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

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Seminar KIT,
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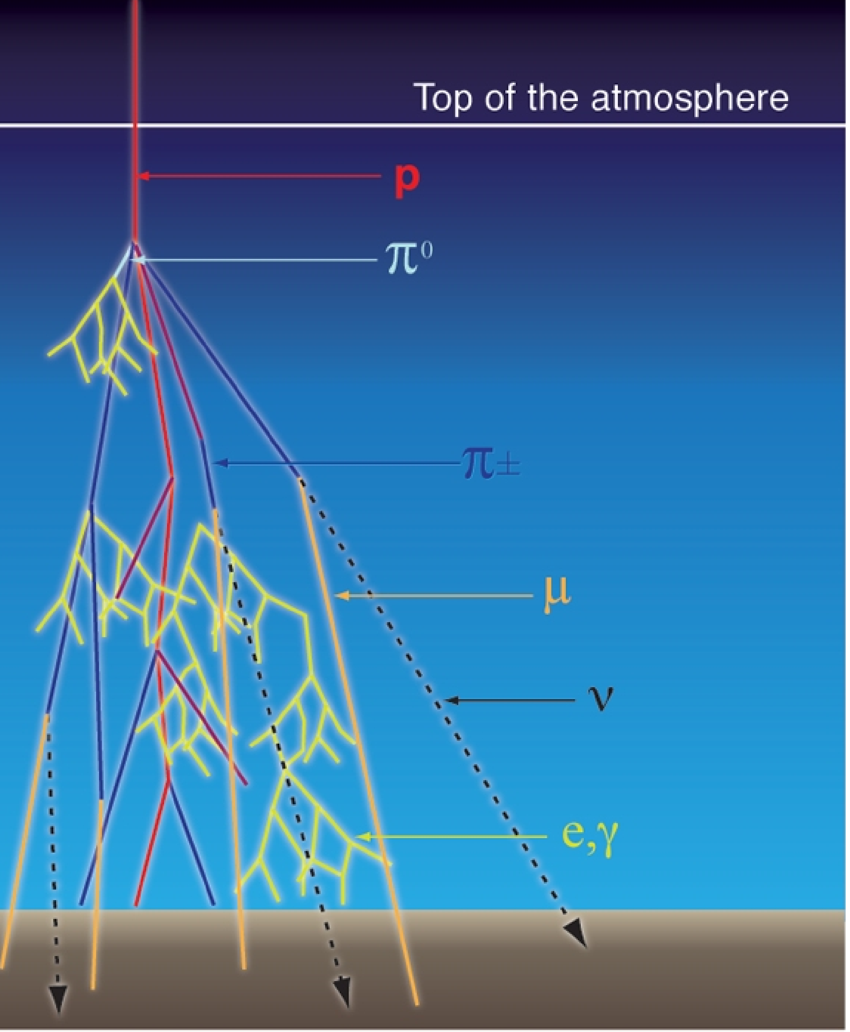
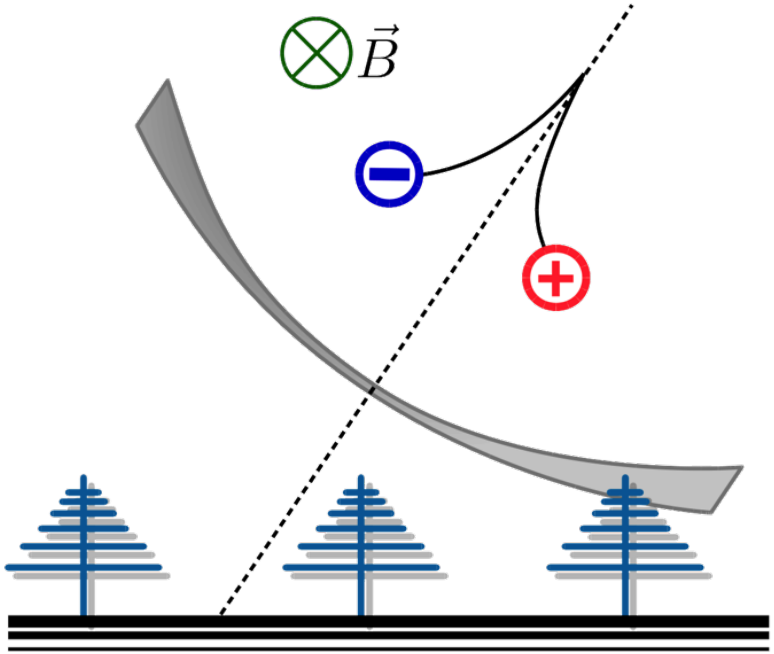
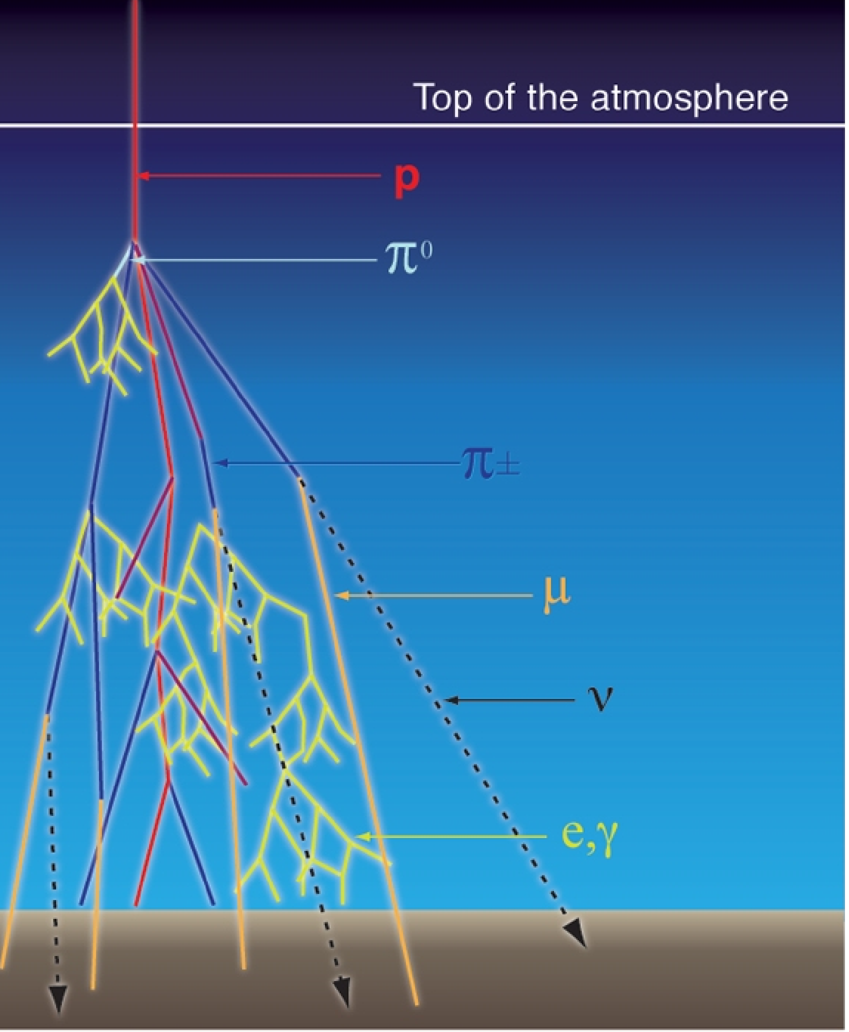


