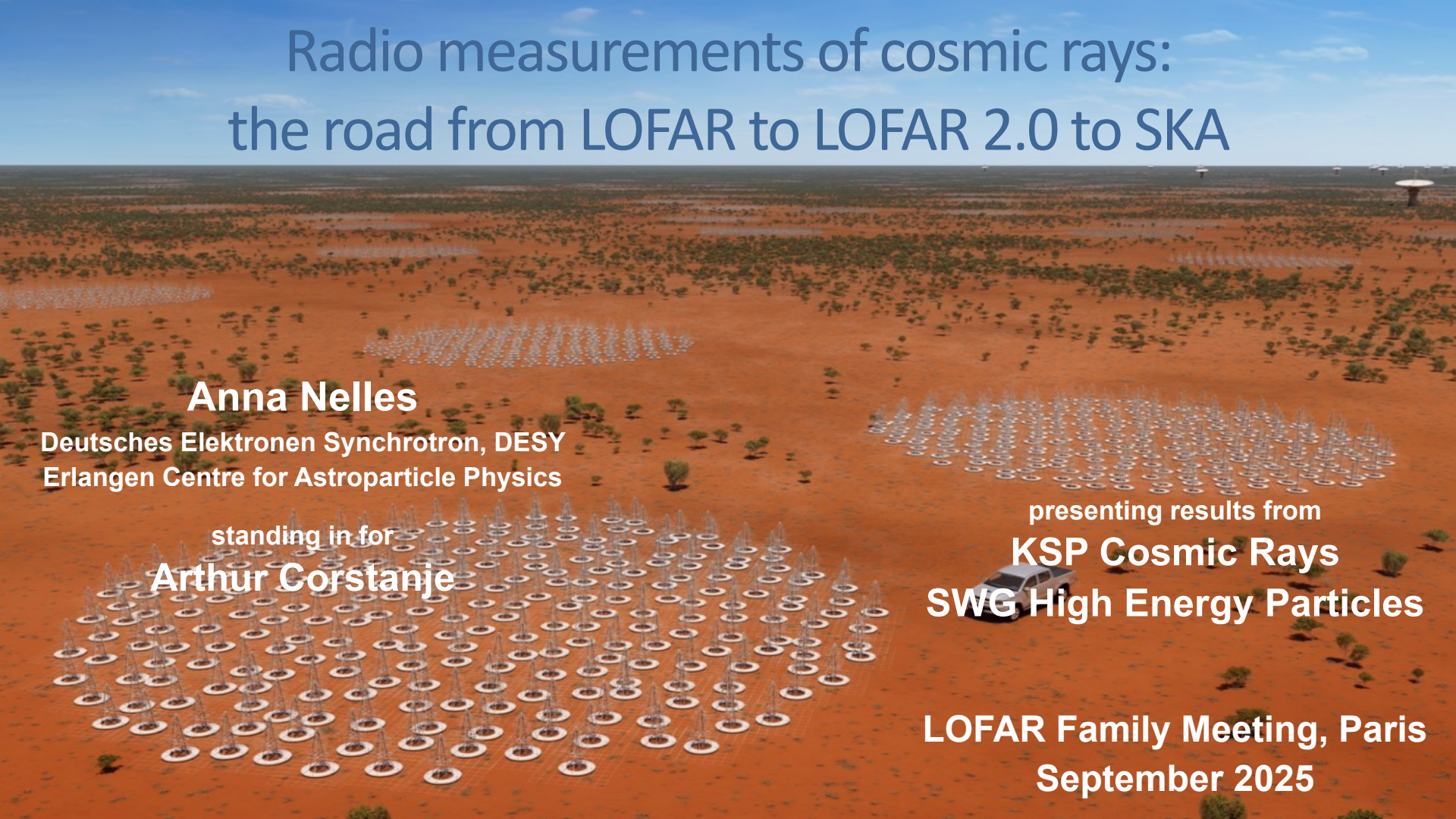
Radio measurements of cosmic rays: the road from LOFAR to LOFAR 2.0 to SKA



Anna Nelles
Deutsches Elektronen Synchrotron, DESY
Erlangen Centre for Astroparticle Physics

standing in for
Arthur Corstanje

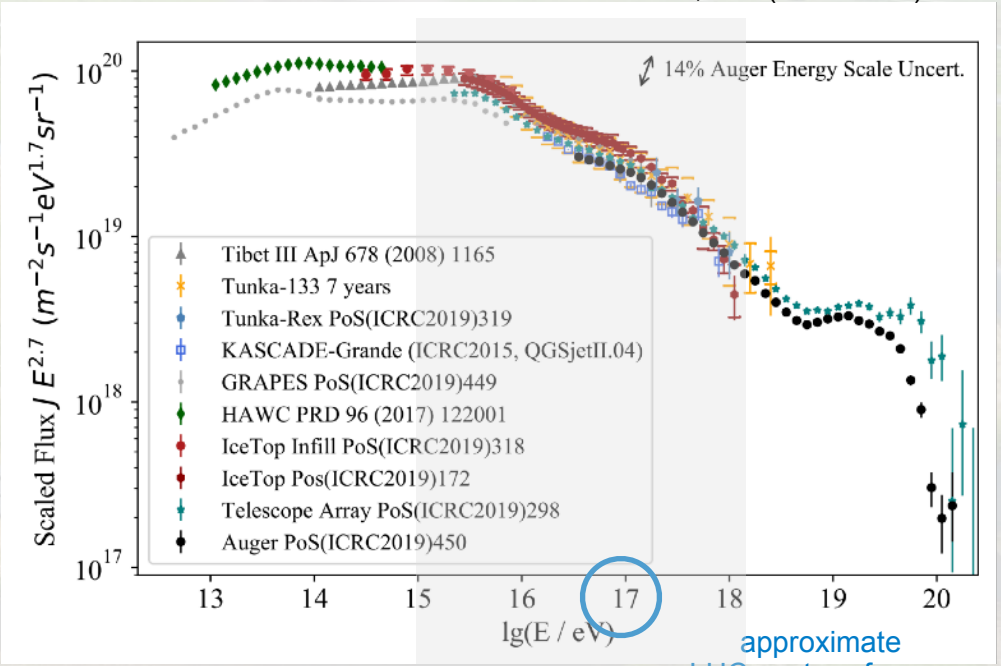
presenting results from
KSP Cosmic Rays
SWG High Energy Particles

LOFAR Family Meeting, Paris
September 2025

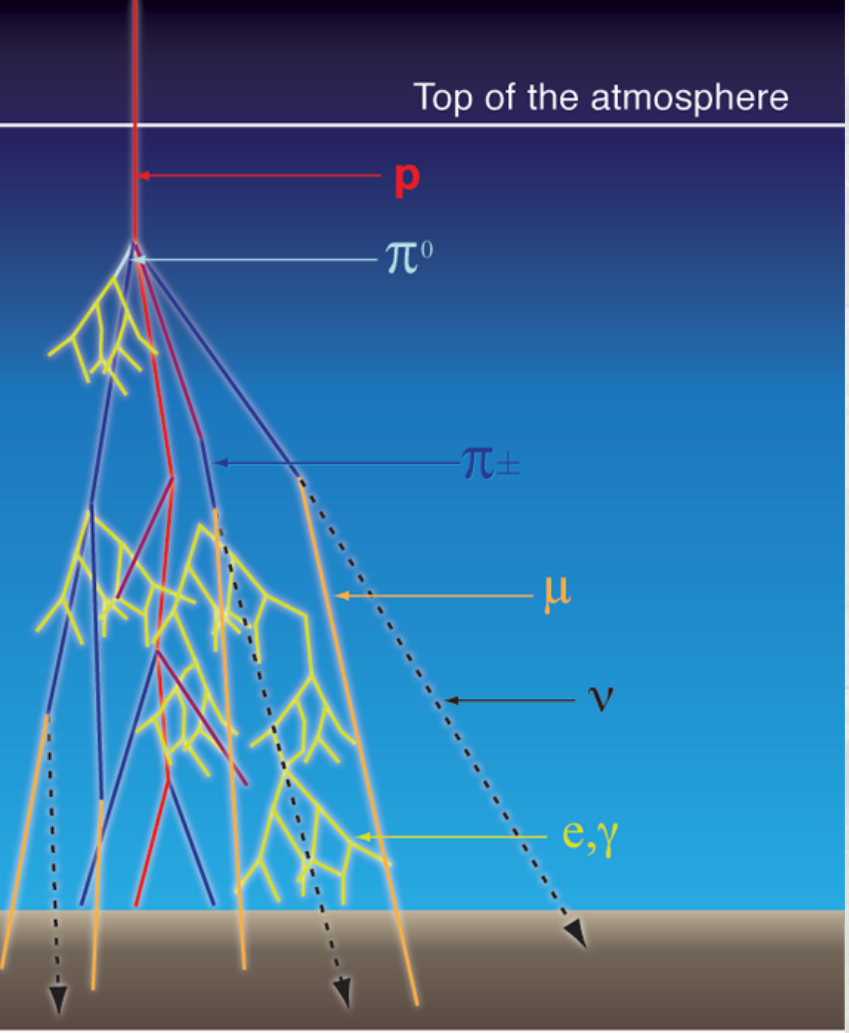
Open questions in cosmic ray physics

- What are the **Galactic sources** and how do they influence their surroundings?
- Are spectral features related to **propagation** or **acceleration**? How does the particle composition change?
- Is there a measurable flux of **gamma-rays** at PeV energies and can it help to pin-point sources?
- Is there new **particle physics** at energies not reachable with accelerators?

F. G. Schröder, PoS(ICRC2019)030

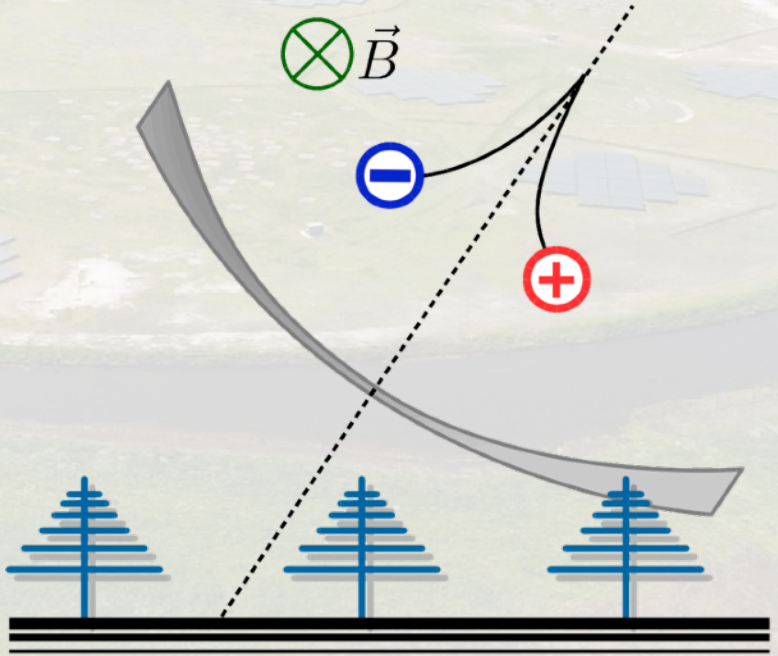


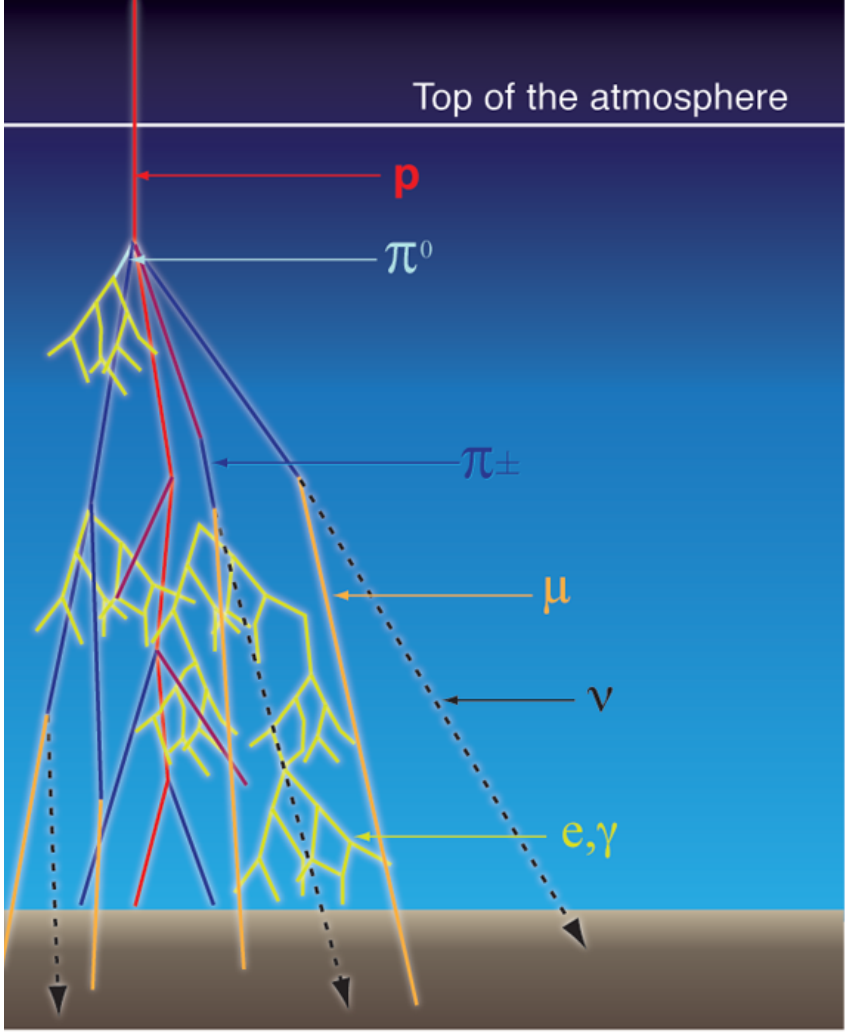
The sources of (extra-)galactic cosmic rays are still unknown



