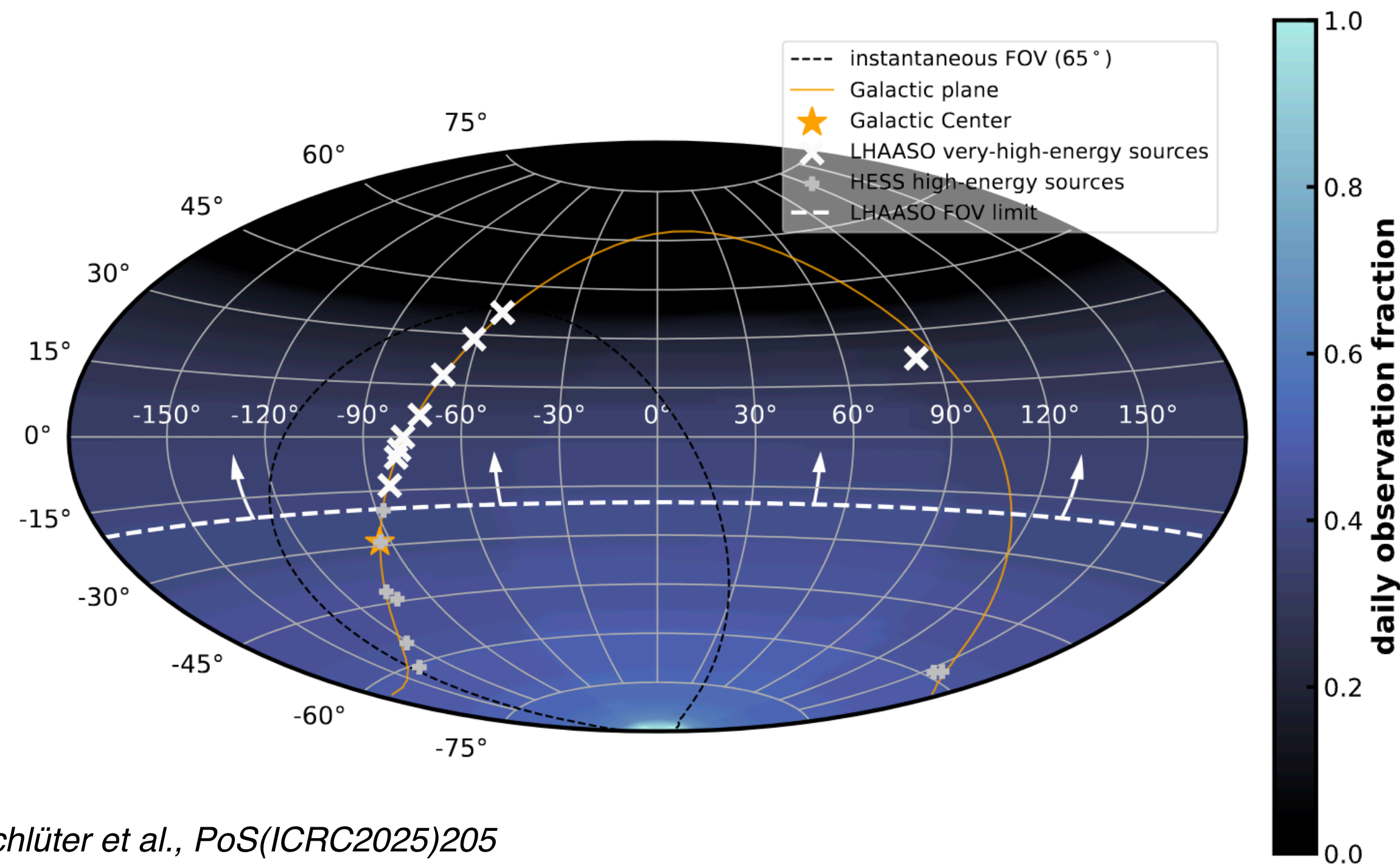


*S. Buitink, V. De Henau et al.*  
*SKA Science Book 2026*