Extensive air showers

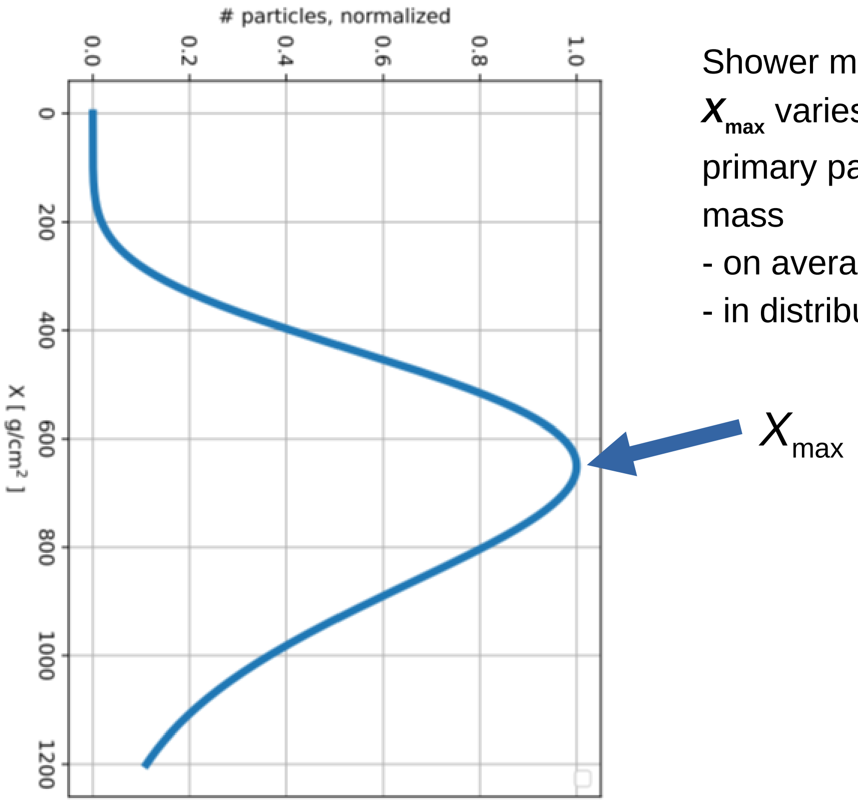
Radio signals from air showers





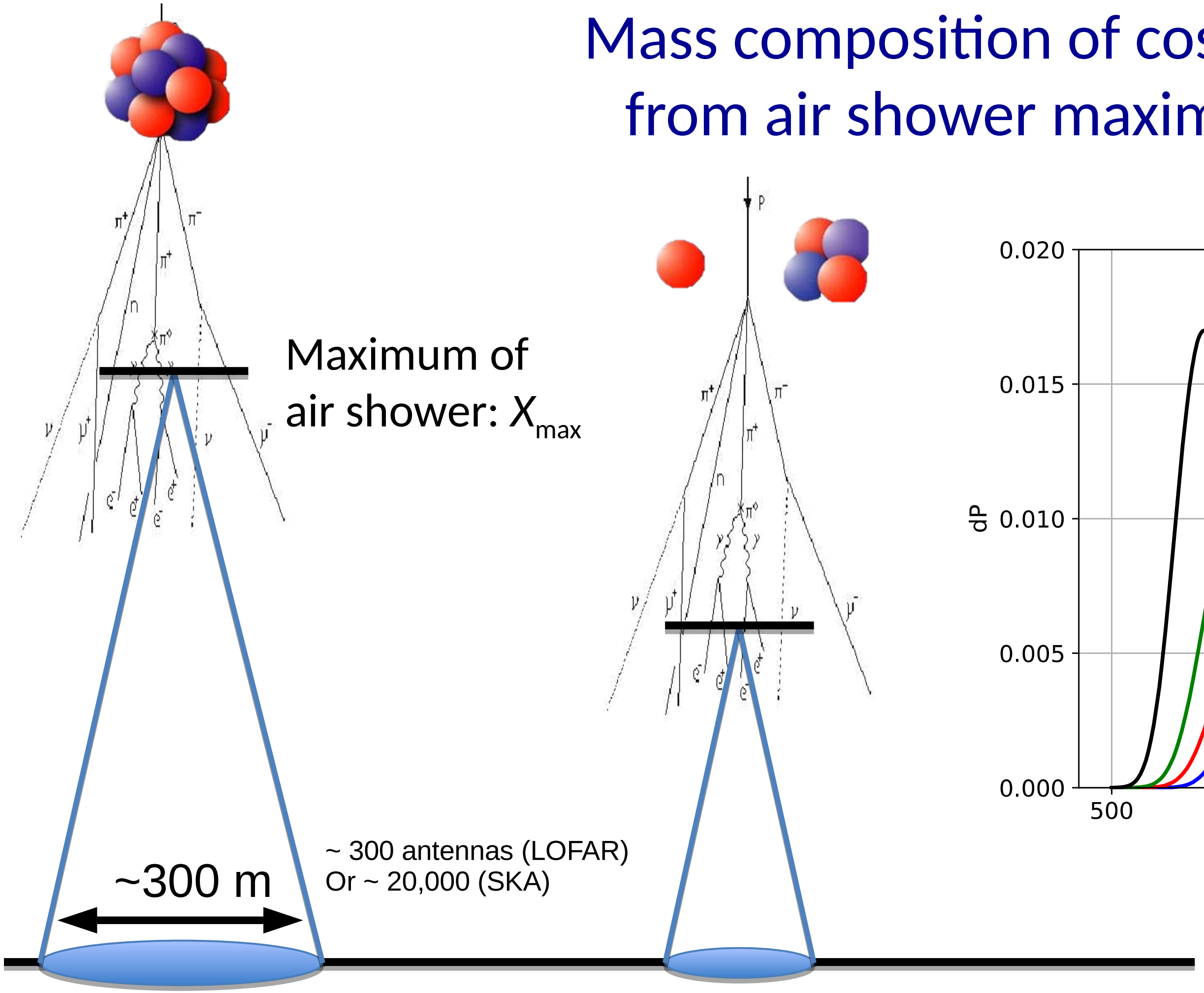
Extensive air showers

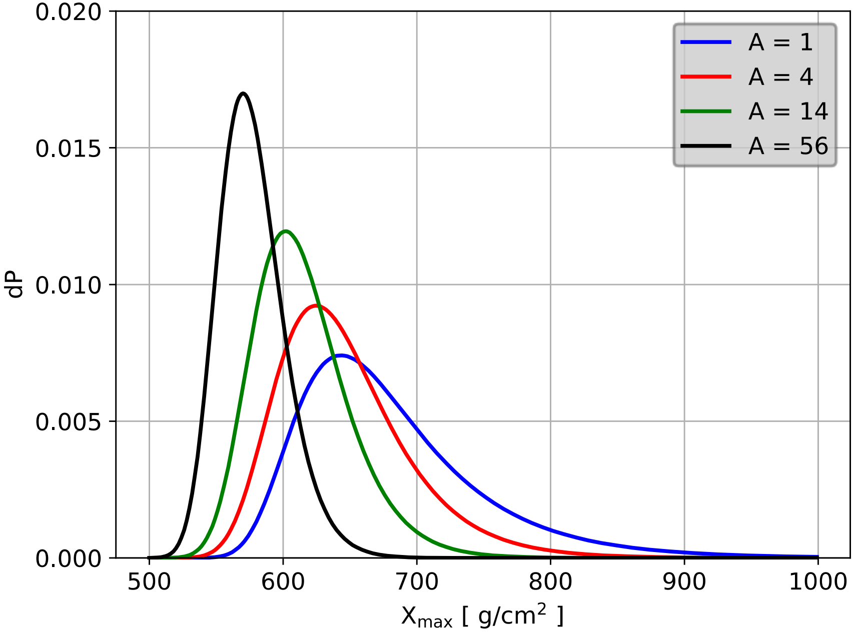
Longitudinal profile of number of particles



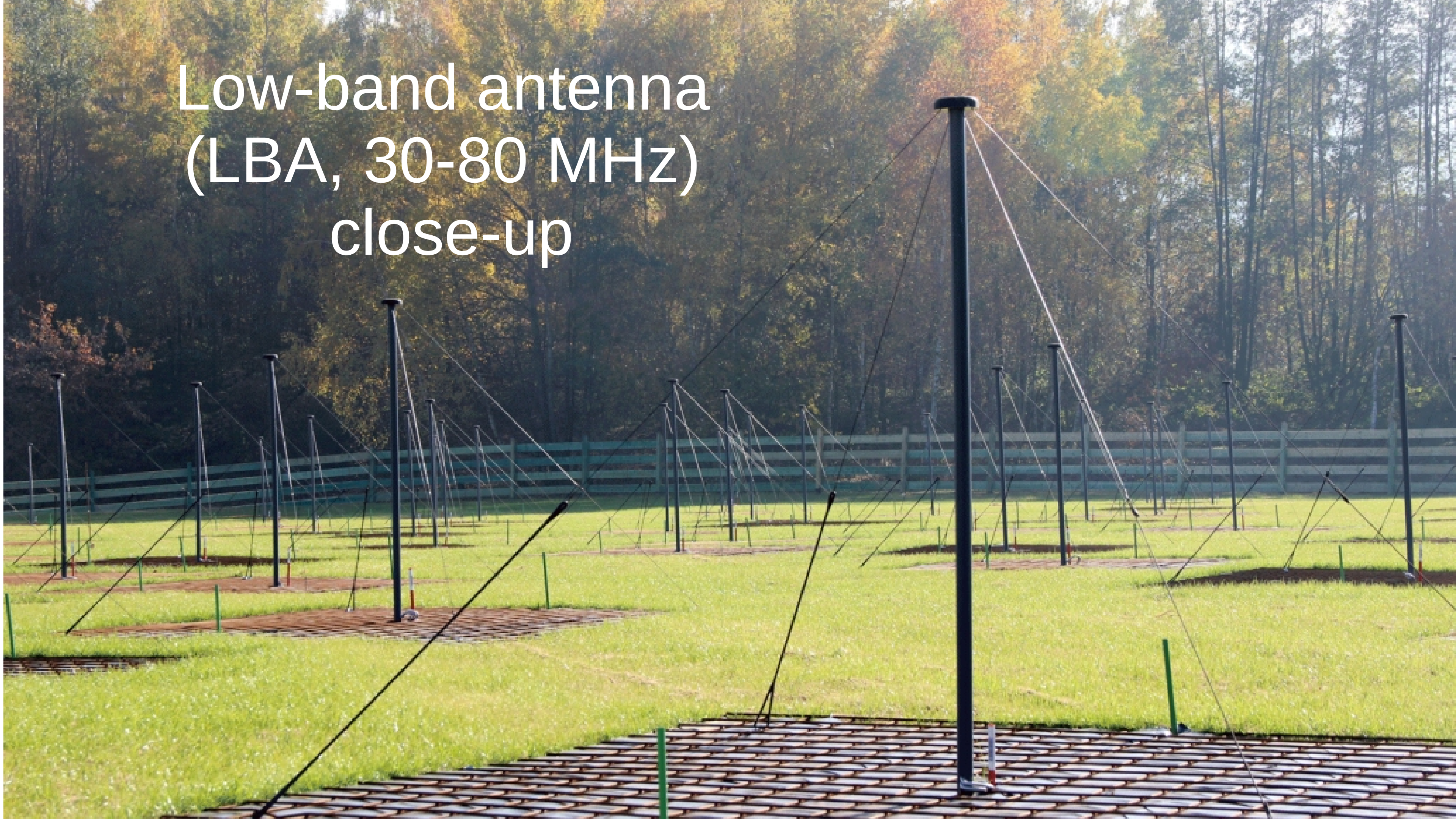
Shower maximum X_{max} varies with primary particle mass
- on average
- in distribution