Extensive air showers

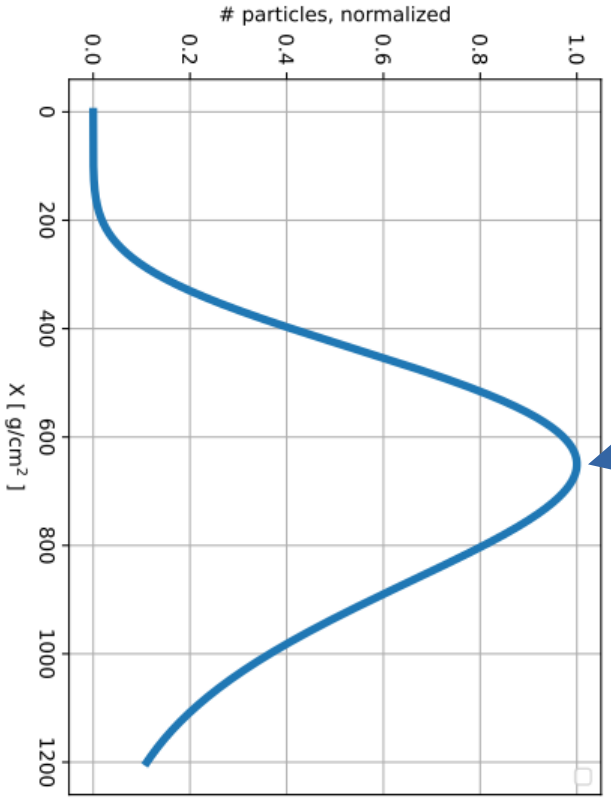
Our tool:
Radio signals from air showers





Extensive air showers

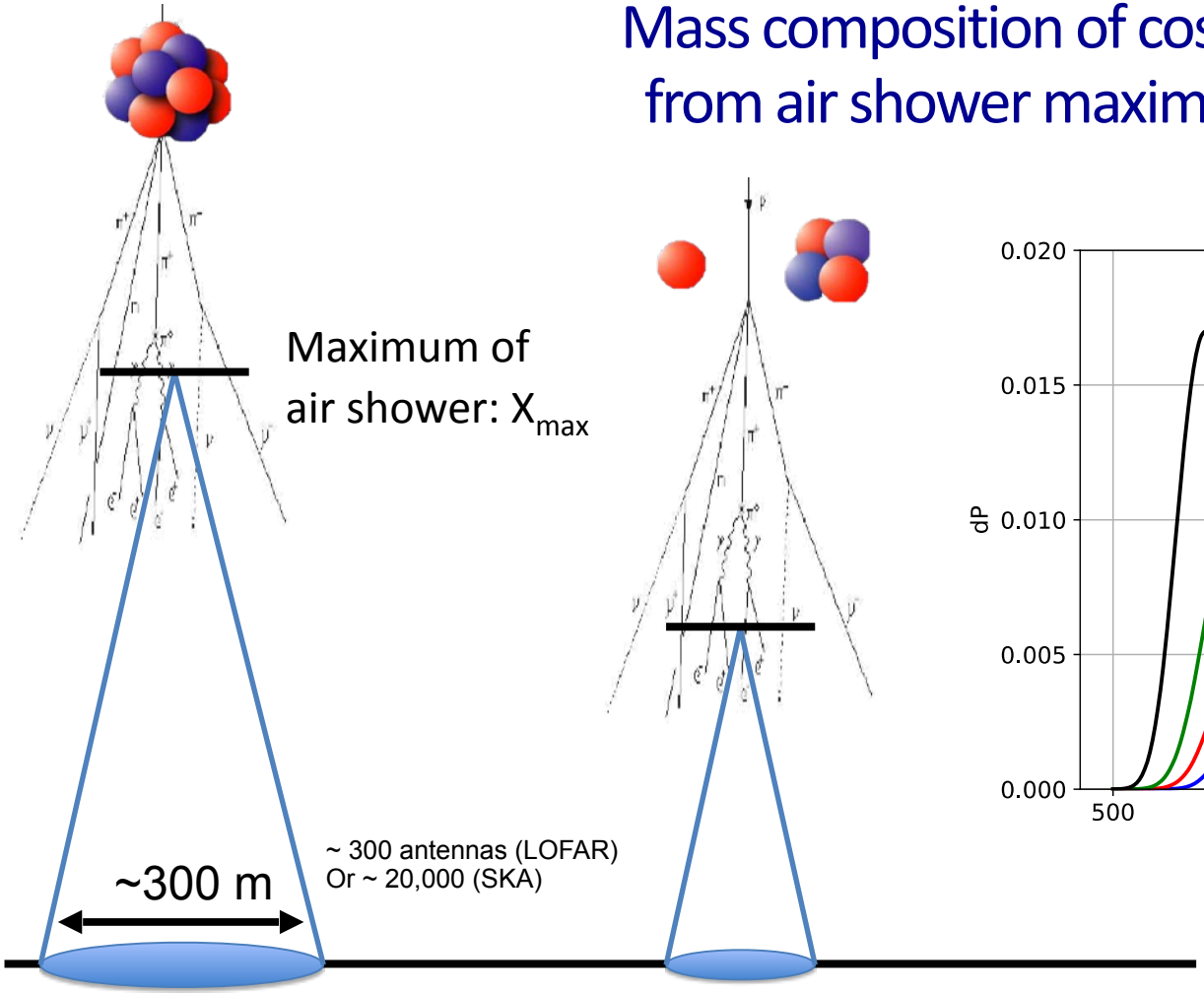
Longitudinal profile of number of particles

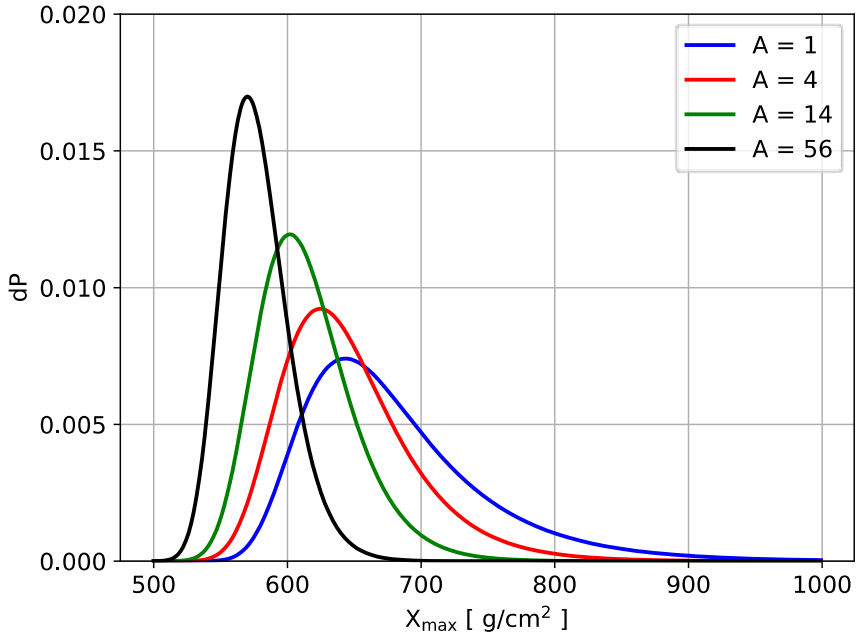


Shower maximum X_{max} varies with primary particle mass
- on average
- in distribution

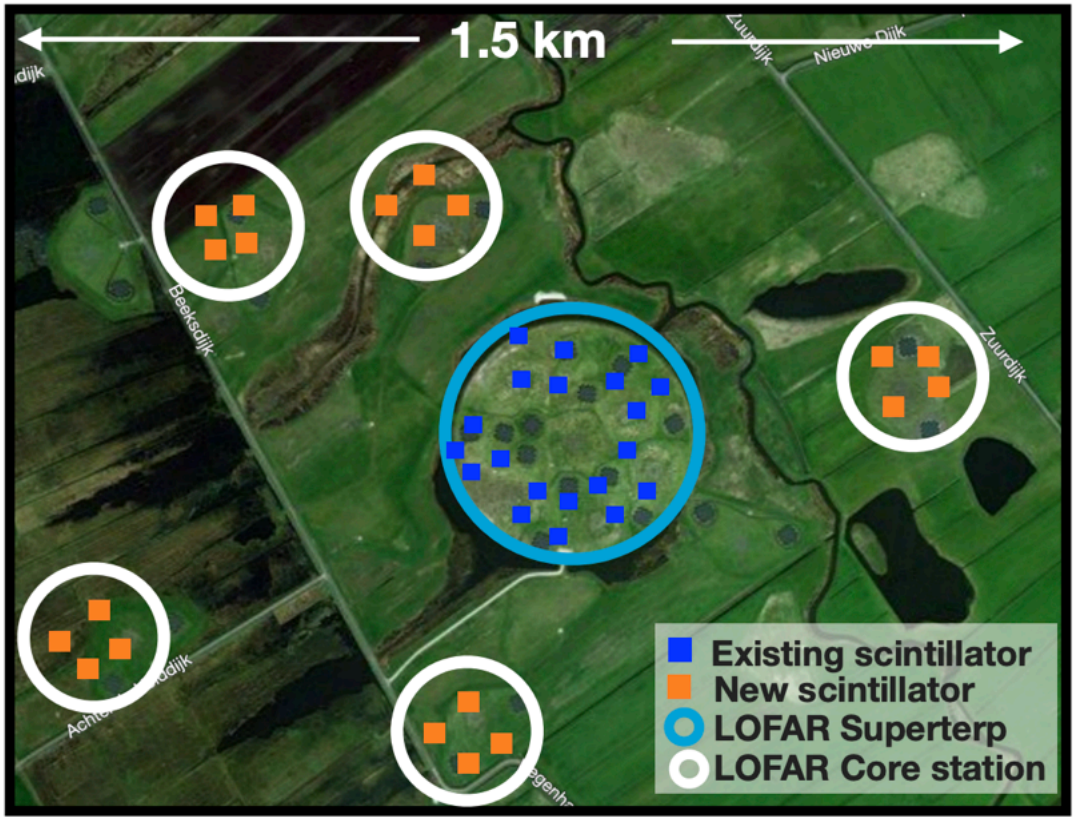
X_{max}

Mass composition of cosmic rays, from air shower maximum X_{max}



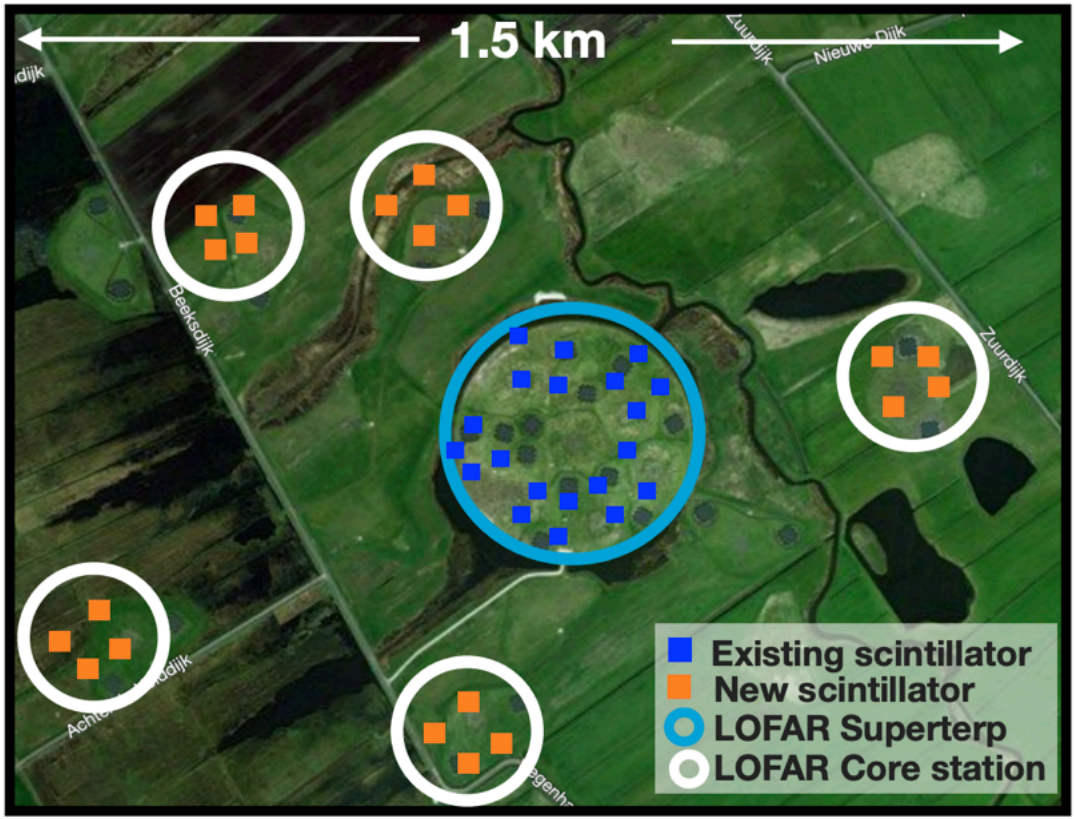


How do we do this in practice at LOFAR (LORA)