**Talk from Vital De Henau**  
**Thursday 11:45**

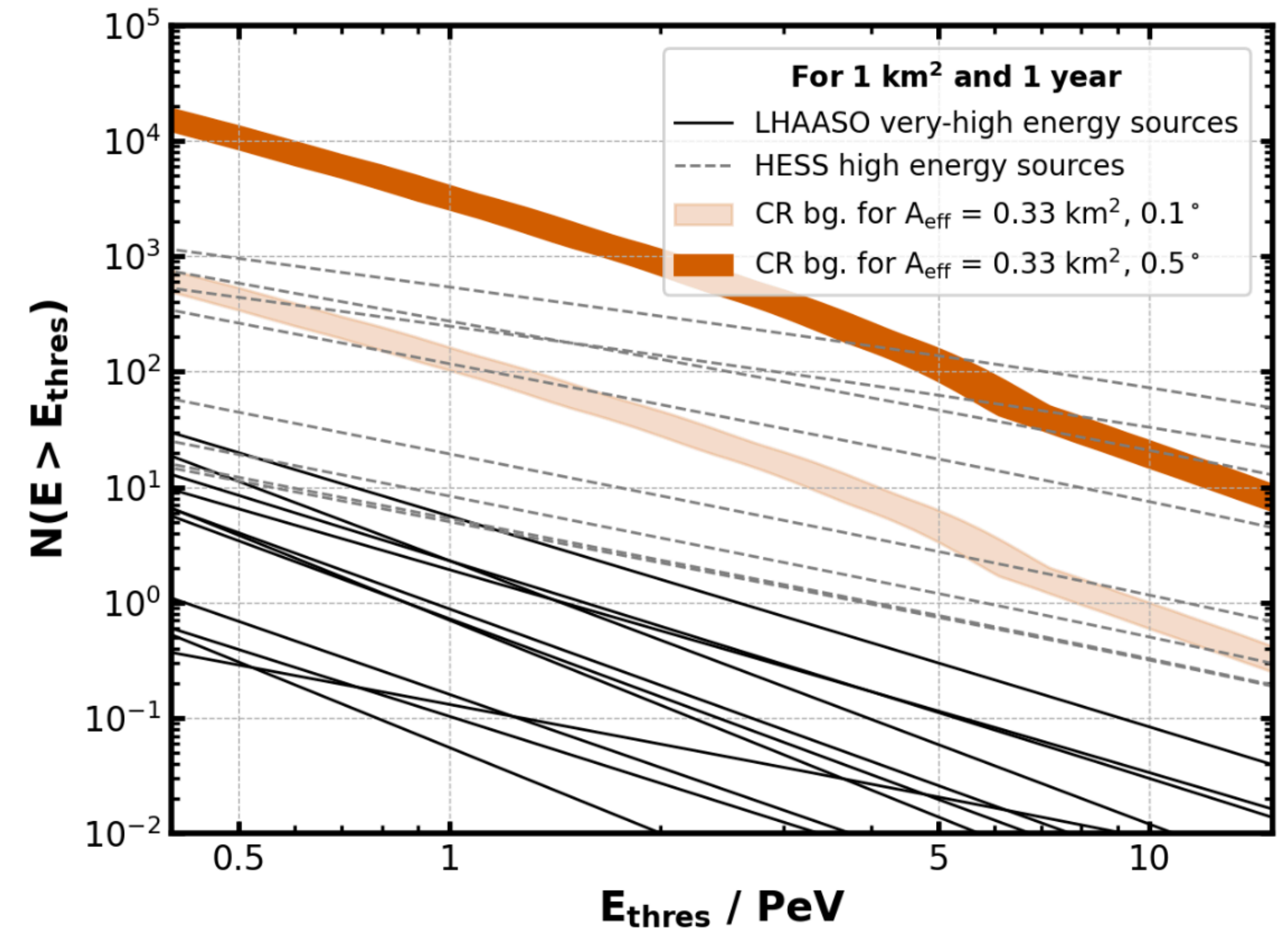