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



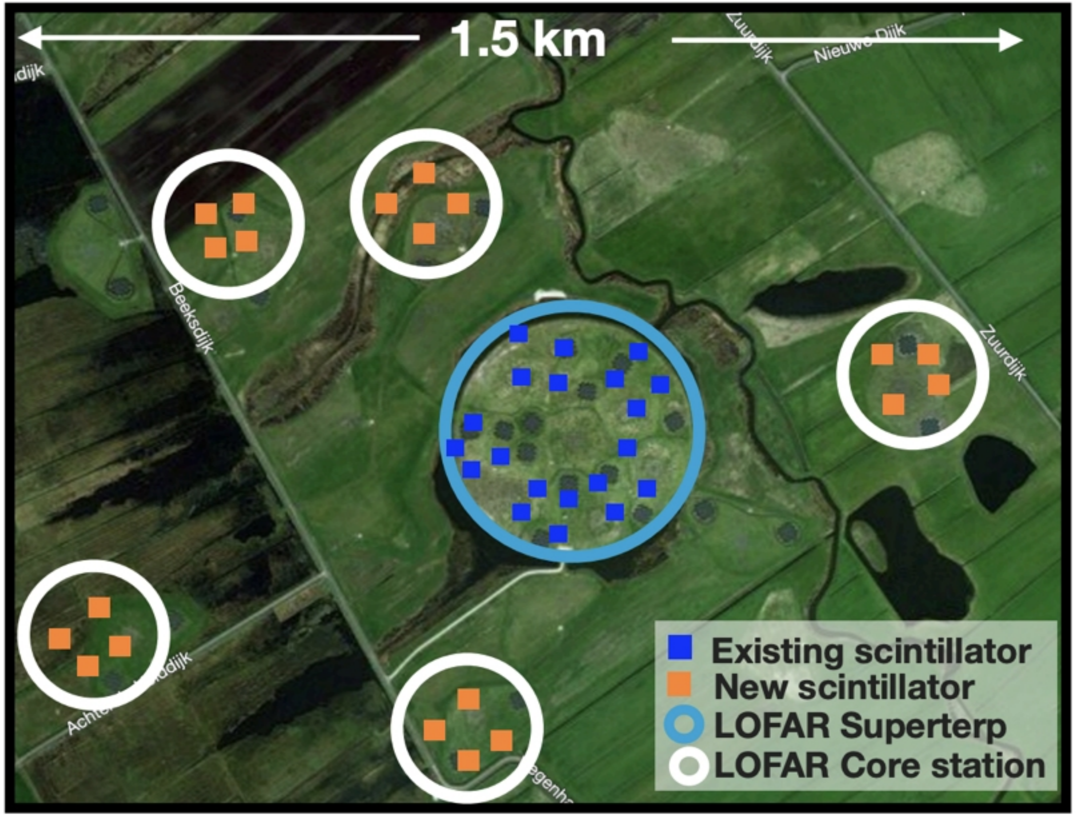



The LOFAR Superterp


Low-band antenna
(LBA, 30-80 MHz)
close-up

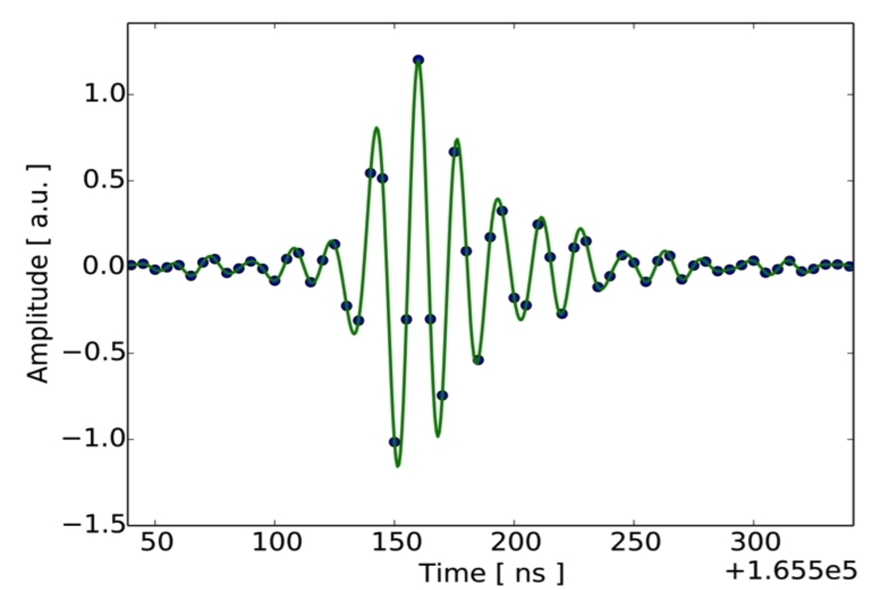
Trigger using particle detector array (LORA)

Figs by K. Mulrey

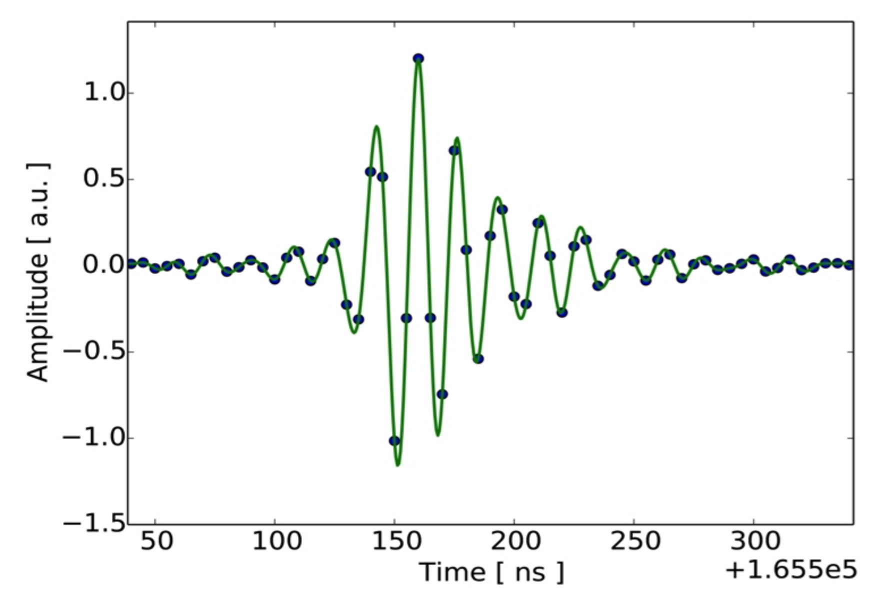


Used to trigger a readout of the transient buffers of each antenna

Pulses in LOFAR antennas



Pulses in LOFAR antennas



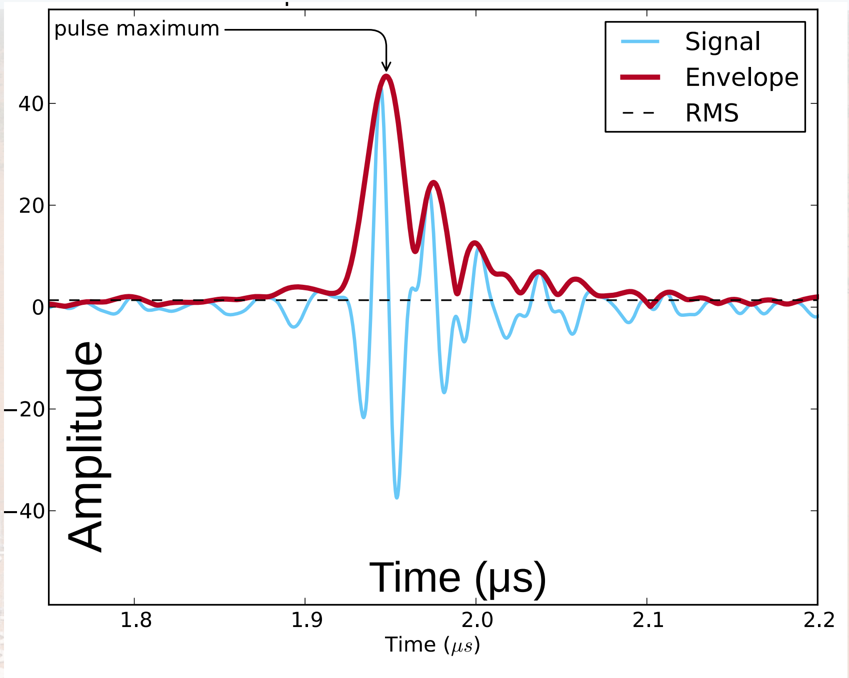
Our raw material:

One pulse in every dipole
(unprocessed time series)

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

Pulse analysis steps

- Measure arrival time using Hilbert envelope
  - Sub-sample accuracy, < 1 ns LOFAR
  - Used for **arrival direction**
  - Contains info on shower development



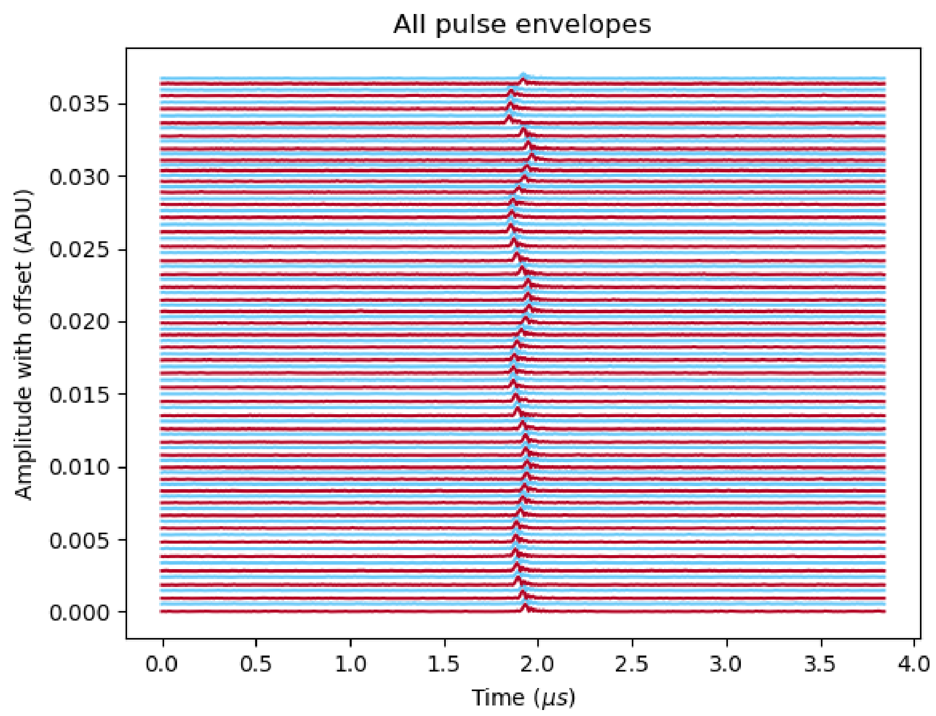
- Measure integrated power (energy fluence)
  - To construct **radio footprint** and compare to simulations