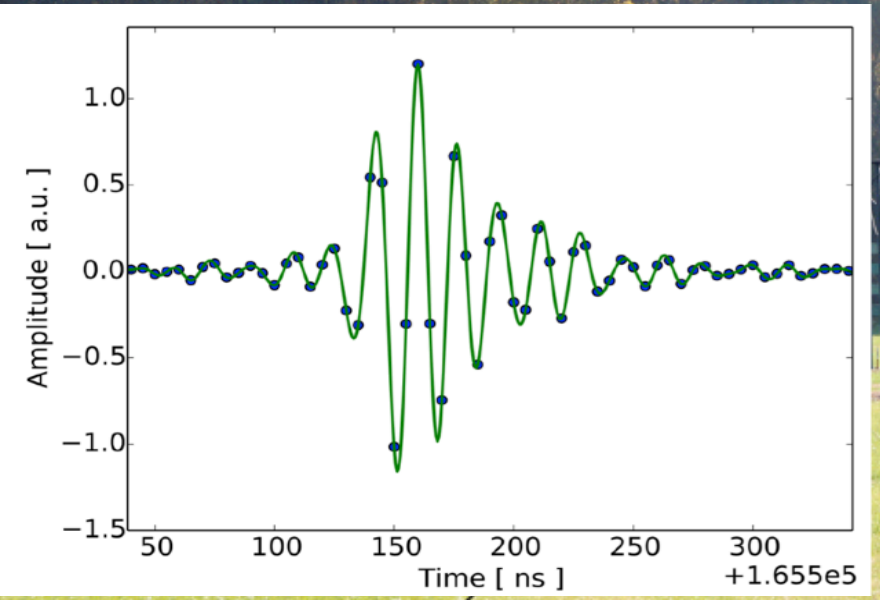
Used to trigger a readout of the TBB buffers of each antenna

How do we do this in practice at LOFAR (LORA)

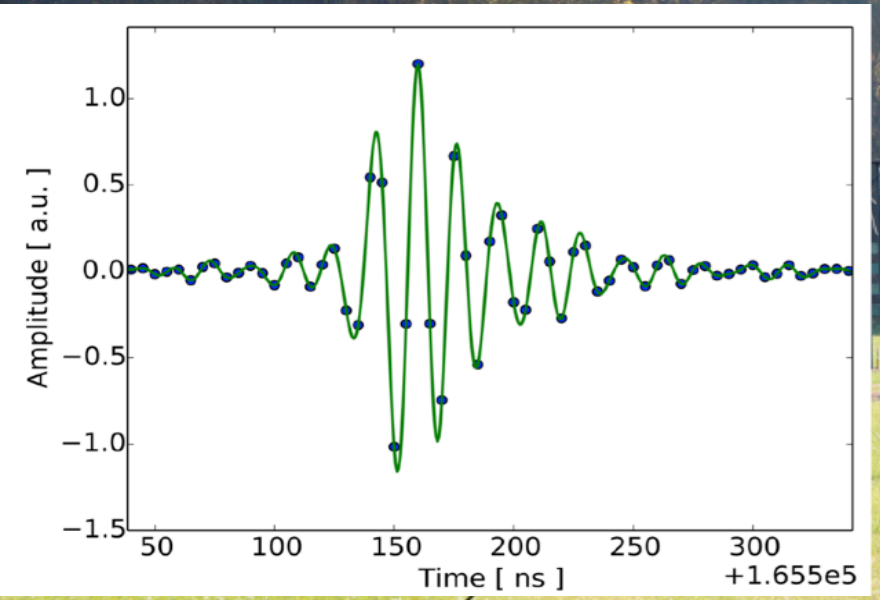


Used to trigger a readout of the TBB buffers of each antenna

Pulses in LOFAR antennas



Pulses in LOFAR antennas

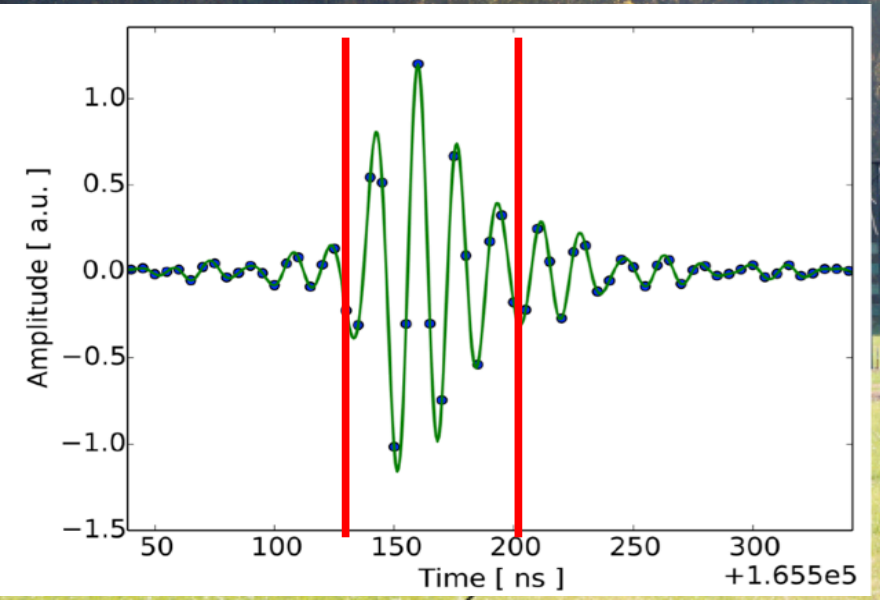


Our raw material:

- One pulse in every dipole
- (unprocessed time series)

- Amplitude & integrated power
- Arrival time
- Polarization
- Shape / spectrum

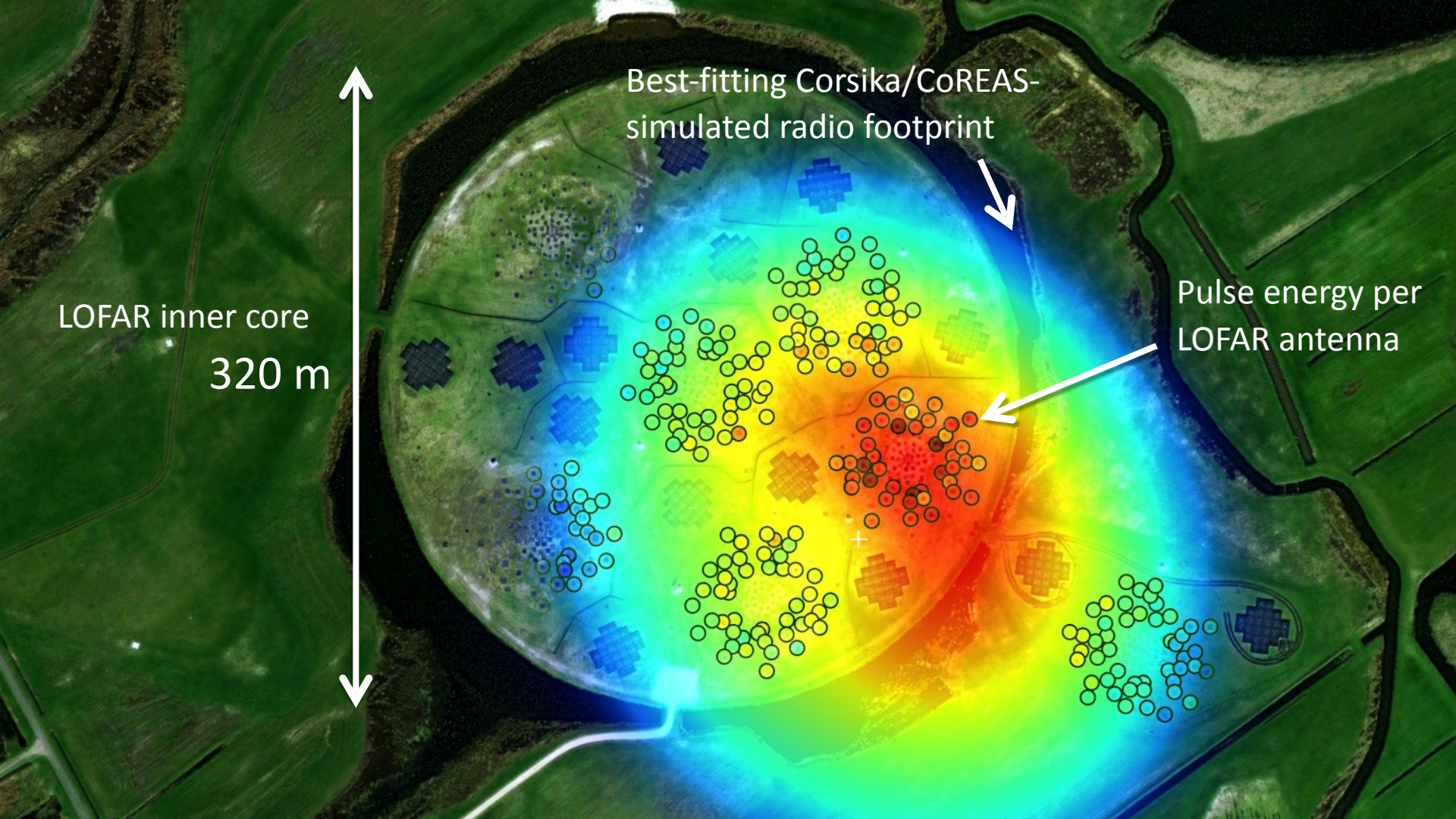
Measuring energy fluence



Integrate ‘power’ in a time window

- Width of time window not too large (noise

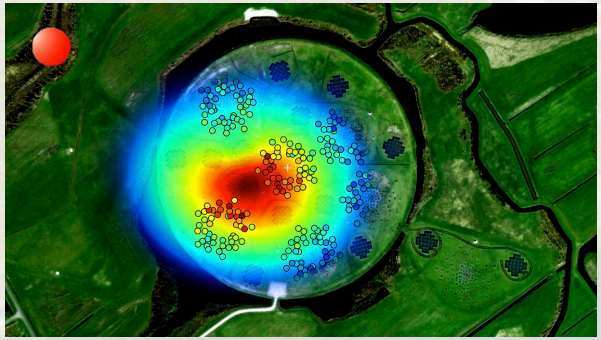
This is the simplest and most robust case with respect to antenna and system modeling issues


Best-fitting Corsika/CoREAS-simulated radio footprint
Pulse energy per LOFAR antenna
LOFAR inner core
320 m