# PeV showers & gamma rays



*F. Schlüter et al., PoS(ICRC2025)205*

*A. Nelles, P. Laub, H. He, F. Schlüter, SKA Science Book 2026*

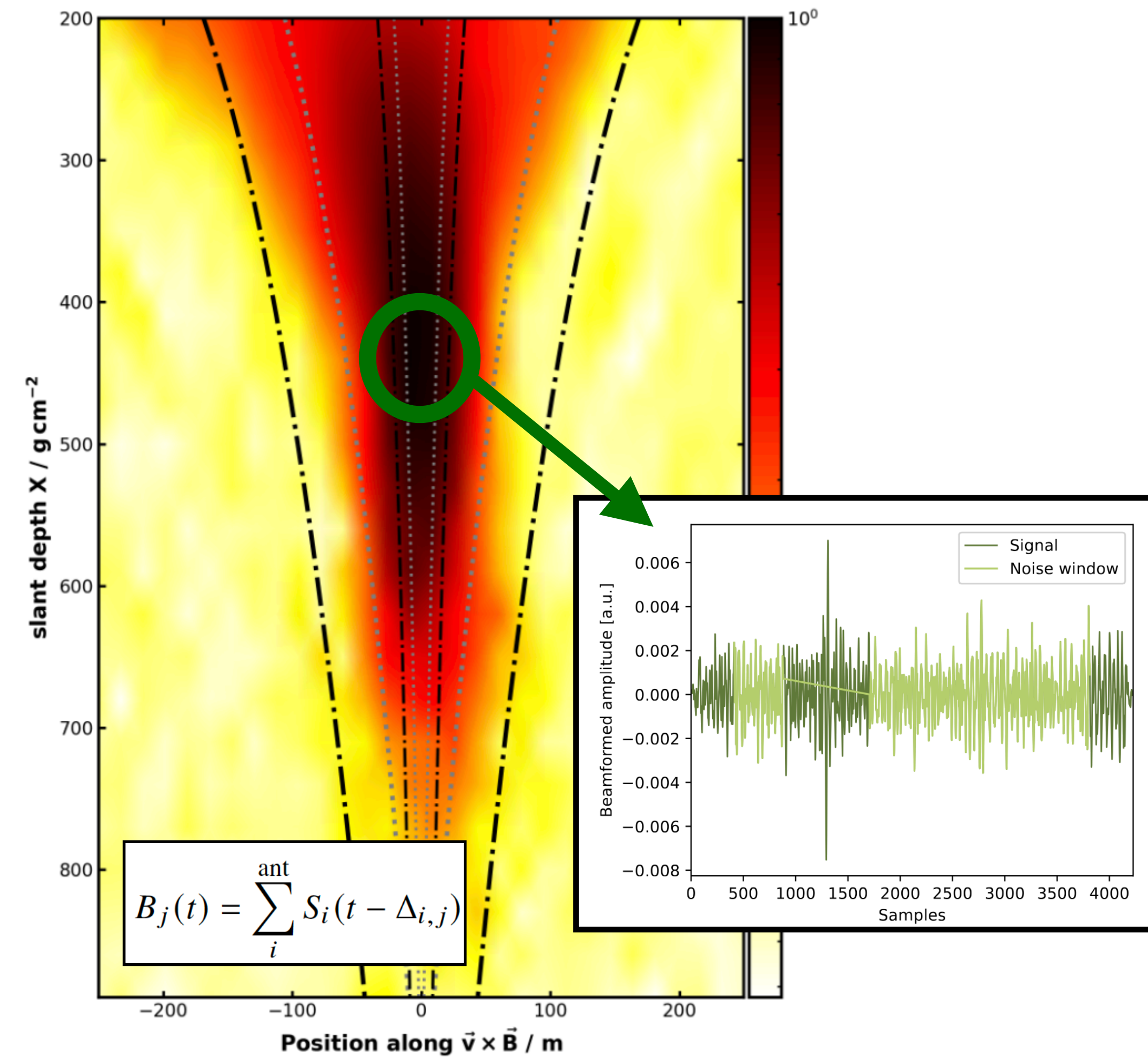
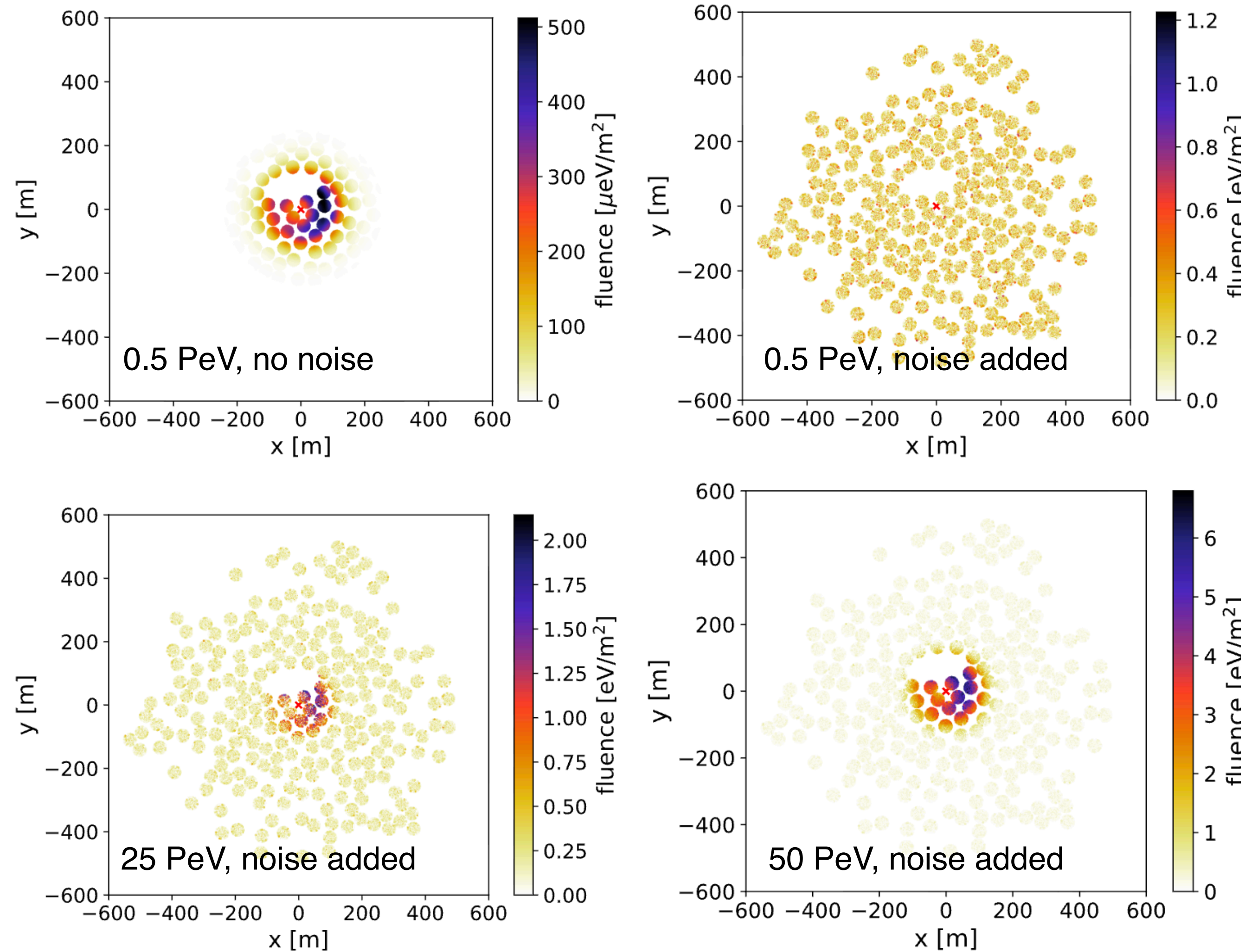