- Polarization signature
- Pulse shape

Pulse analysis steps: arrival time

- Measure arrival time using Hilbert envelope
  - Pulse detections in one LOFAR station

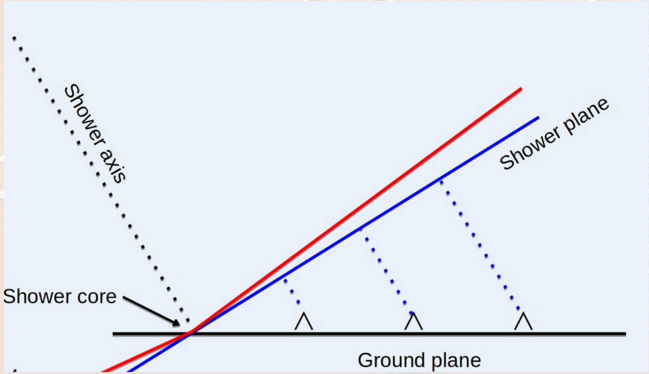
- **Requires**: up-to-date timing calibration per antenna
  - From observatory, ideally
  - From phases of narrow-band RFI (A&A 2016, arXiv:1603.08354)
  - From drone-based calibration signal

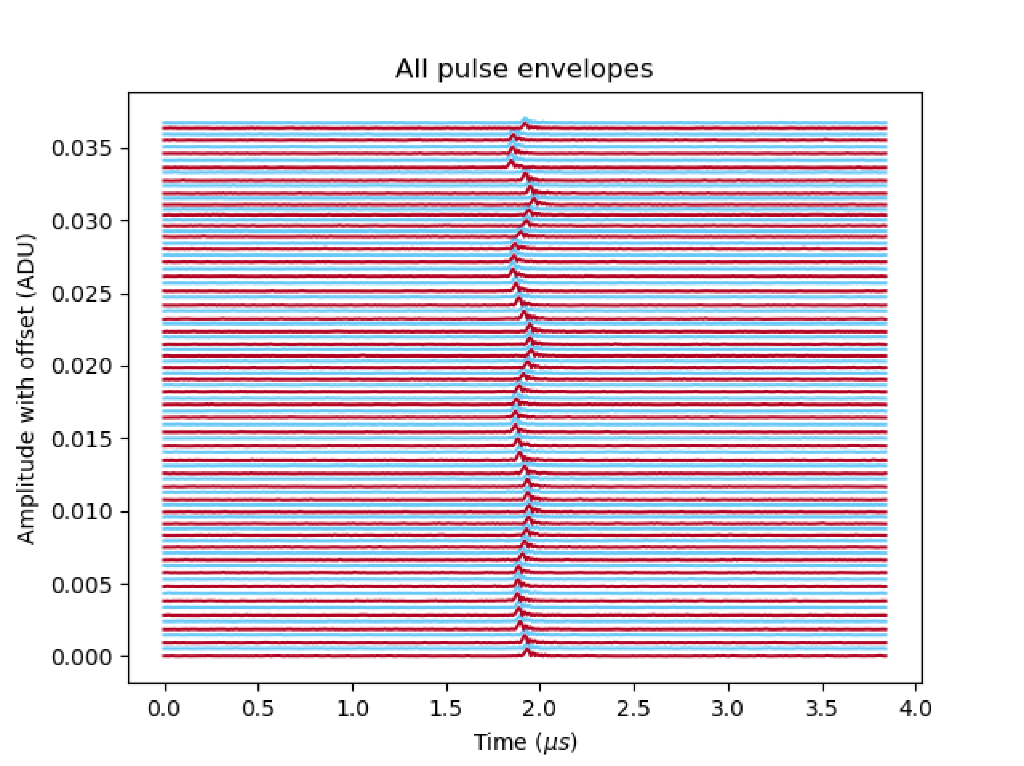


Pulse analysis steps: beamforming (far field)

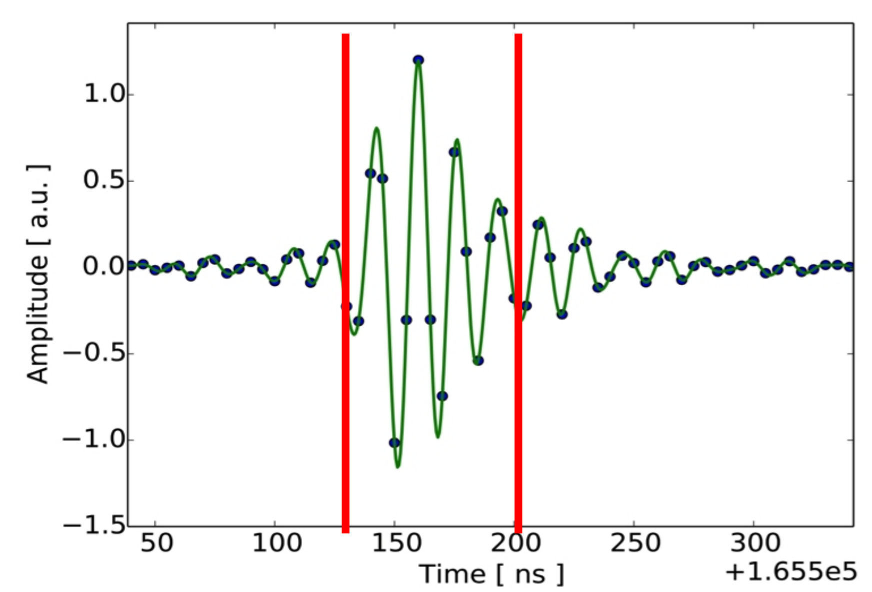
- Beamforming by time-shifting each trace according to geometric delay

- Far-field approximation works well for small stations (~ 30 m)
  - Used to identify pulse location in trace
  - Generally speaking, more complex wavefront shape: **hyperboloid**





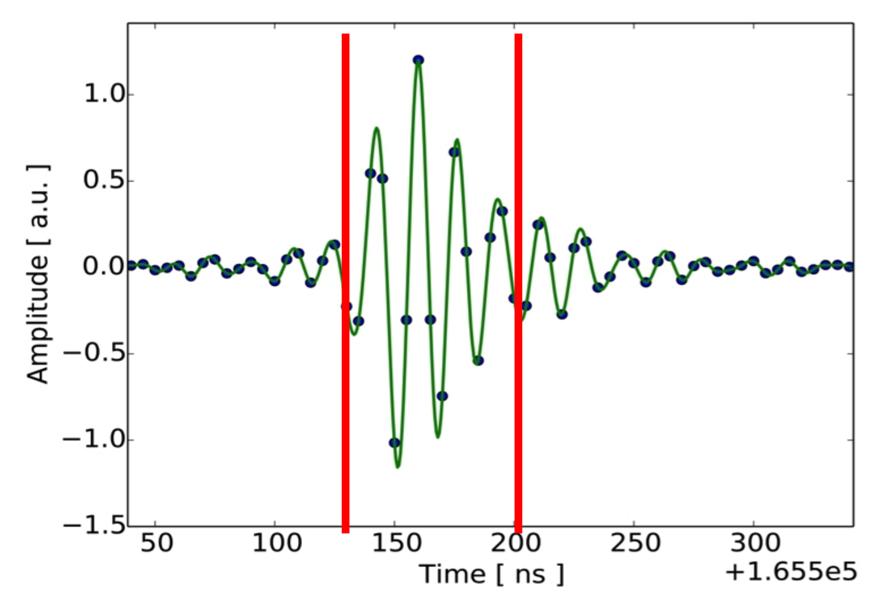
Measuring energy fluence



Integrate ‘power’ in a time window

- Width of time window not too large (noise)