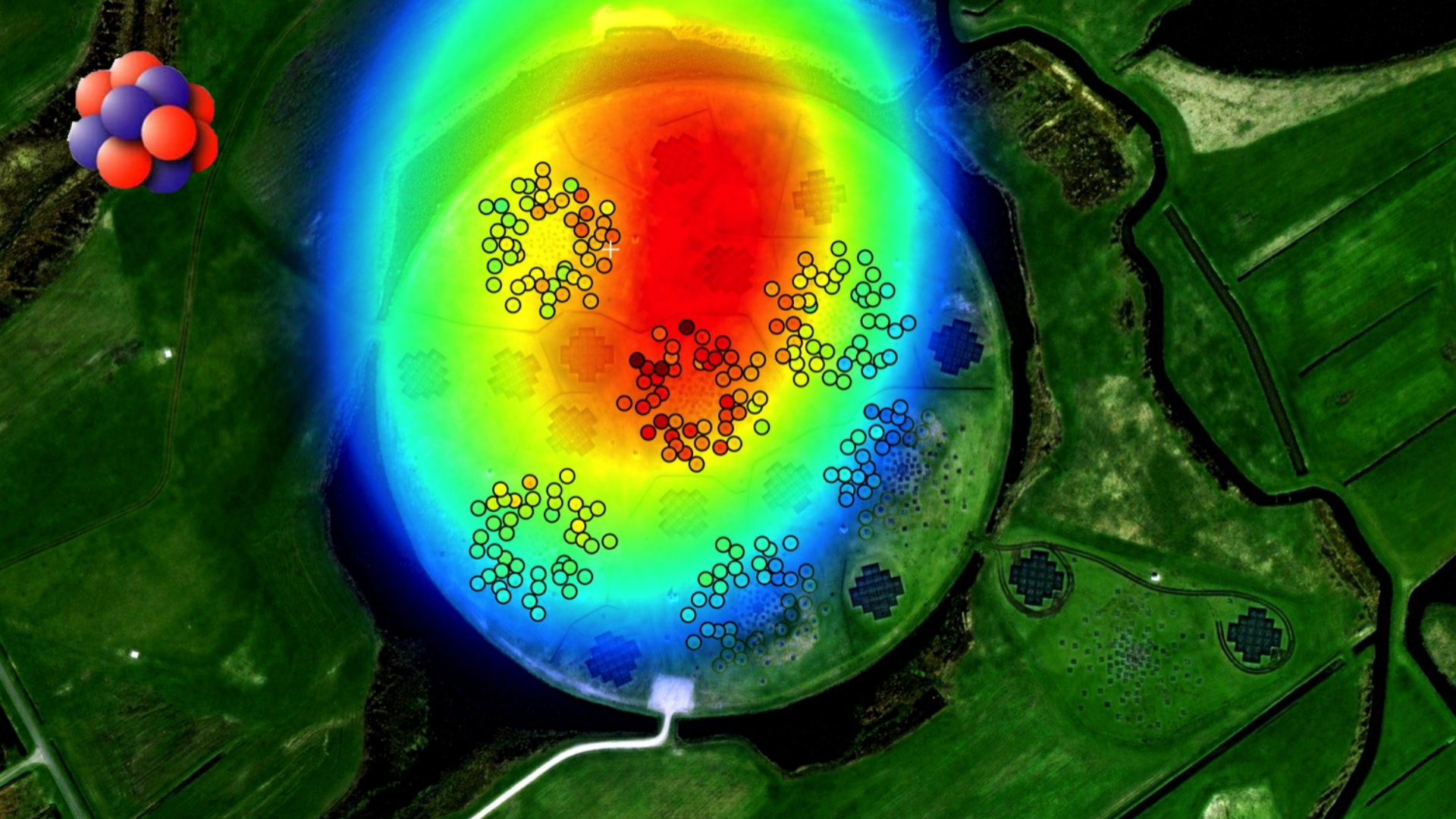
Cosmic rays with LOFAR a success story

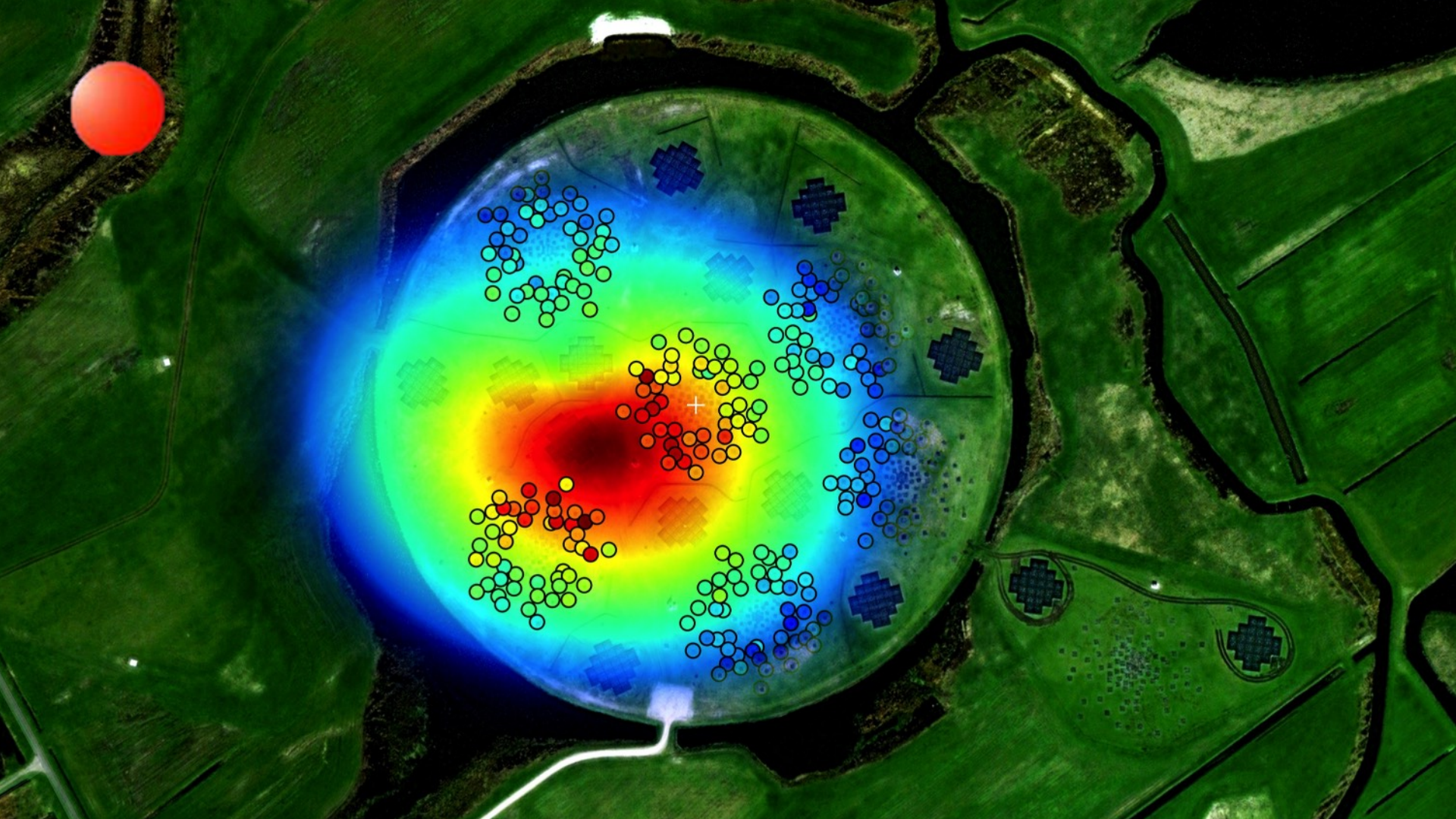
- First cosmic rays with LOFAR in 2011
- LOFAR was the standard-setting experiment to understand the emission and push the envelope of what is possible
- It lead to a serious effort in improving simulations: the data was too good for the simulations
- Spin-offs: Lightning (see talks on Friday)

The reason: the number of antennas



A&A 560 (2013); Phys. Rev. D 90, 082003 (2014); JCAP P10 (2014) 014; AstroPart Phys, 61, 22-31 (2015); Astropart Phys, 65, 11-21, (2015); JCAP 05 (2015) 018; Phys. Rev. Lett. 114, 165001 (2015); JINST 10(2015)P11005; A&A 590, A41, (2016); Nature 531, 70-72, (2016); Phys. Rev. D 93, 023003 (2016); Phys. Rev. D 94, 103010 (2016); Phys. Rev. D 95 (2017) 8, 083004; Astropart.Phys. 111 (2019) 1-11; Astropart. Phys. 123 (2020) 102470; JCAP 11 (2020) 017; Phys. Rev. D 103, 102006 2021; Phys. Rev. D 108, 083041 2023; Eur. Phys. J. C (2023) 83: 1146; Phys. Rev.D 110 (2024) 10, 103036; Geophysical Research Letters, 52 (2025) 8

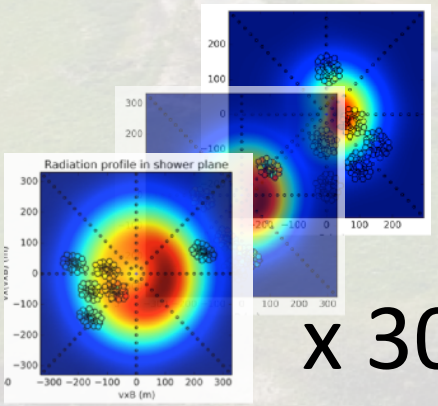


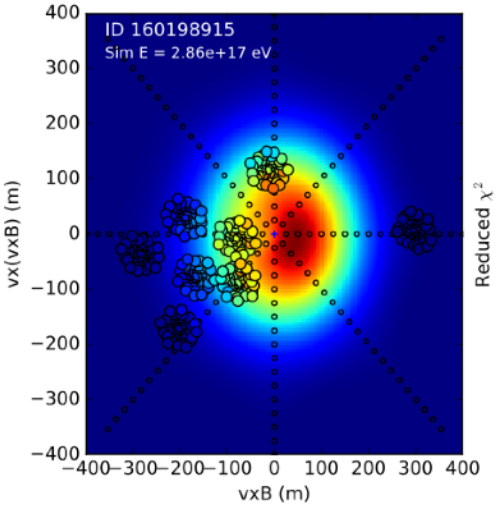


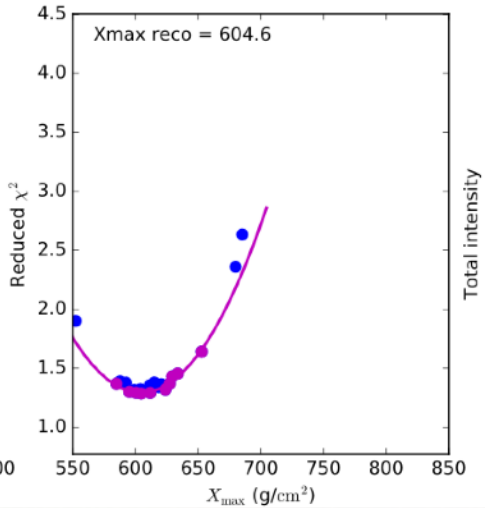
Matching simulated footprints to data

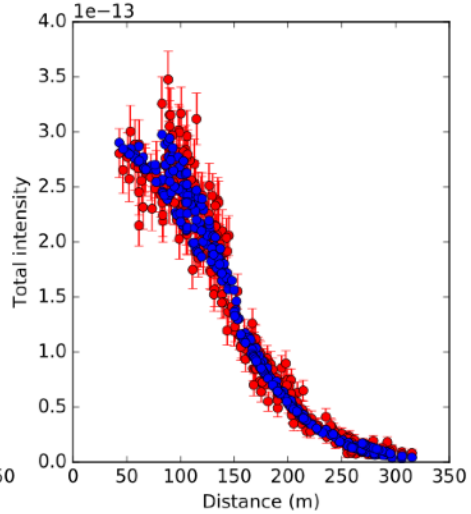
- Simulate about 30 showers per measured shower
- Fit them to data, observe X_{max} of best fit

- Resolution (@LOFAR) about 20 g/cm²
- Systematic uncertainties < 9 g/cm²
- In line with state of the art in the field

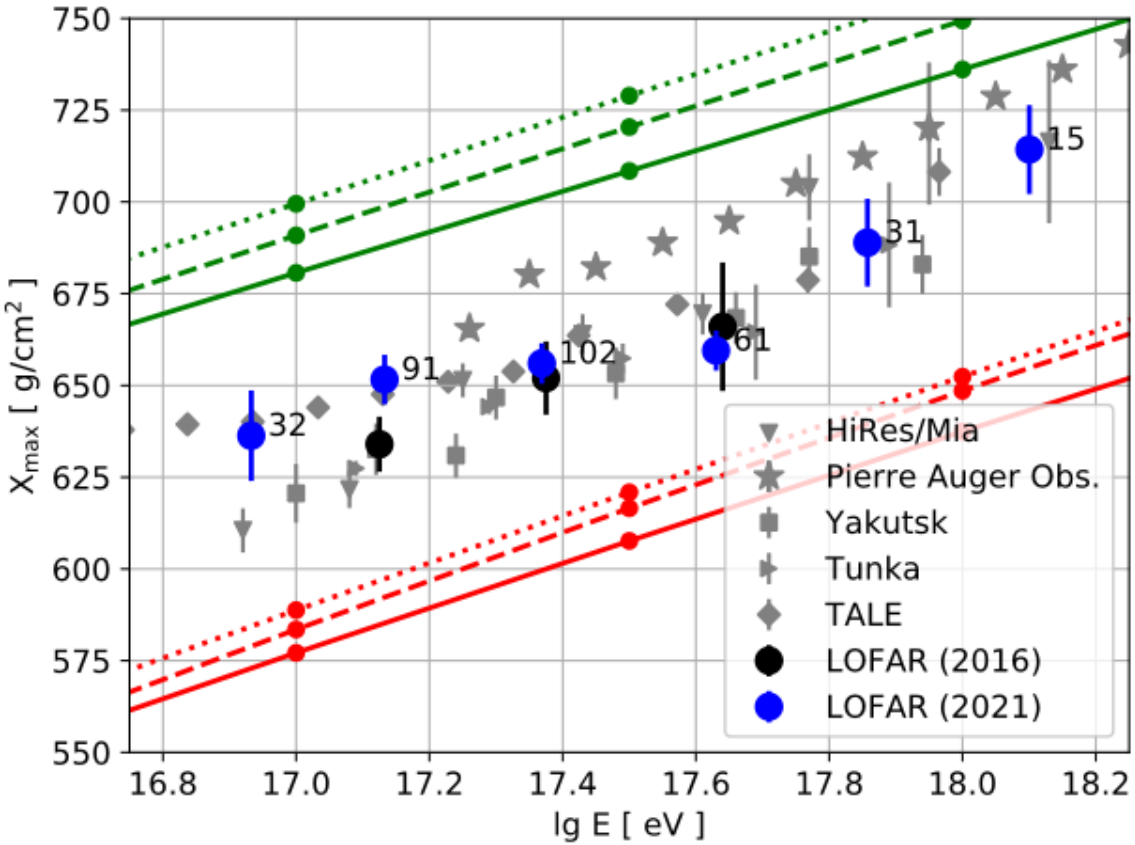








Result: Average X_{max} versus primary energy

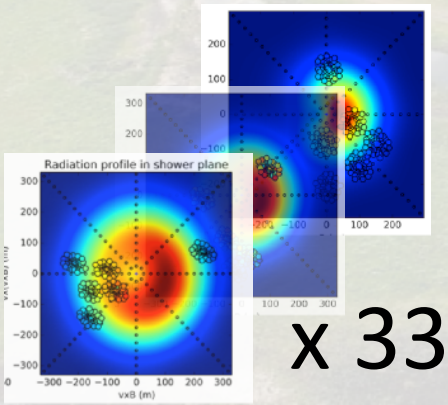


- Green lines: average X_{max} for pure proton composition
- Red lines: average X_{max} for pure iron composition