- Known LHAASO and HESS sources + Galactic Center in SKA sky
- Possible strategy: form beams on candidate sources (0.1 - 0.5 degree resolution)
- Main challenge: triggering and photon/hadron separation

See talk from Philipp Laub  
up next



# PeV showers & gamma rays



A. Nelles, P. Laub, H. He, F. Schlüter, SKA Science Book 2026



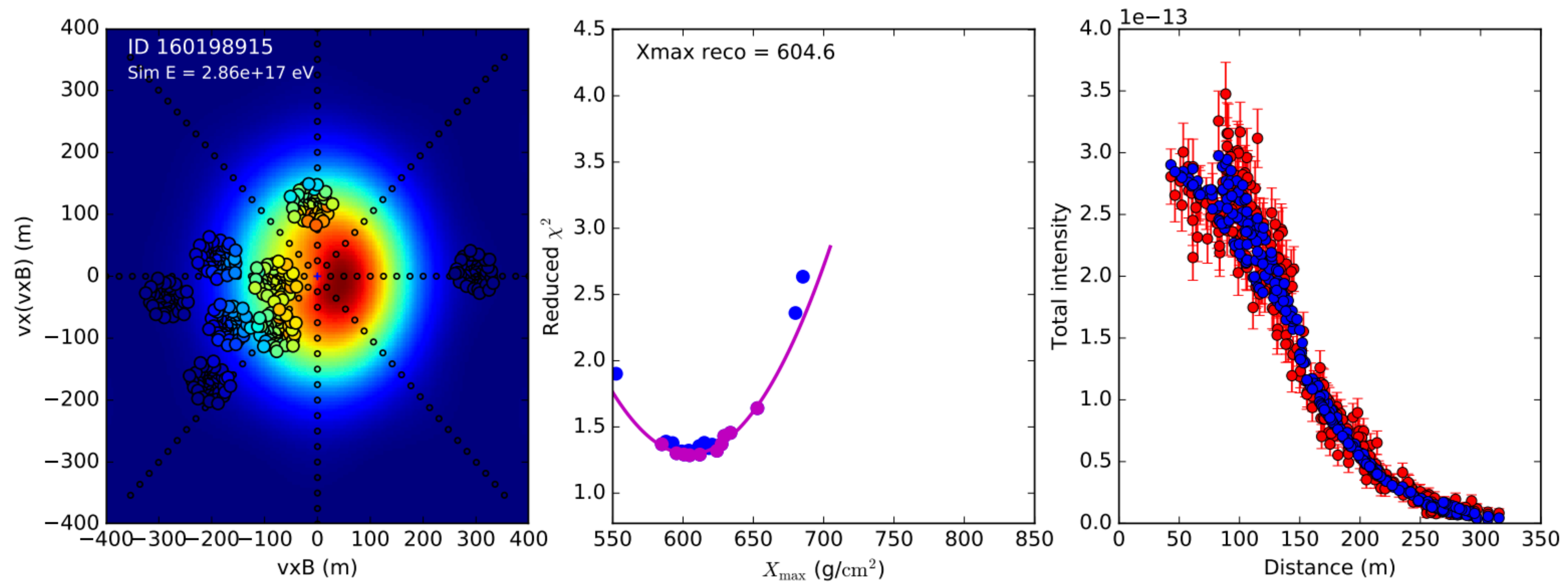
# Contributions from the SKA group

- Prospects of detecting PeV gamma rays with SKA-Low by  
*Philipp Laub, Tuesday 16:15*
- Detection of cosmic-rays at over 100 MHz and multi-GHz frequencies with radio telescopes  
*Sjoerd Bouma, Tuesday 16:30*
- Detecting inclined air showers with small-scale radio antenna arrays  
*Chao Zhang, Tuesday 17:15*
- The case for studying anomalous showers with the SKA  
*Stijn Buitink, Wednesday 9:30*
- Radio Interferometric Reconstruction of Air Shower Parameters with the SKA  
*Subhadip Saha Thursday 9:15*
- A bayesian air-shower reconstruction method, applied to LOFAR data  
*Karen Terveer, Thursday 9:45*
- Beyond  $X_{\max}$ : Reconstructing Air Shower Profiles with IFT with SKA-Low  
*Keito Watanabe, Thursday 10:15*
- A simulation template-based air shower reconstruction method  
*Arthur Corstanje, Thursday 11:30*
- Reconstruction of anomalous air showers with SKA-Low  
*Vital De Henau, Thursday 11:45*