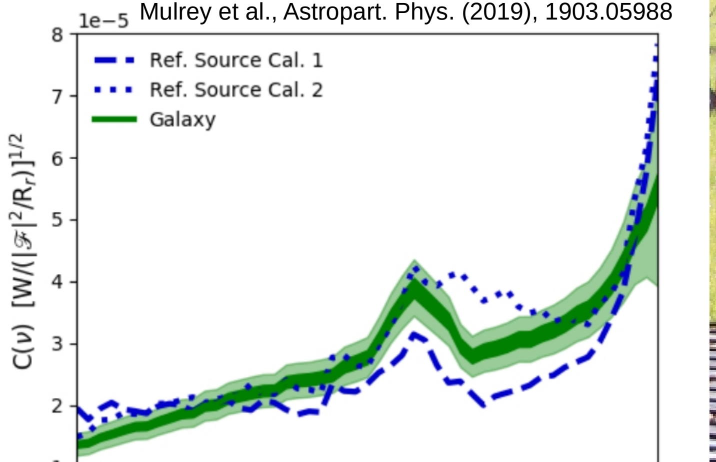
Measuring energy fluence

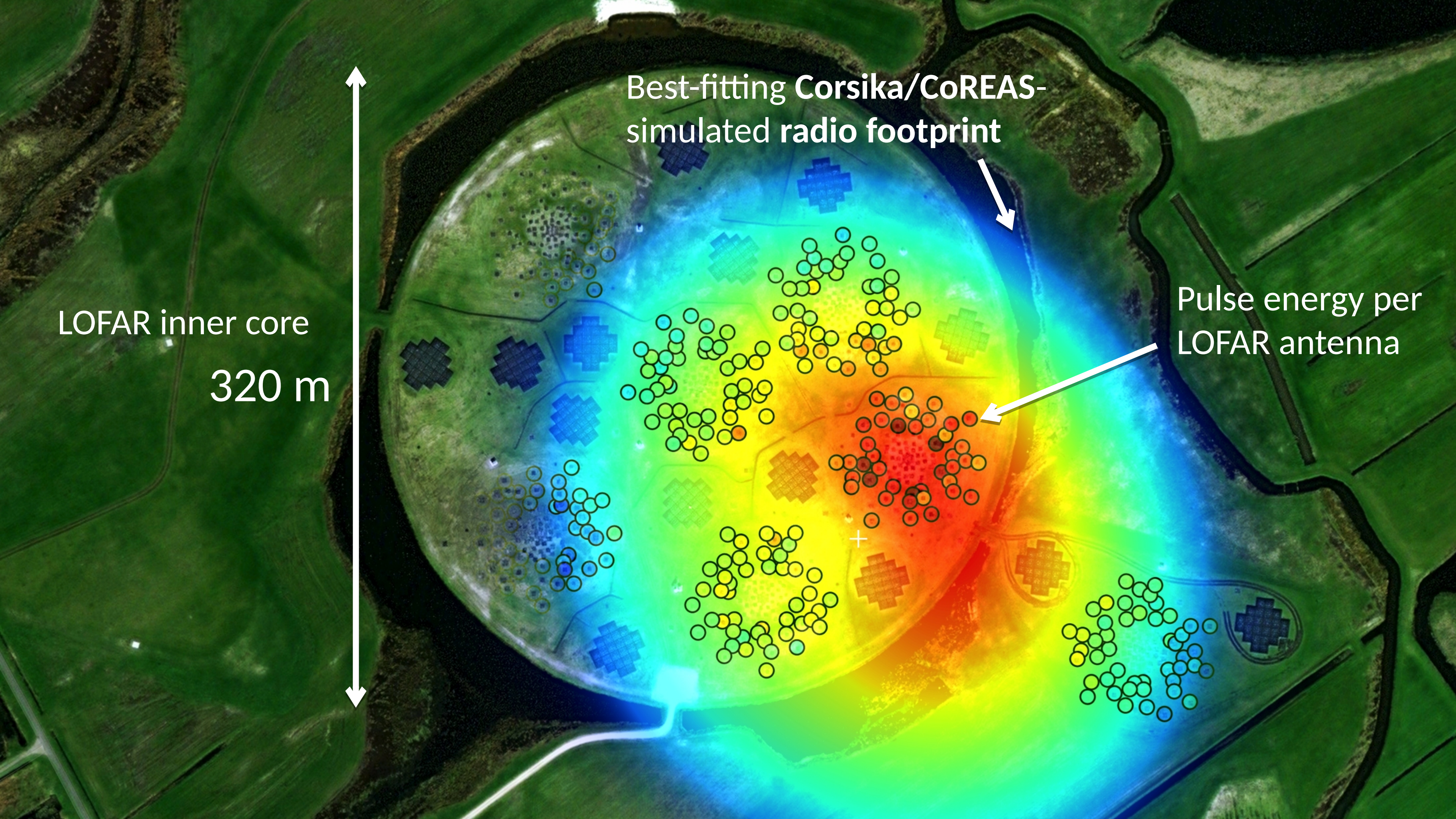


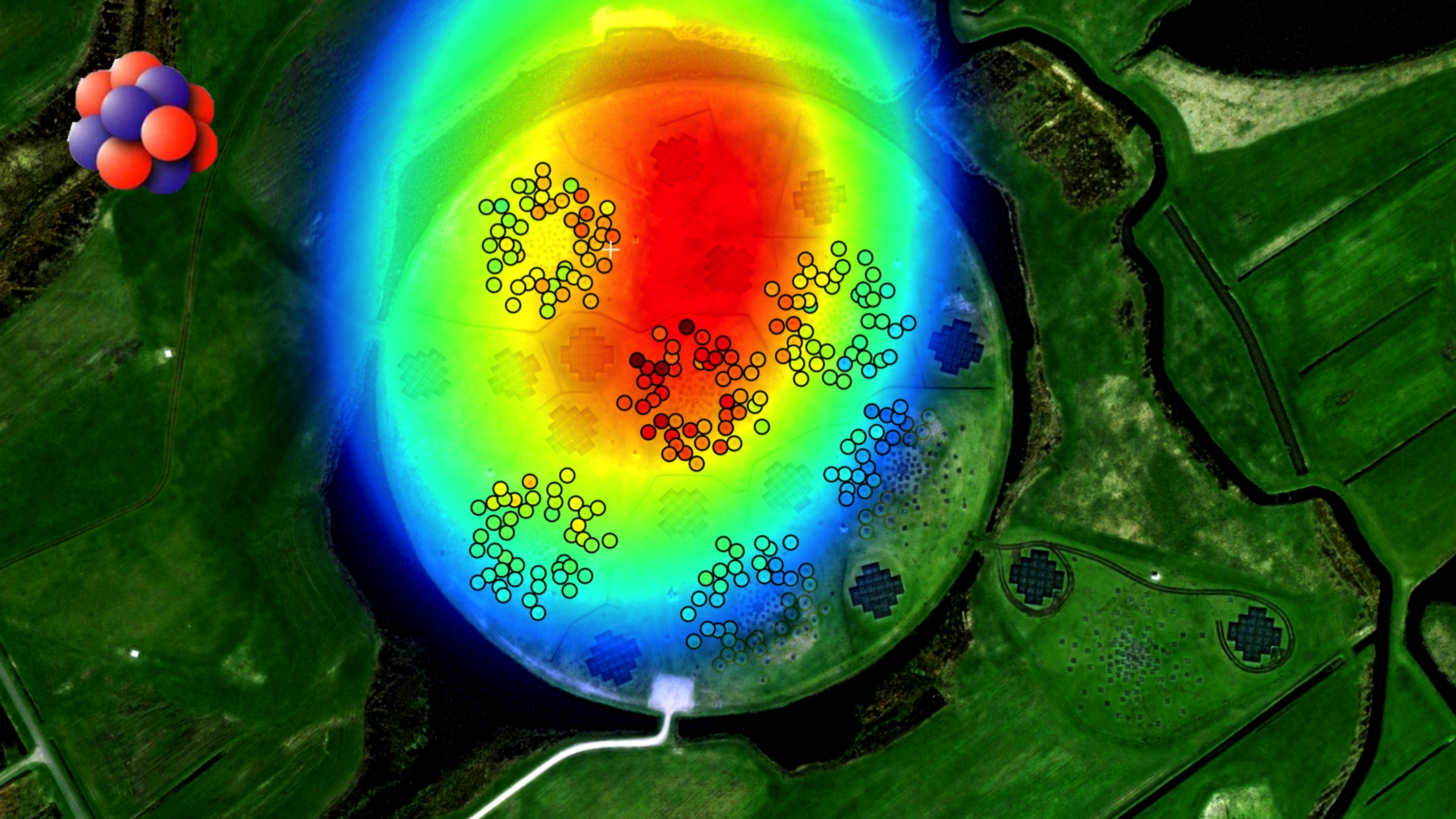
Integrate 'power' in a time window

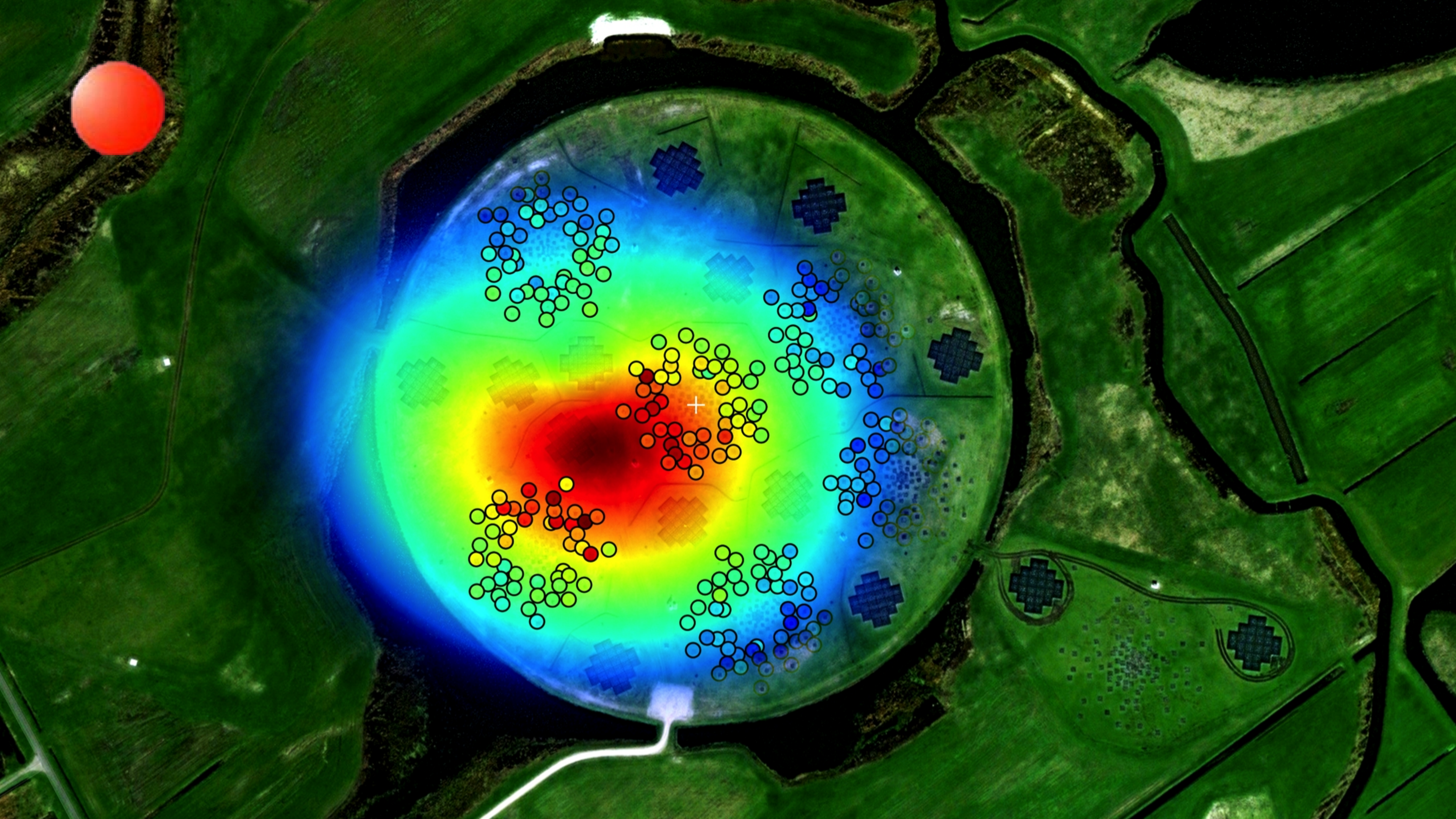
- **Requires**: absolute gain calibration per antenna