Corstanje et al., Phys Rev D 103, 102006 (2021)
arXiv: 2103.12549

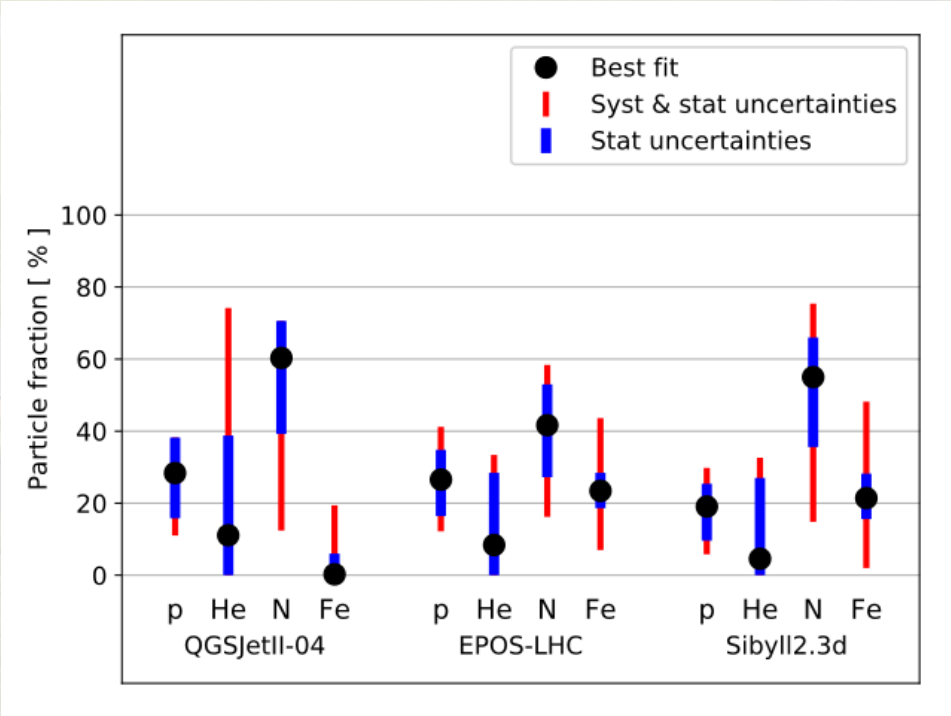
LOFAR 1.0 results on mass composition

- Light-mass component (p+He) of 23 to 39% at best fit
- Still considerable (correlated) uncertainties, some inevitable
  - overlap of X_{max} distributions
  - Hadronic interaction models



x 334

Main coverage in lg E: 17.4 +/- 0.3



Corstanje et al., Phys Rev D 103, 102006 (2021), arXiv: 2103.12549

Towards LOFAR 2.0

- Current analysis **limited by statistics**: need factor 10 to have composition trend with energy, and better resolution

→

- **Continuous observations in background**
- **Expanded particle detector array**
- Access to HBA unbeamformed data together with LBA: (see next slides)
- Use beamforming to expand energy range downward

- Analysis so far only measures shower maximum:
  - Get smarter for better H/He separation

→

- New methods in development for LOFAR 2.0 and SKA-Low

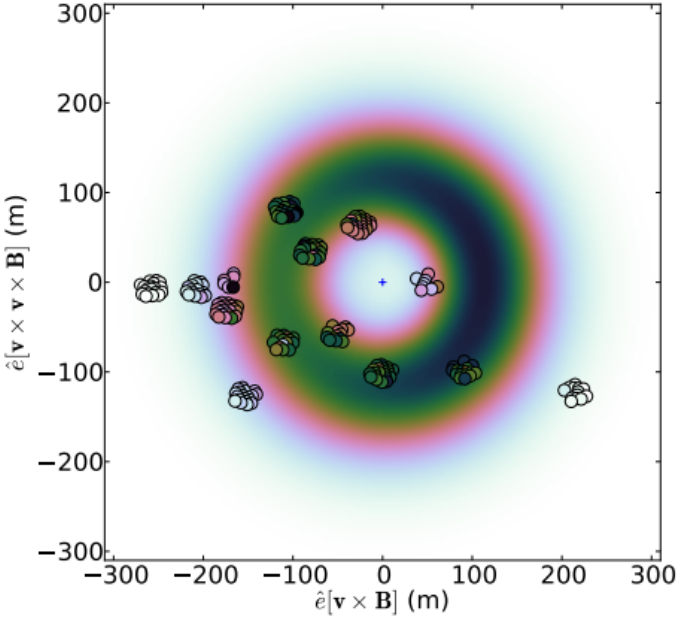
Towards LOFAR 2.0 and SKA

- Same principles, same objectives: but many, many more antennas
- Synergies by using the same software framework (https://github.com/nu-radio/NuRadioMC)
- Develop new, advanced analysis techniques to be used at both observatories
- Measure North-South differences, if any (same systematics, mostly!)

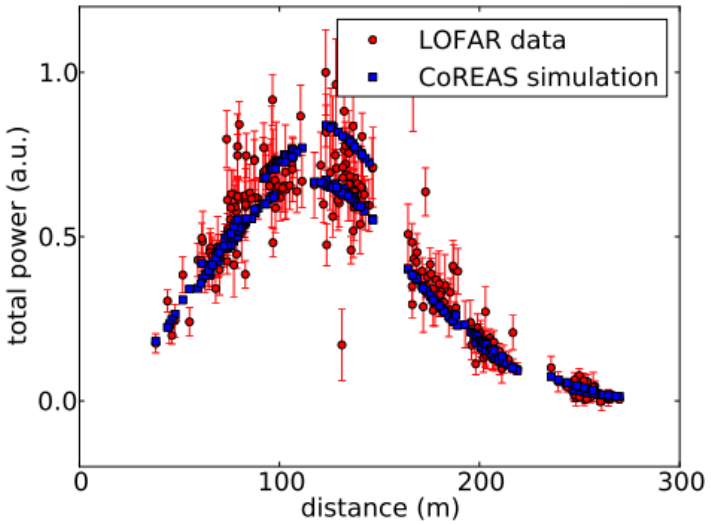
The power of LOFAR lies in the accumulated data-set, SKA has to play catch-up

The high frequencies: Example of HBA data

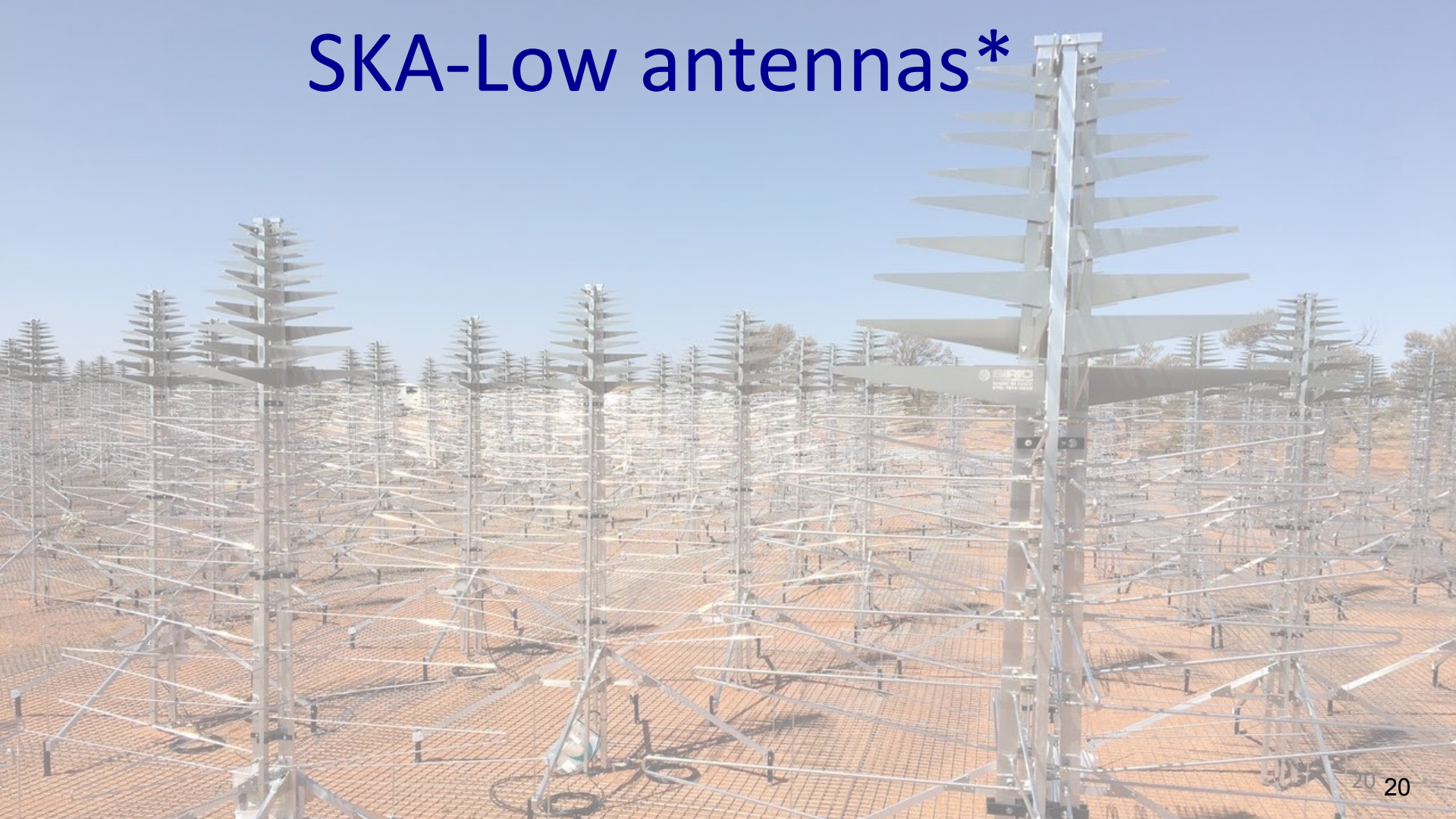
- We have tried this around 2014 (arXiv:1411.6865)
- Had to be lucky in pre-beamformed HBA data, whenever it aligned with arrival direction
- Cherenkov ring: sharper features at higher frequencies



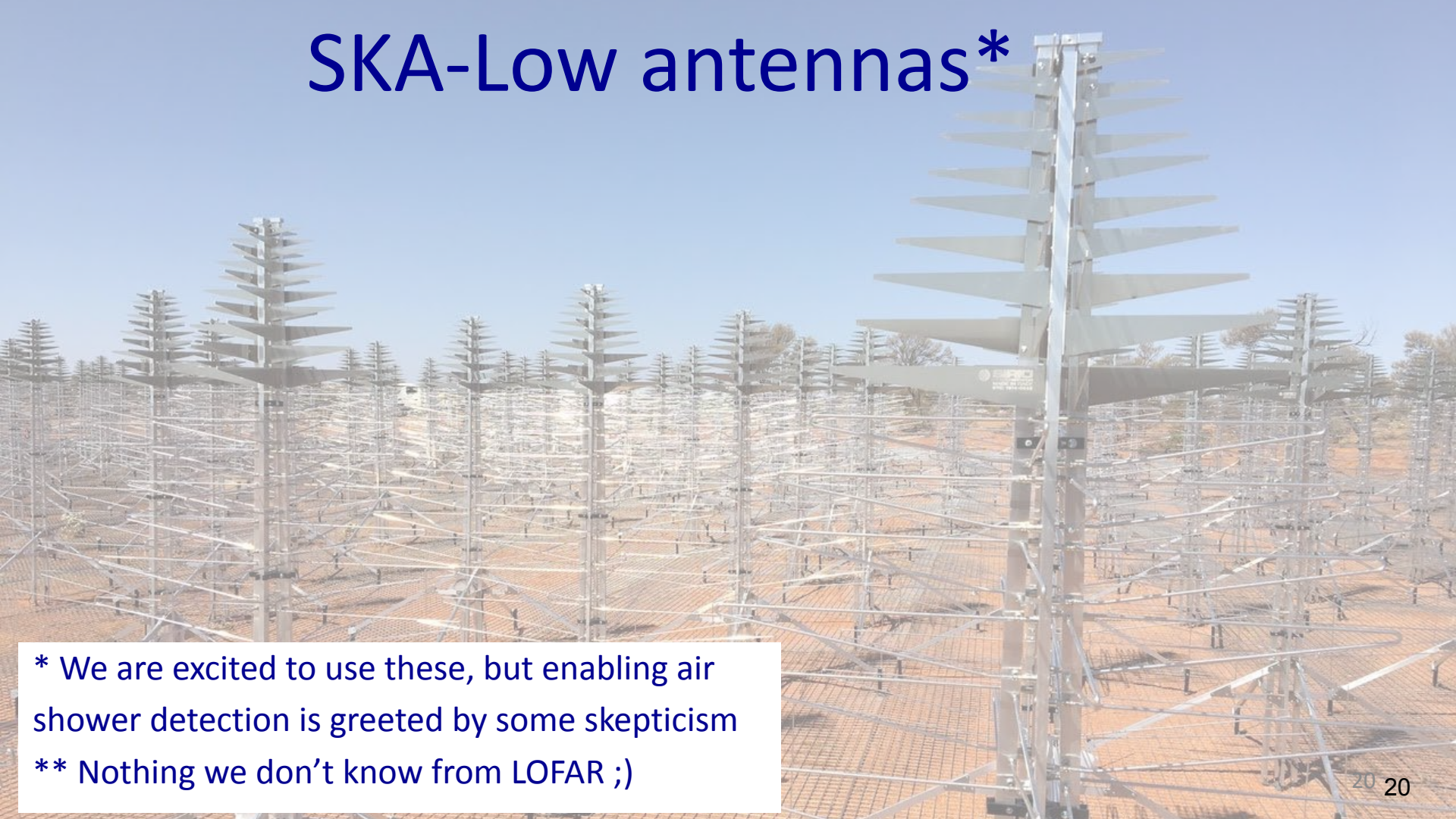
Nelles et al., AstroPart Phys, 61, 22-31 (2015)