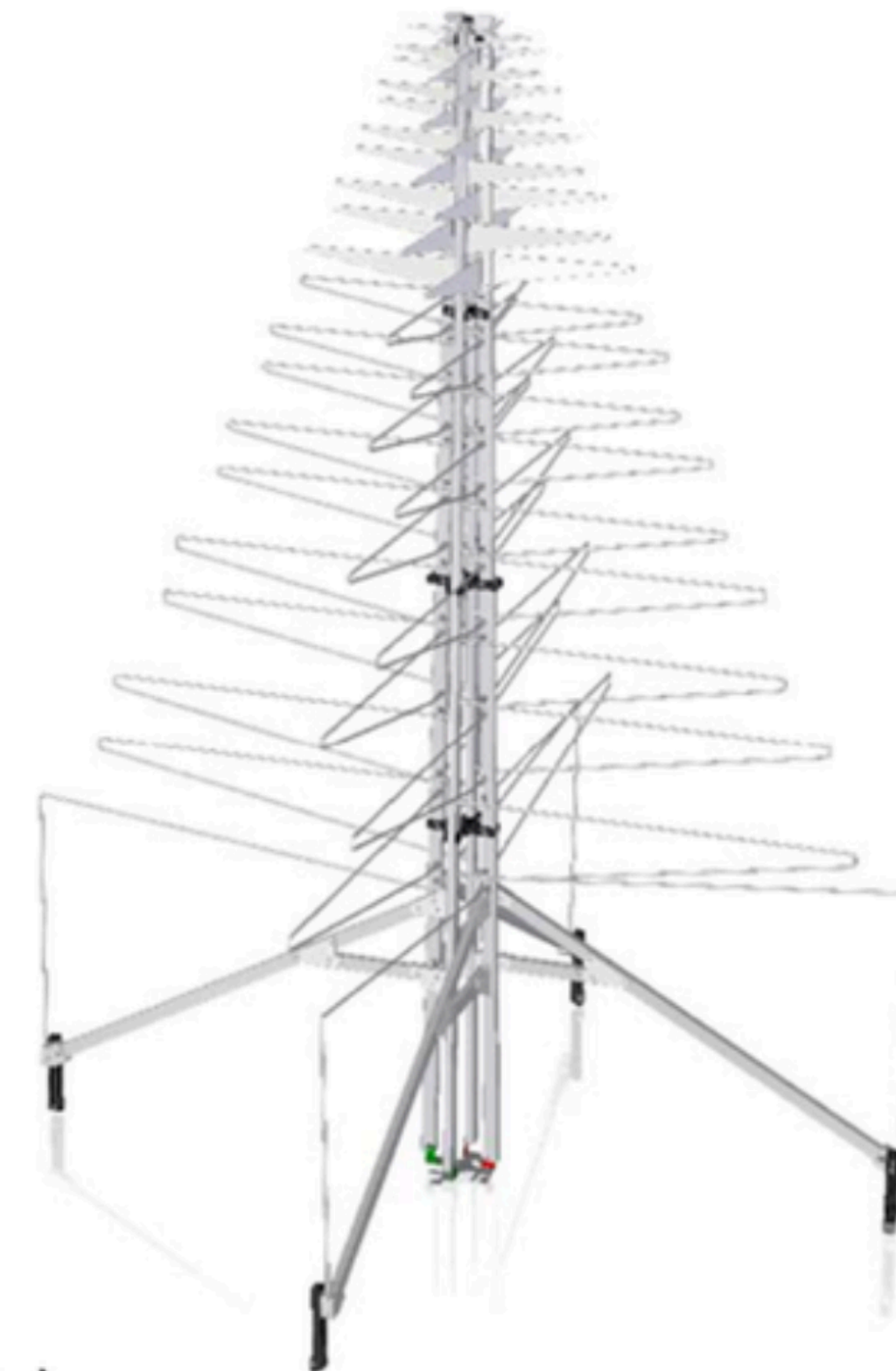