Mulrey et al., Astropart. Phys. (2019), 1903.05988




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

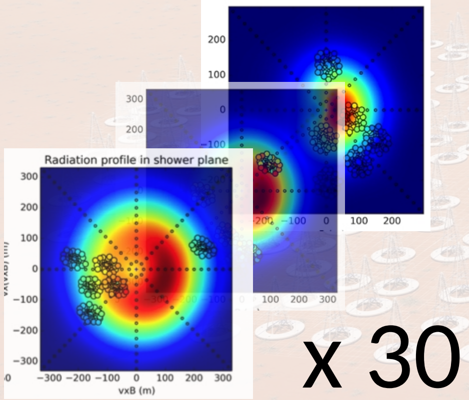


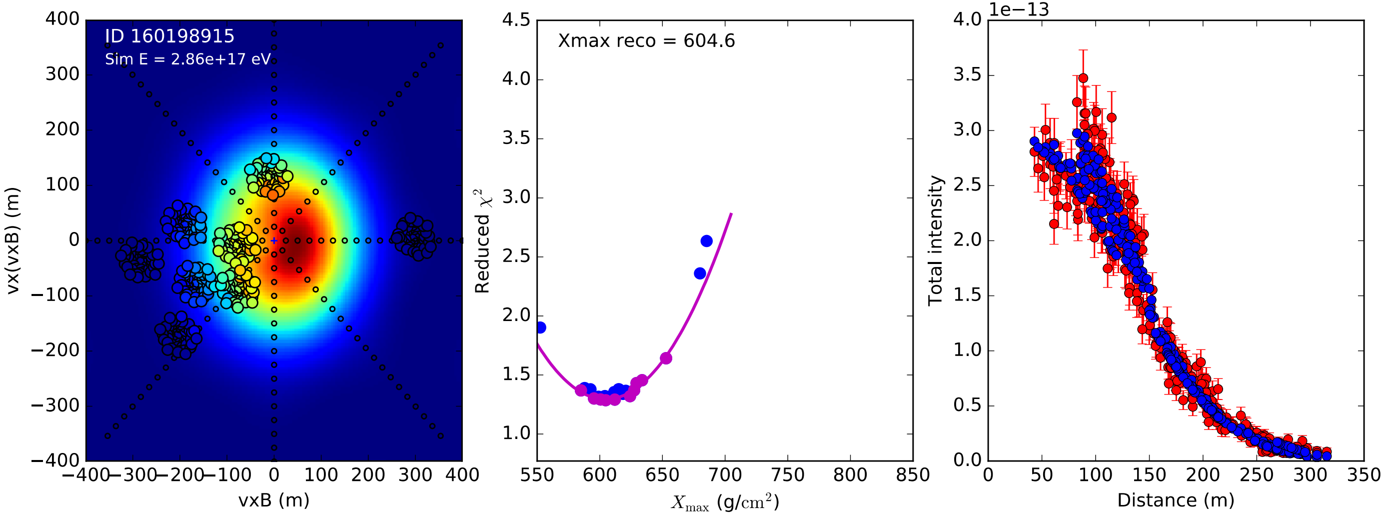


Matching simulated footprints to data

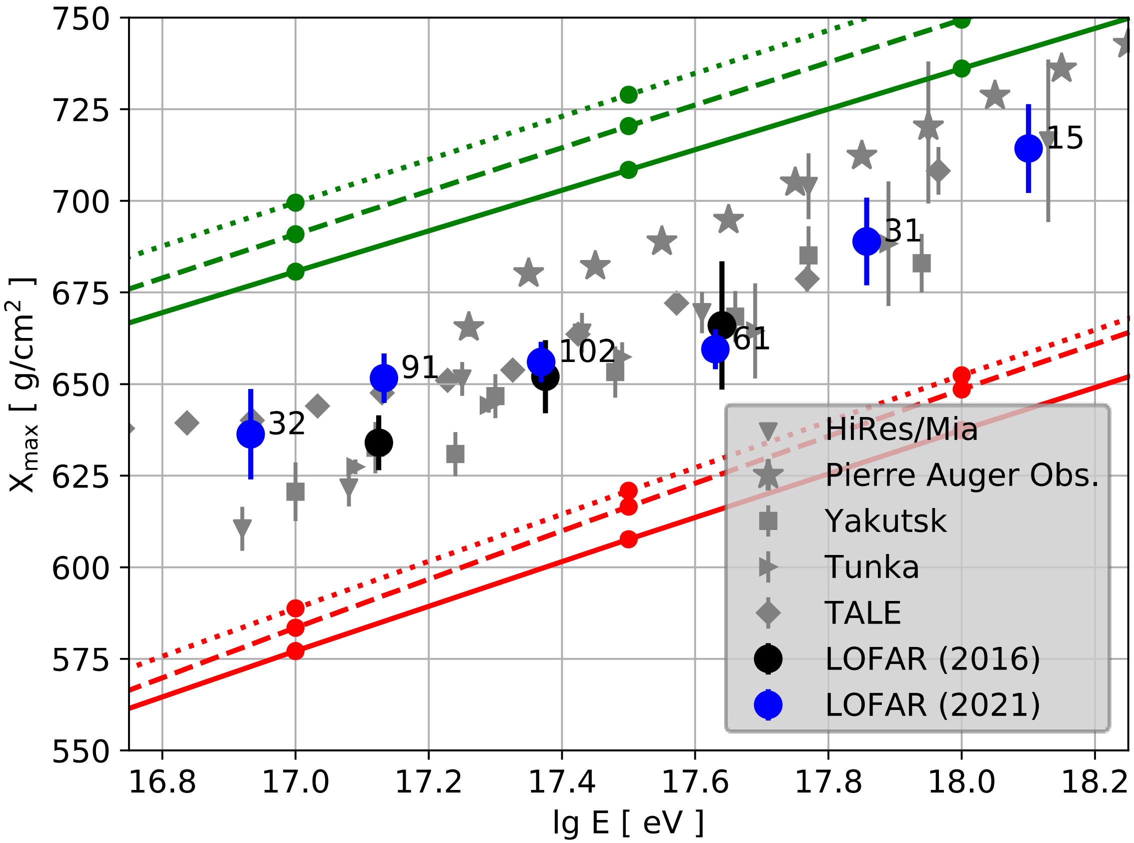
- Simulate about 30 showers per measured shower
- Fit them to data, observe X_{max} of best fit

- Resolution (@LOFAR) about 20 g/cm^2
- Systematic uncertainties < 9 g/cm^2
- In line with state of the art in the field





Result: Average X_{max} versus primary energy

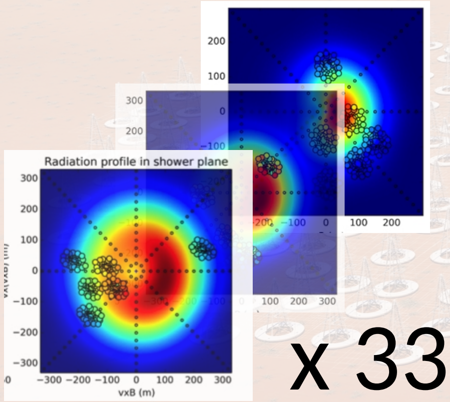


- Green lines: average X_{max} for pure proton composition
- Red lines: average X_{max} for pure iron composition