SKA-Low antennas*



SKA-Low antennas*



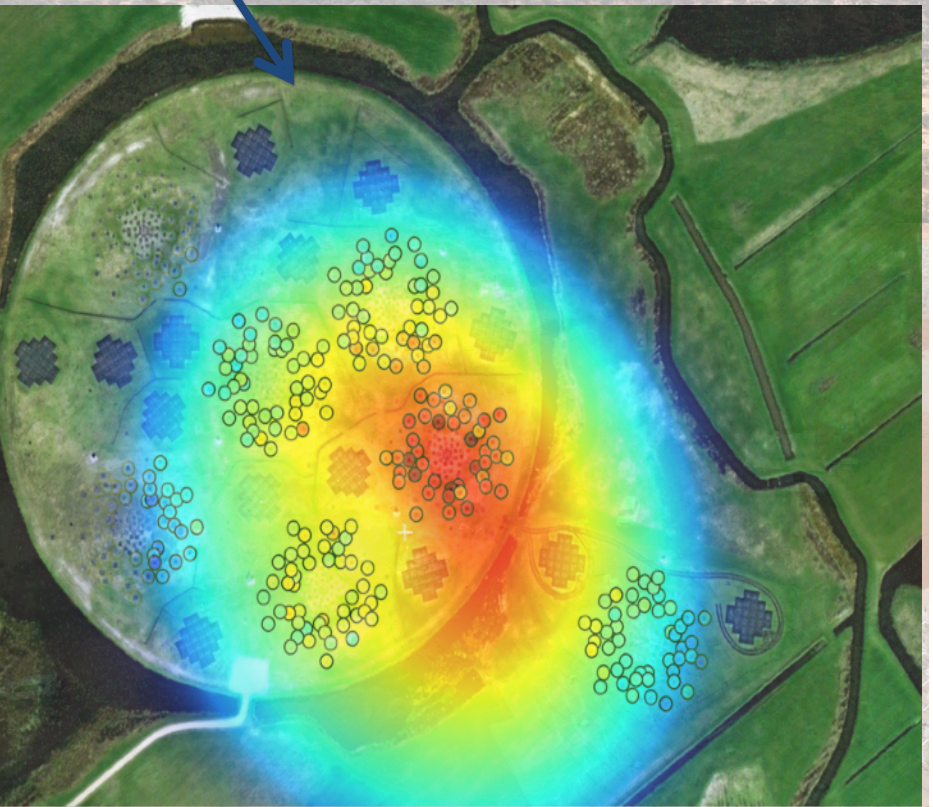
* We are excited to use these, but enabling air shower detection is greeted by some skepticism

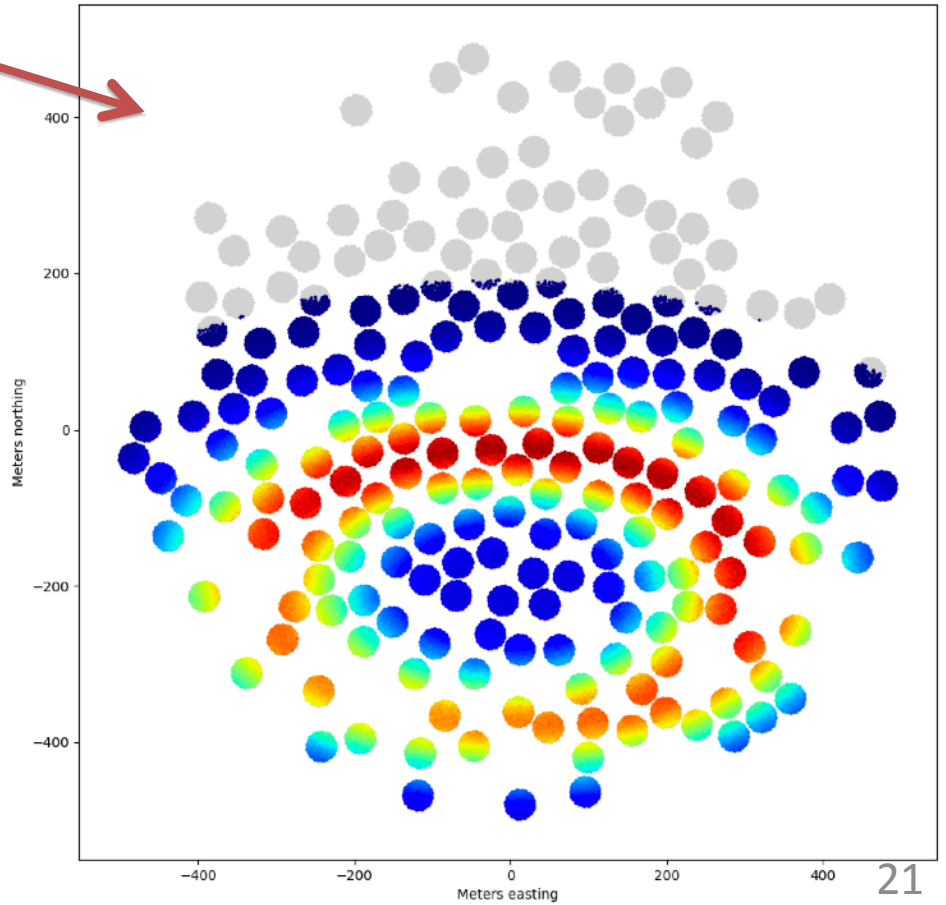
** Nothing we don't know from LOFAR ;)

SKA-Low, a really dense array

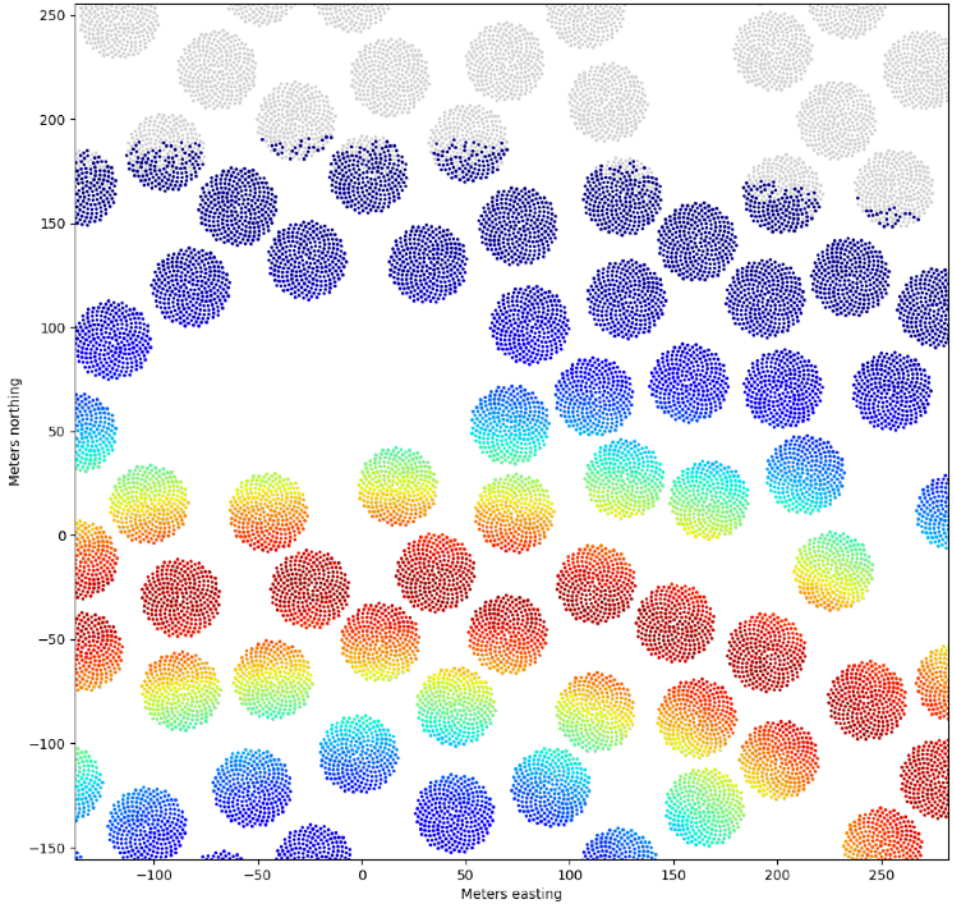
LOFAR

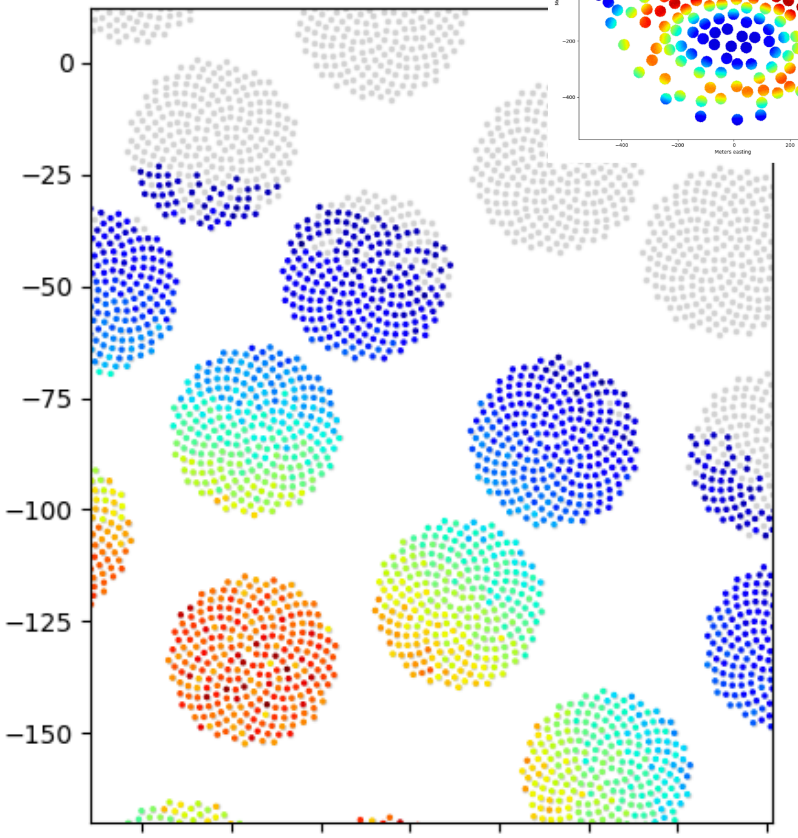
SKA antenna layout

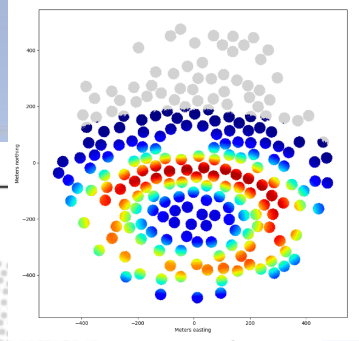




SKA-Low, a really dense array!