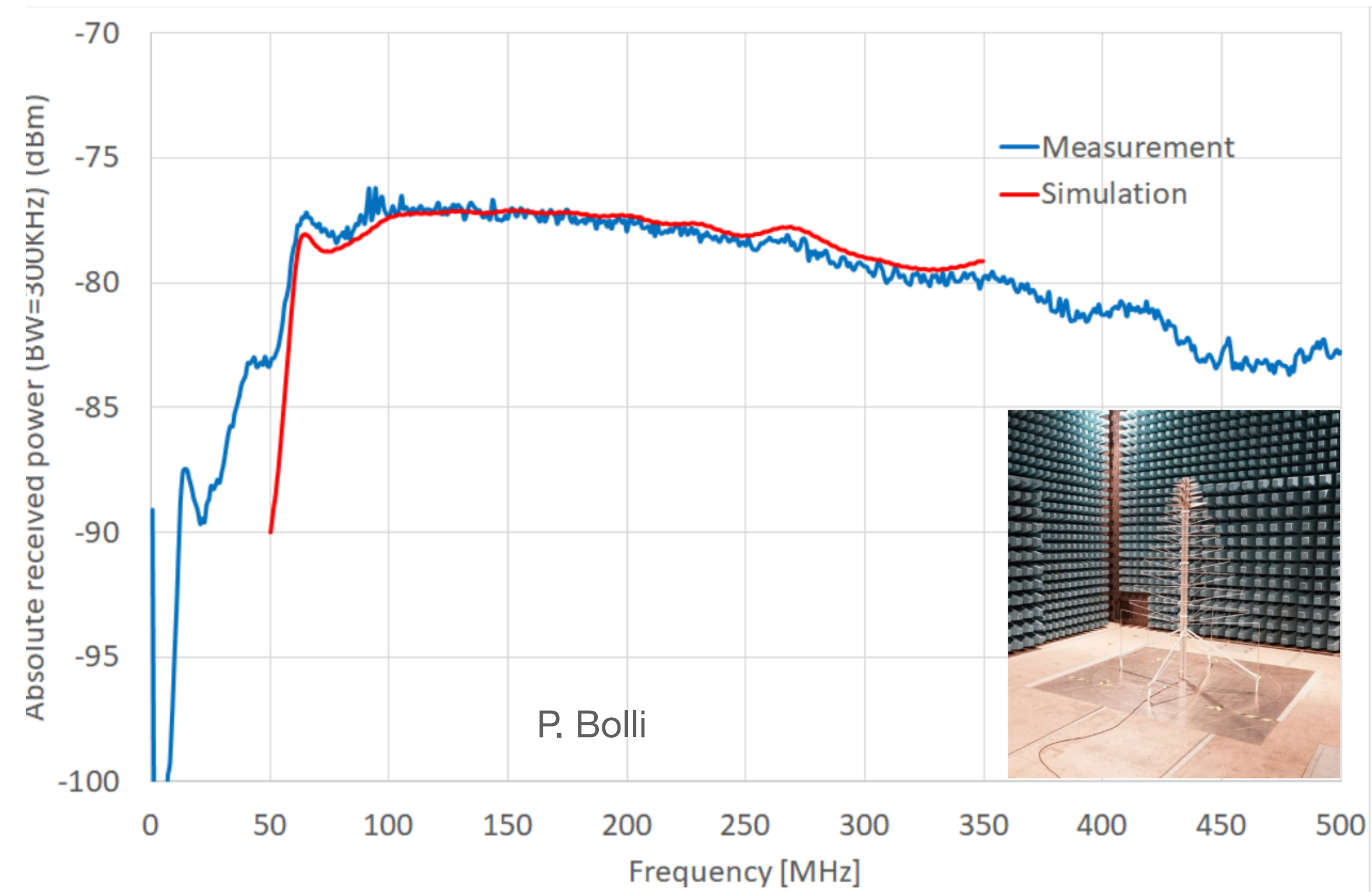