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

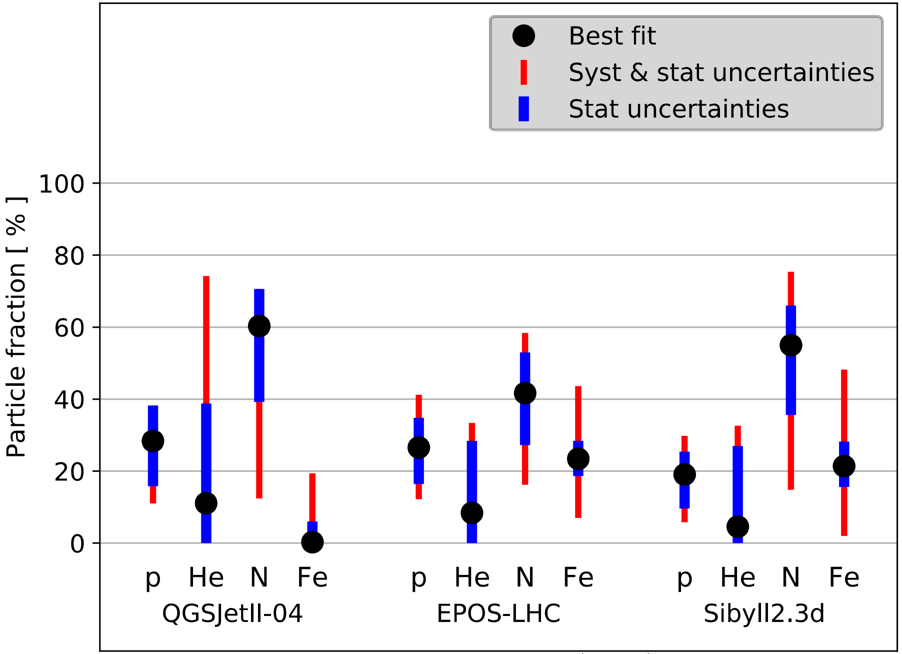
Results on mass composition

- 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



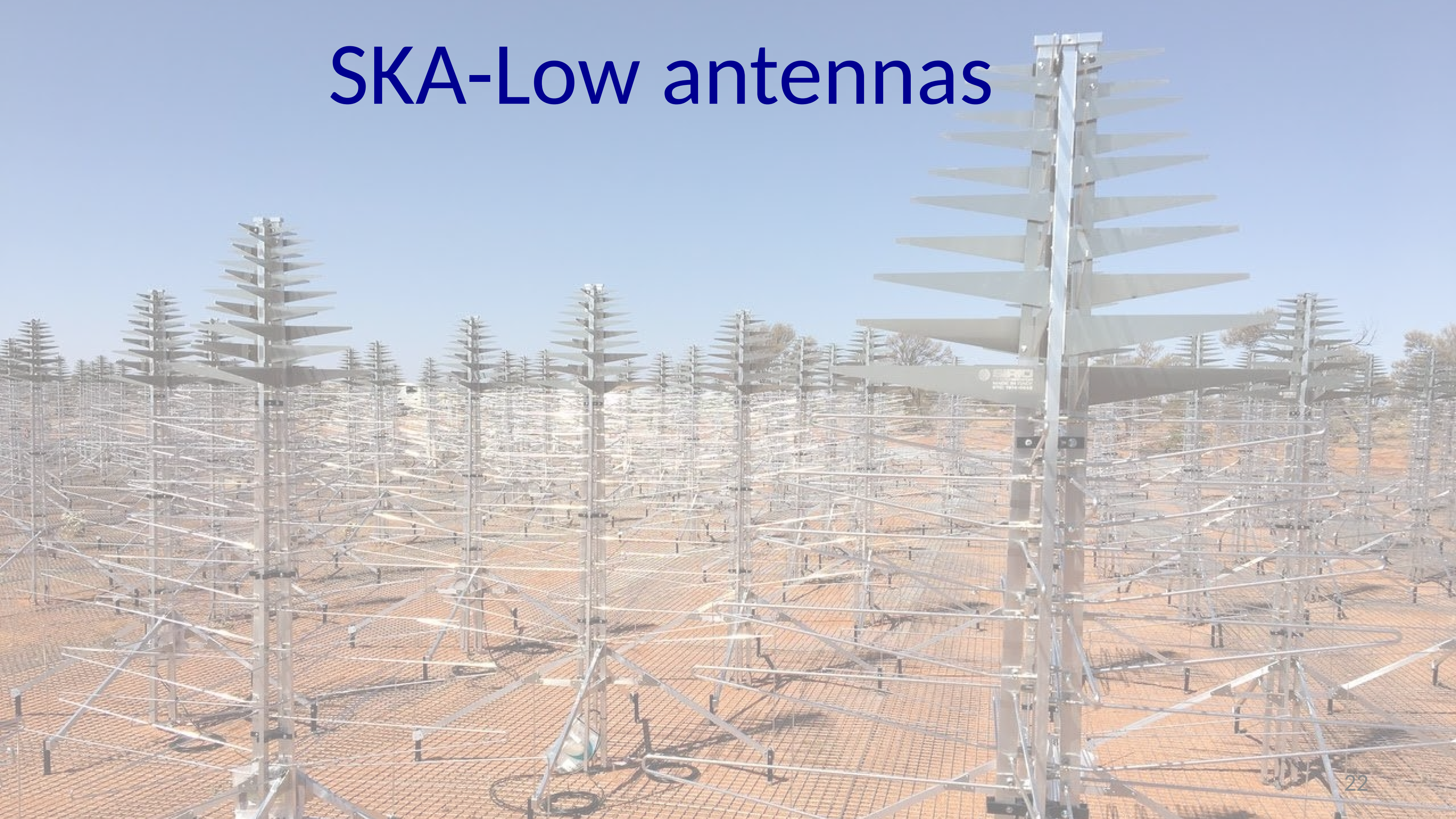
x 334

Main coverage in lg E: **17.39 +/- 0.32**



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

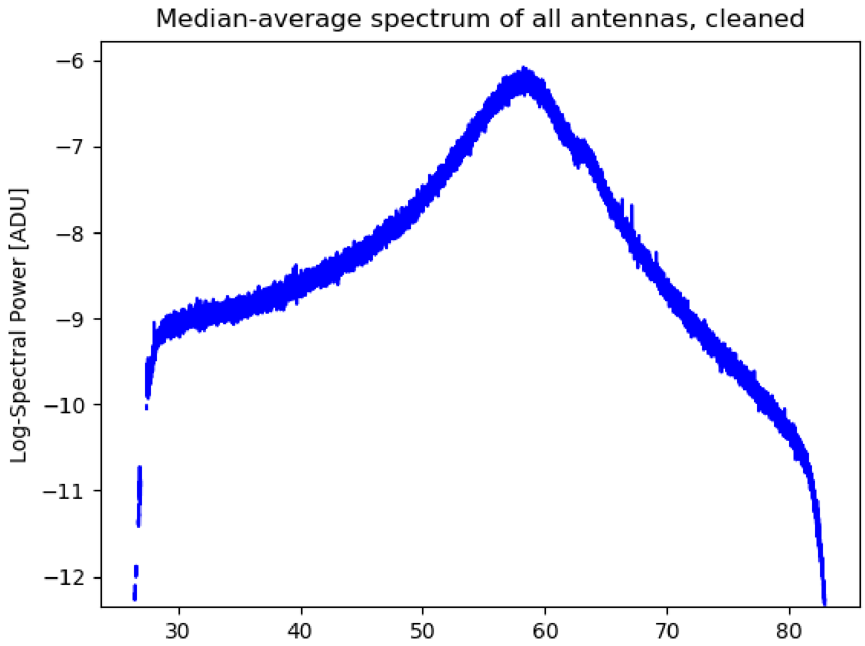
SKA-Low antennas

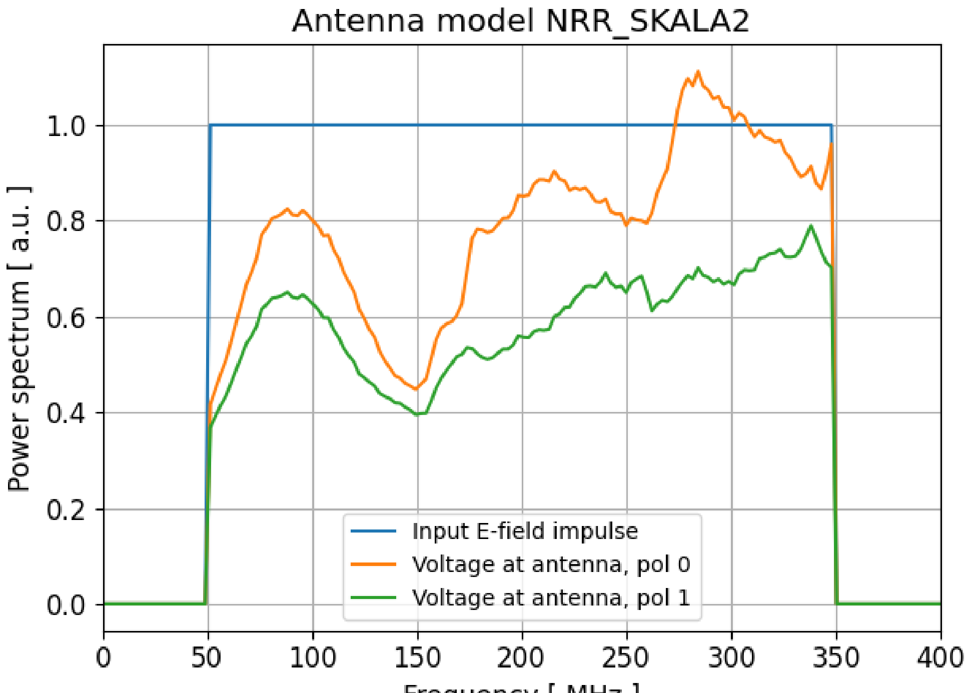


SKA-Low antennas

LOFAR: resonance ~ **58 MHz**
(note log scale!)