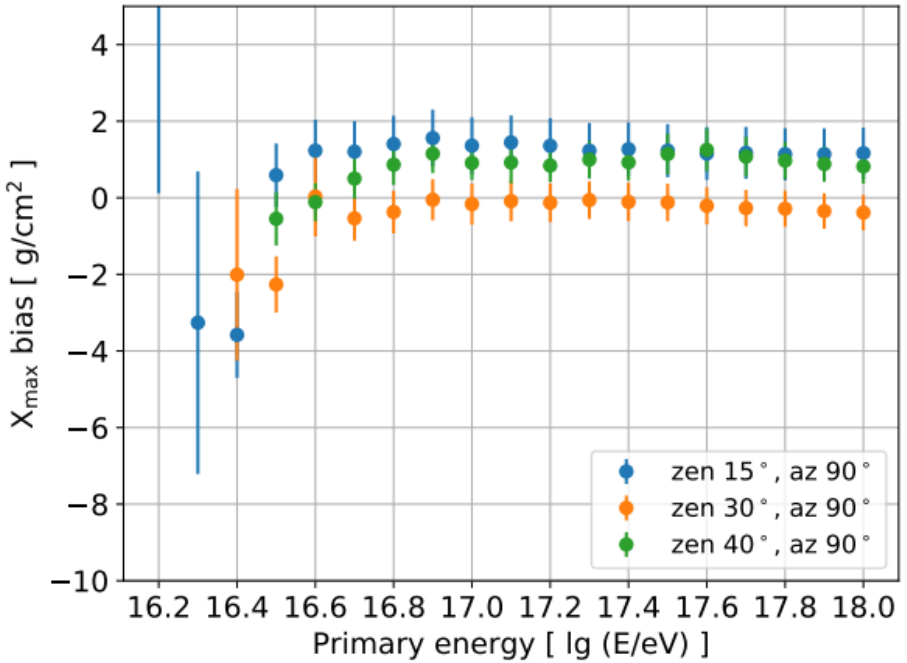




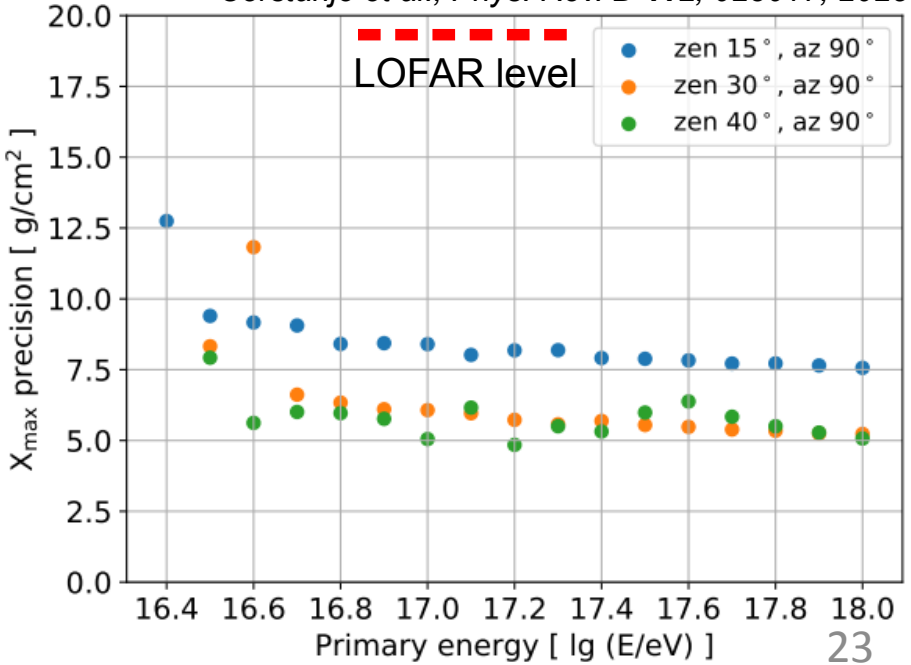


LOAFR methods for SKA-Low

- If we simply use the **'old' methods** developed for LOFAR 1.0 for SKA-Low
- Huge improvement in precision



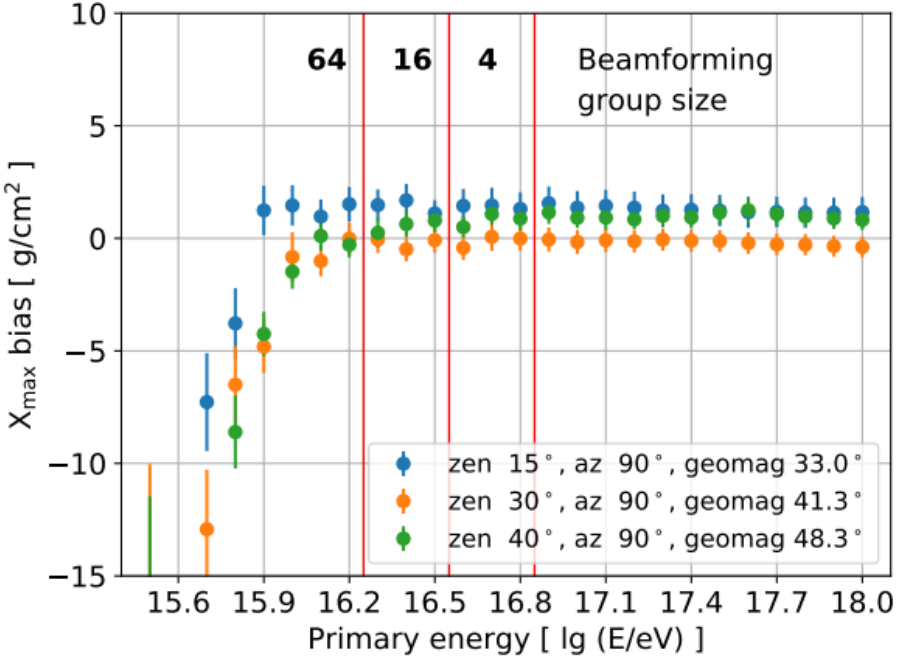
*Corstanje et al., Phys. Rev. D **112**, 023017, 2025*

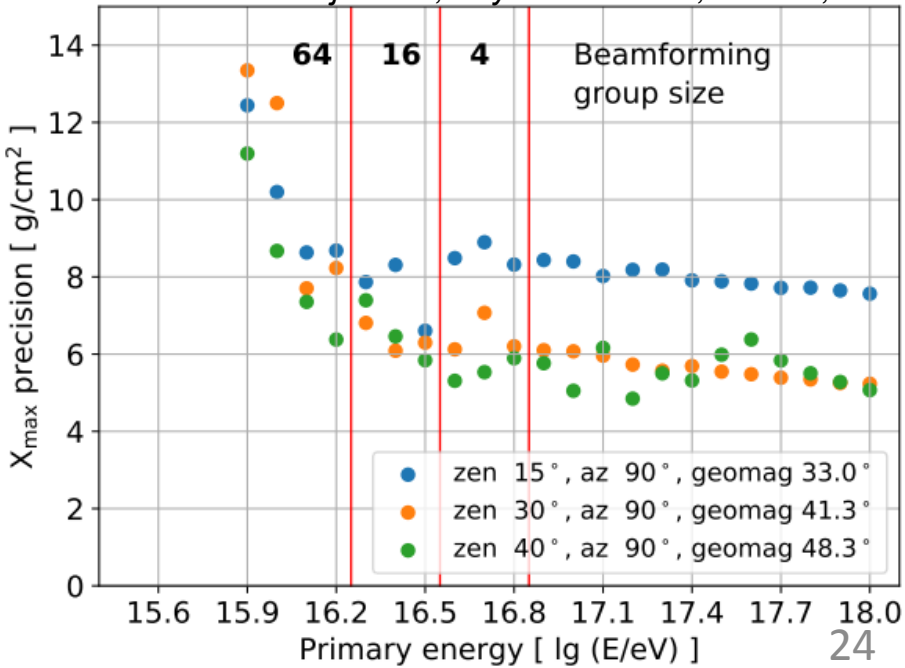


Can we push towards lower shower energies?

- Lower energies needed to access Galactic science
- Results stay good down to 10^{16} eV with pseudo-beamforming, work in progress to go even lower

*Corstanje et al., Phys. Rev. D **112**, 023017, 2025*

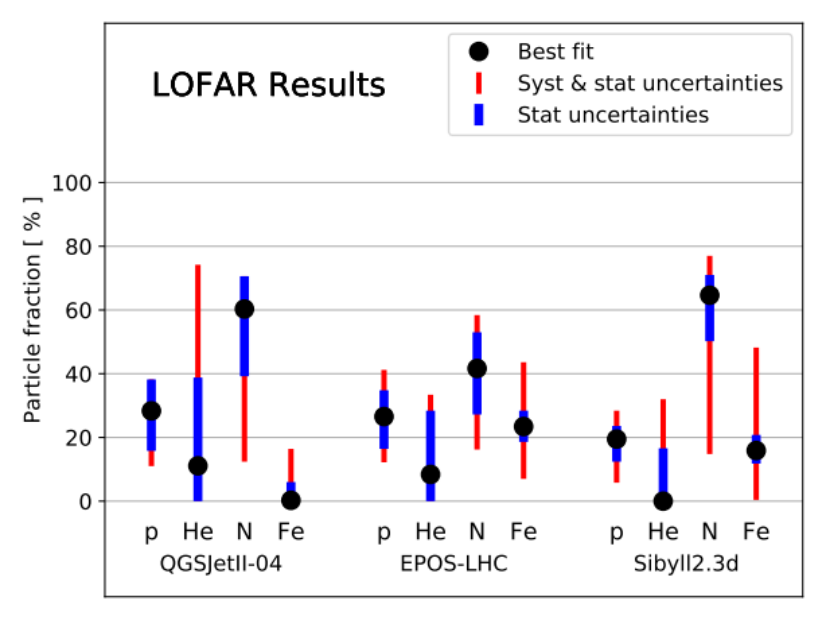


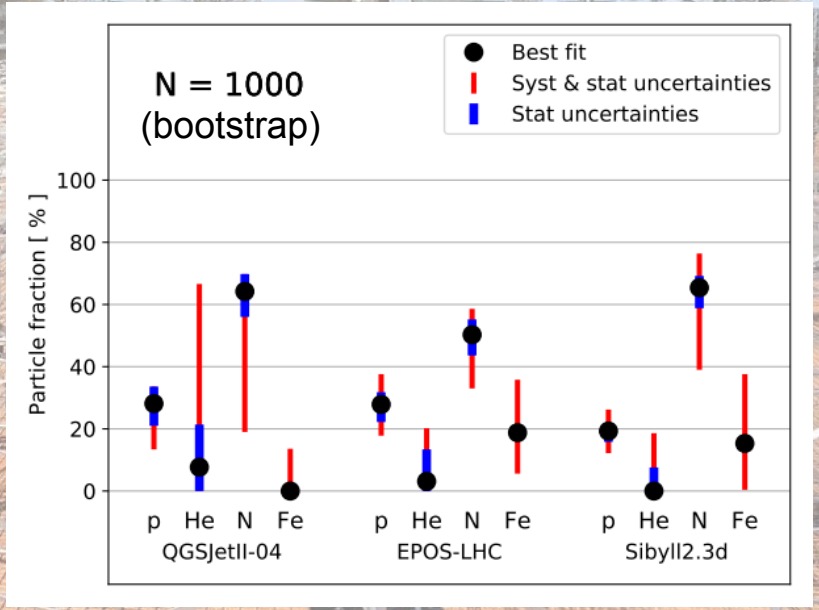


Converting a reconstruction parameter to physics

- How many showers are useful?
  - Systematic uncertainties >> statistical uncertainties
  - A mass composition in narrow energy bins, improving over LOFAR (2021)
- **What do we expect from 1000 SKA showers?**

*Corstanje et al., Phys. Rev. D **112**, 023017, 2025*

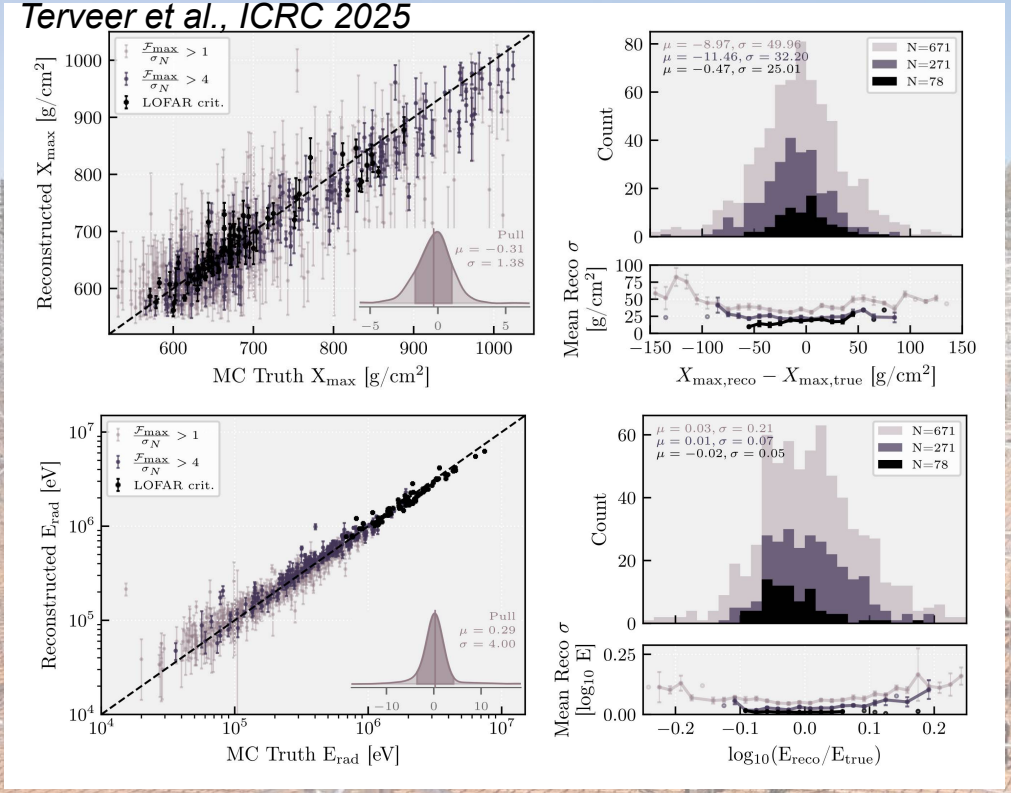




What about ‘new’ methods?