# Back up





## SKALA RX power in anechoic chamber





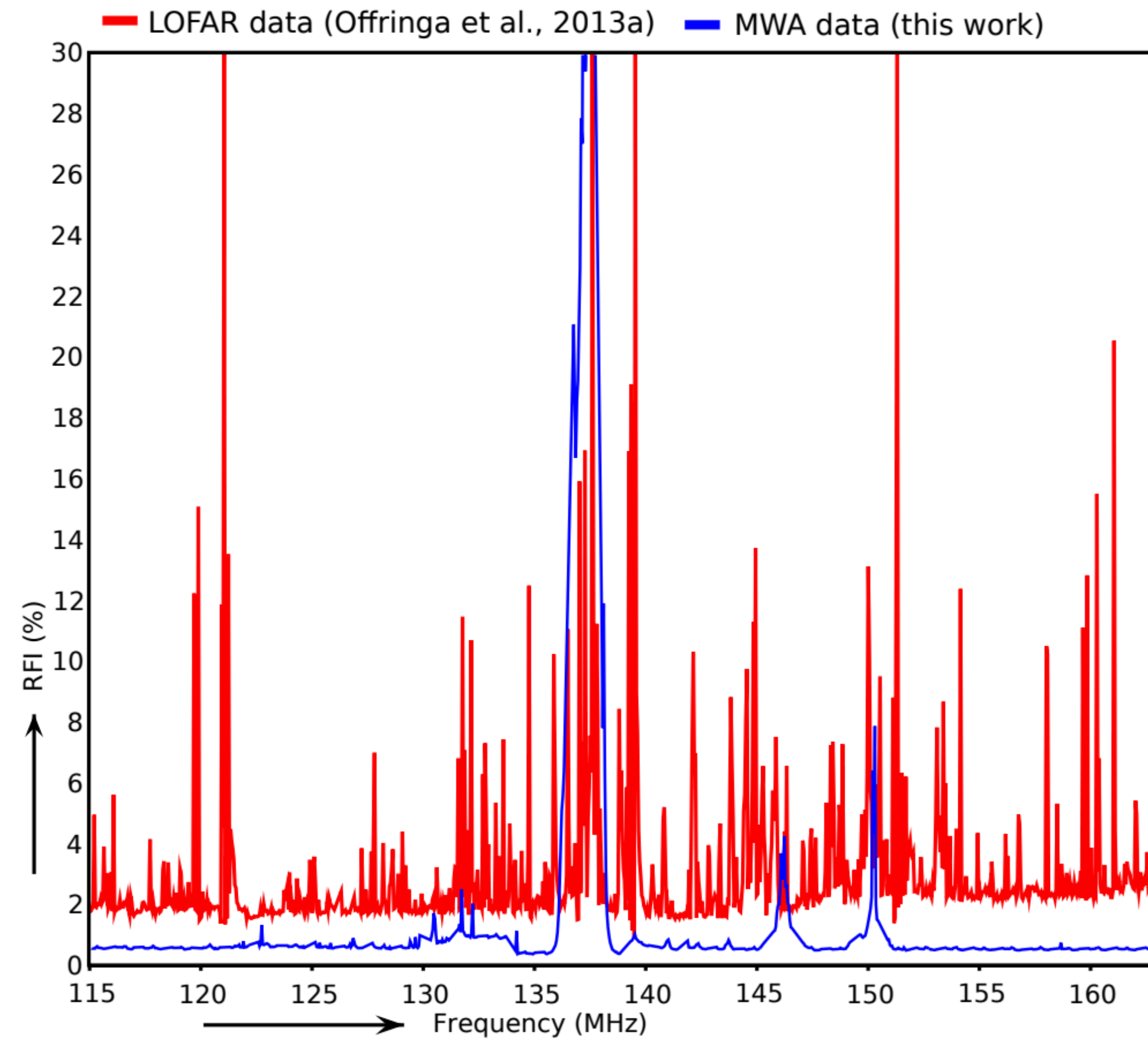
# Back up

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# Back up



A. R. Offringa et al., 2015