- Lots of on-going work to carve out new approaches that give another push

Terveer et al., ICRC 2025



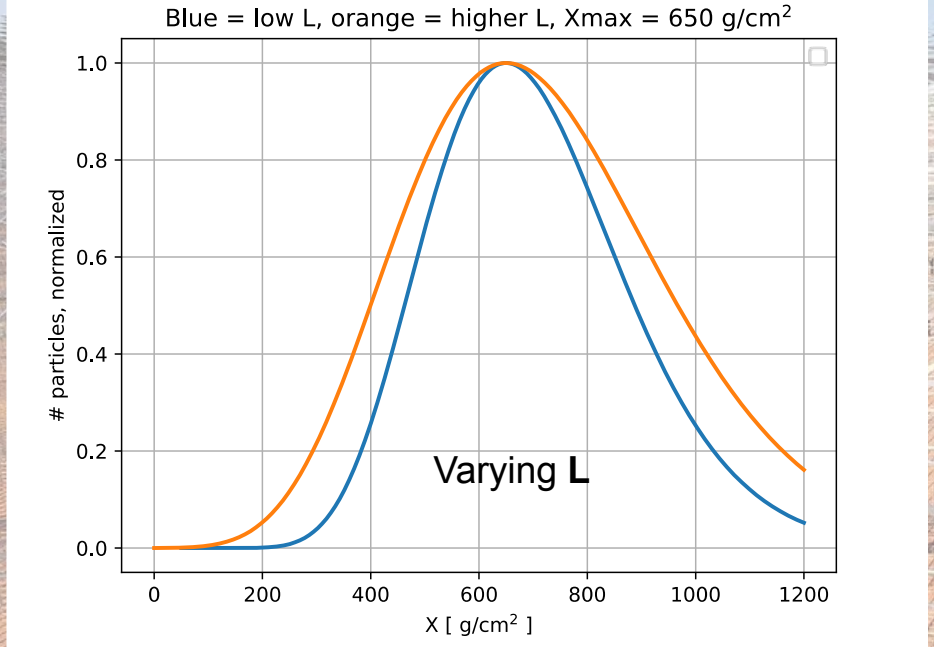
- At LOFAR we have been working with the best events and single key variables
  - very robust and stable, but limited in statistics
- How about using all events and the full waveforms?
  - leveraging ML
  - work in progress for LOFAR
  - new opportunities for SKA

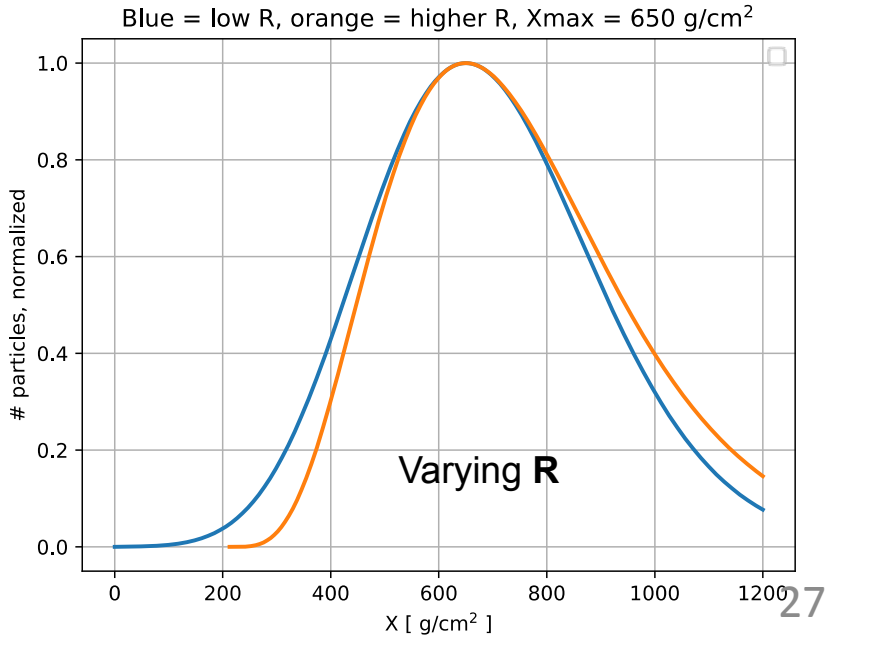
Moving into particle physics: Longitudinal distribution of particles

$$N(X) = \exp\left(-\frac{X - X_{\max}}{RL}\right)\left(1 + \frac{R}{L}(X - X_{\max})\right)^{\frac{1}{R^2}}$$

Parameter **L**: width (variance)
Parameter **R**: asymmetry (skewness)

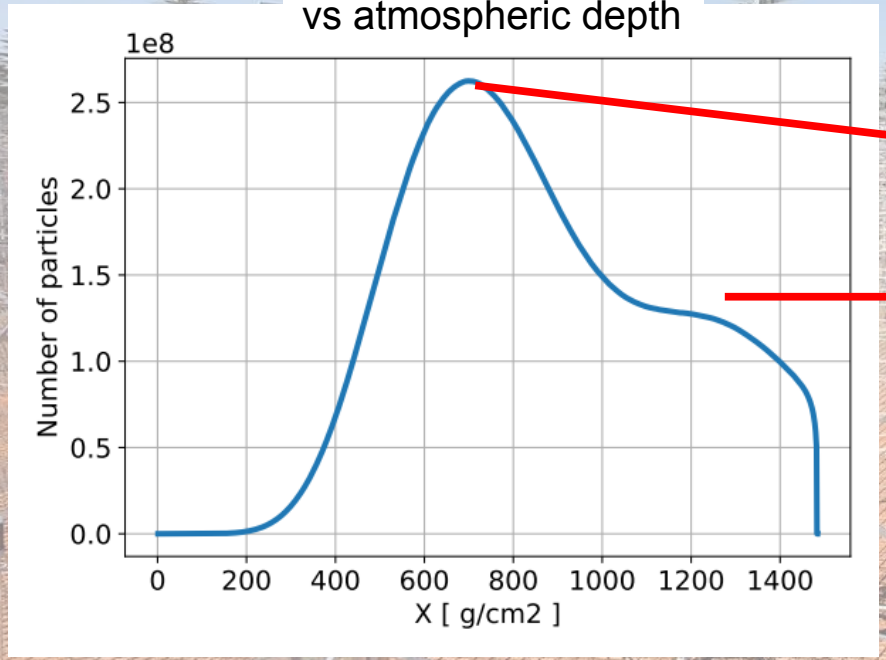
Oddest showers fro **helium**: Independent handle on proton fraction!

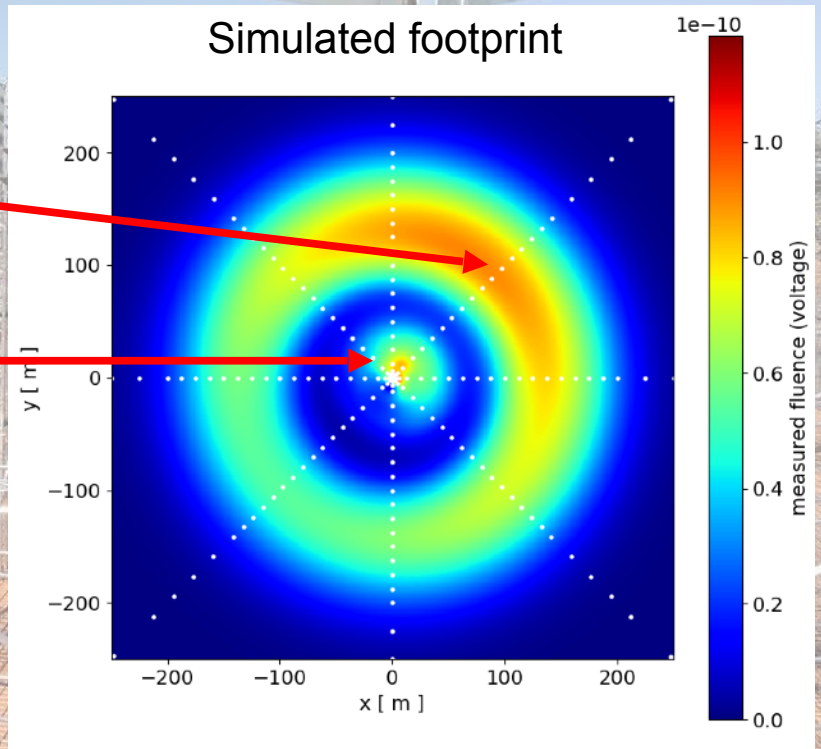




Outlier showers, ‘double bumps’, new physics

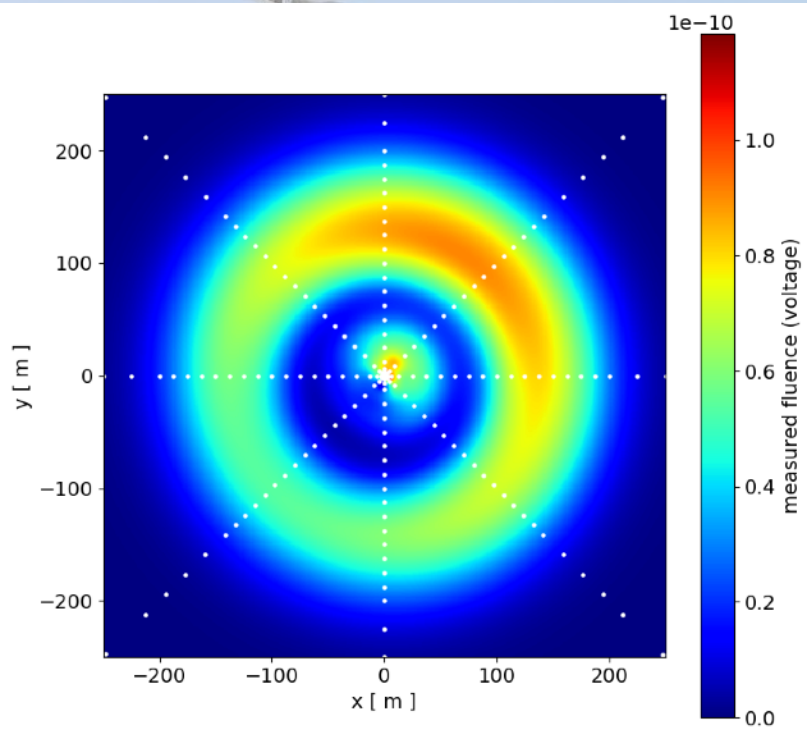
- Fraction of these ~ few %, varies with mass comp & hadronic interaction models
- Filter to 150 – 350 MHz band for sharper features

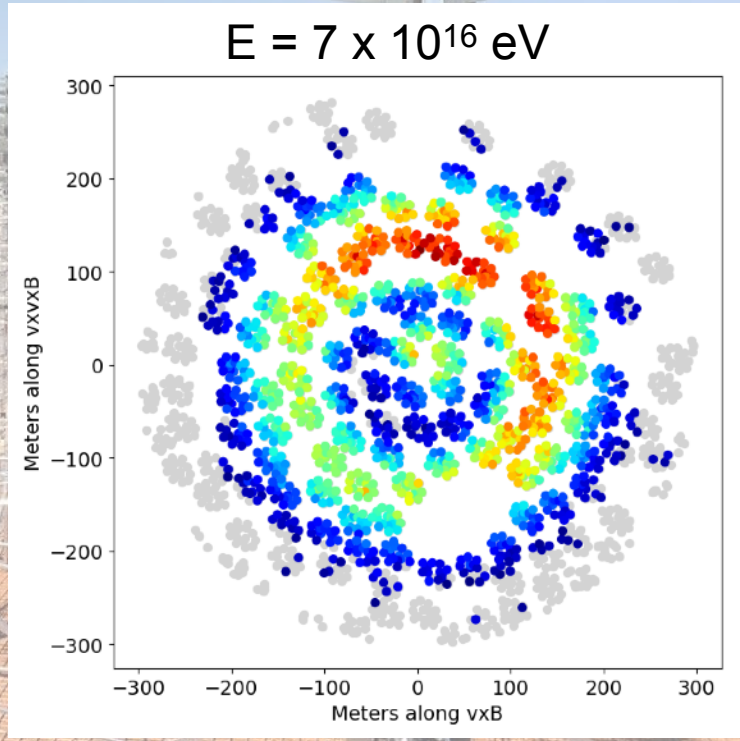




Outlier showers with SKA

- In LOFAR there were never enough antennas to do this easily, good hope for SKA
- This is very much work in progress for new methods





Summary

- Two major observatories taking radio-CR measurements to the next level
  - Using new techniques developed for SKA
  - Using same analysis code, (https://github.com/nu-radio/NuRadioMC)

- **LOFAR 2.0**: full duty cycle, LORA expansion
  - See mass composition trends with energy
  - Competitive statistics over time (multiple obs years)
  - Benefits from new analysis techniques being developed

- **SKA-Low**: “ultimate” precision per air shower
  - New techniques improve particle identification
  - Energy range down to at least **10^{16} eV**
  - Hadronic physics