SKA: much flatter response
over **300 MHz bandwidth** (lin scale)

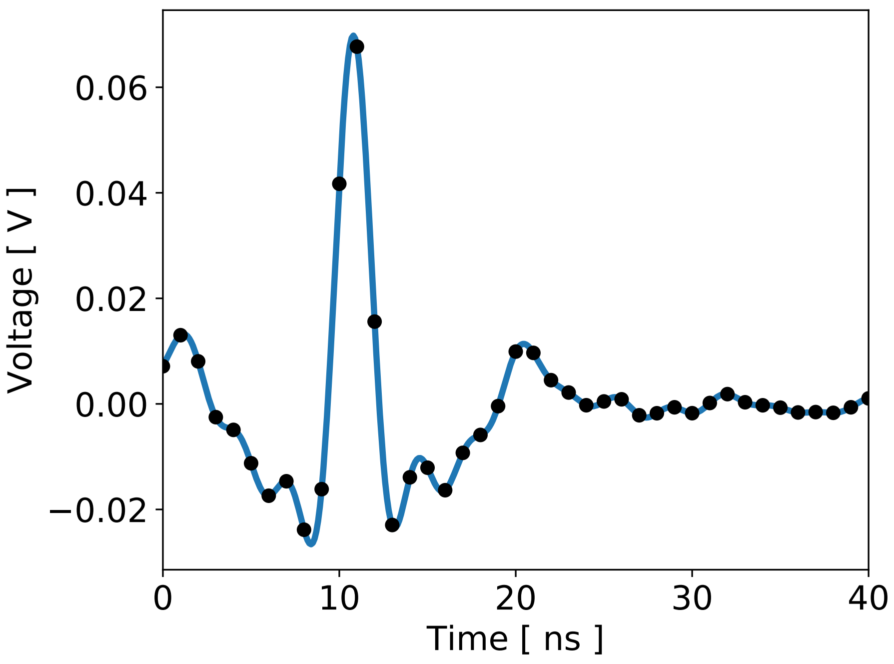




Pulses in SKA-Low antennas

Use raw voltage signals per antenna

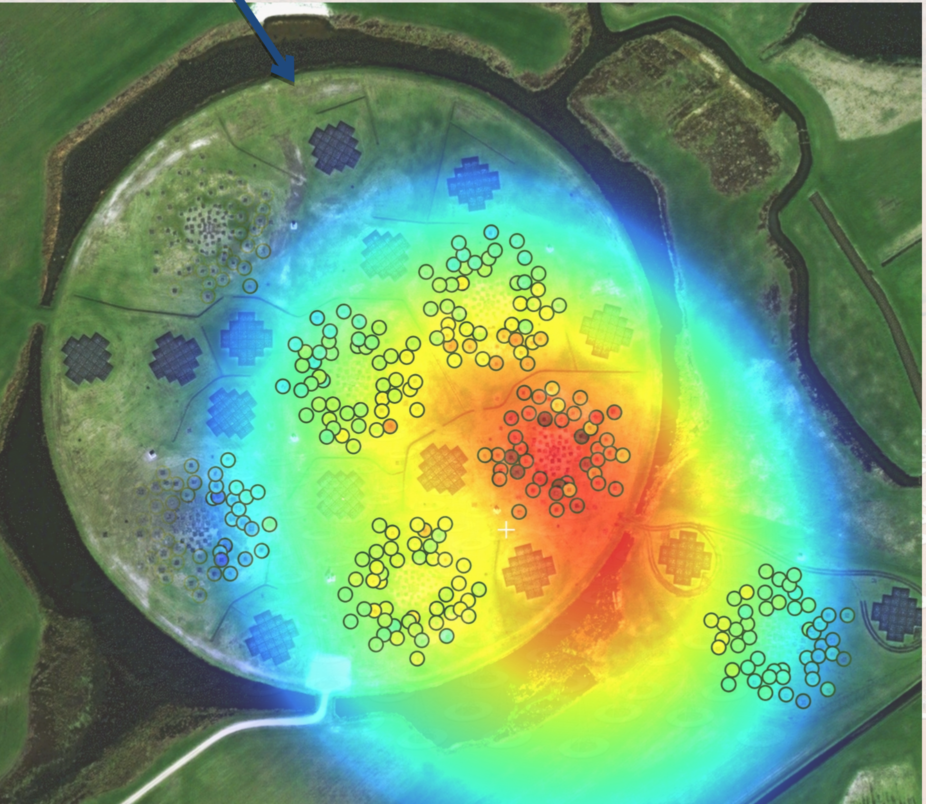
After offline filtering stage (e.g. de-dispersion)

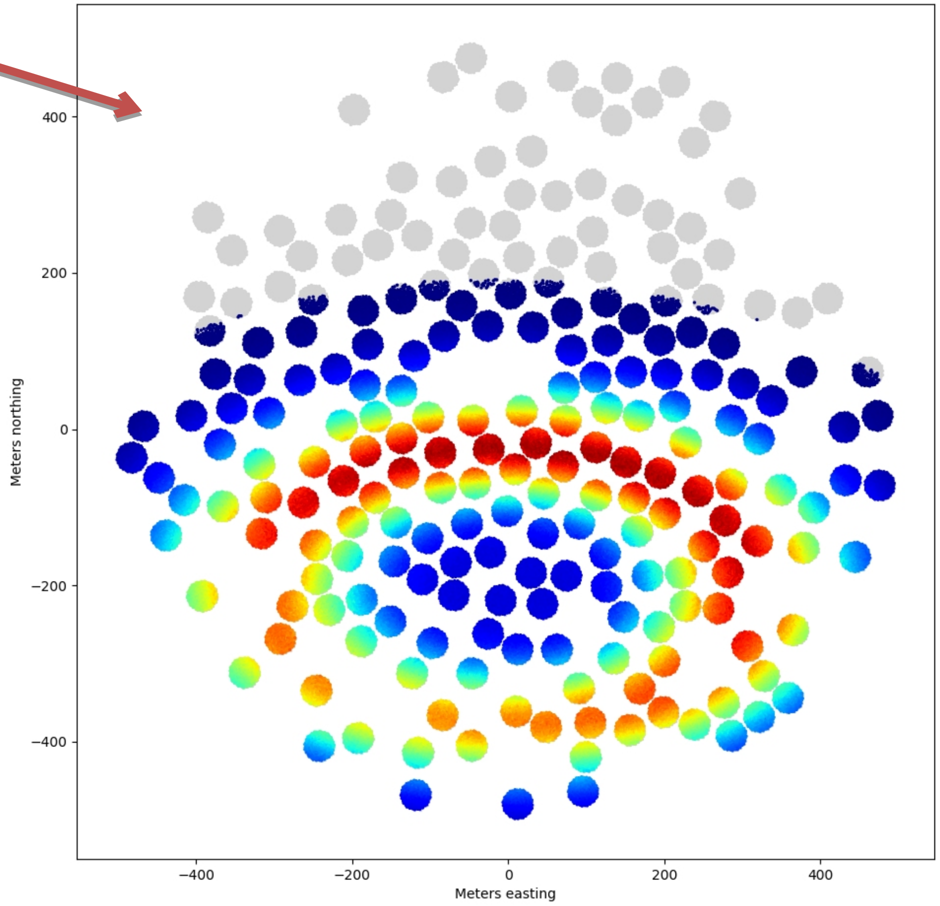


SKA-Low, a really dense array

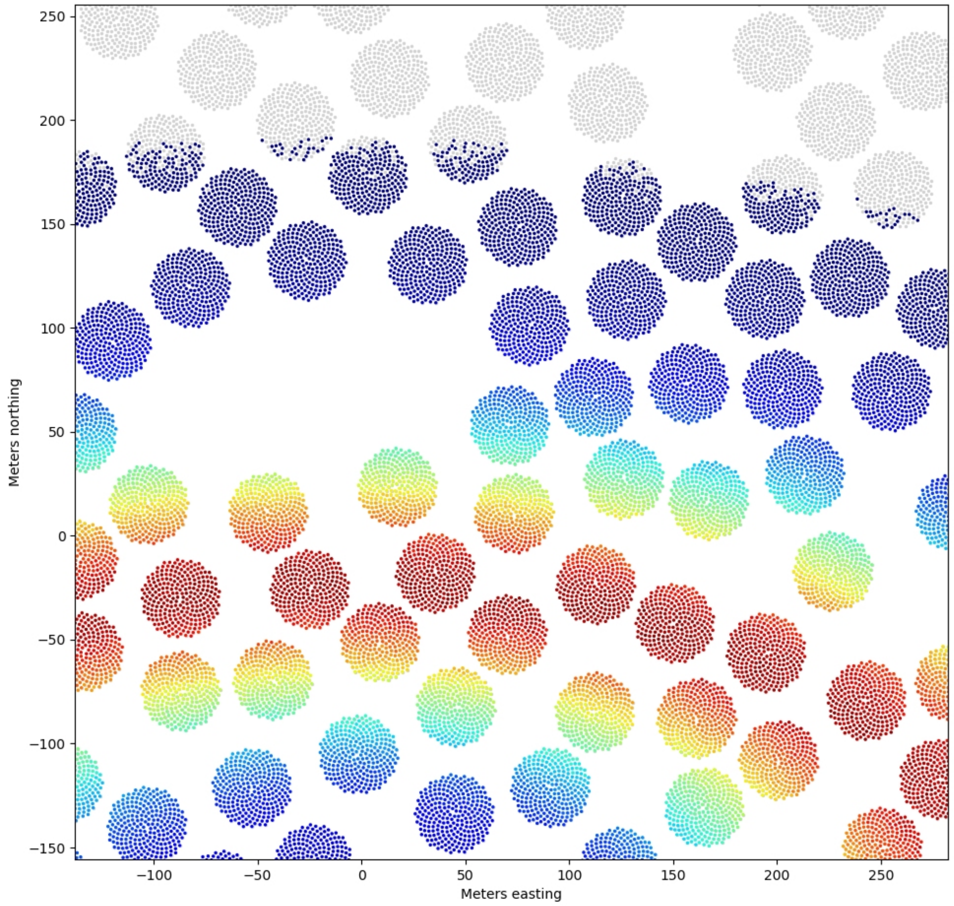
LOFAR

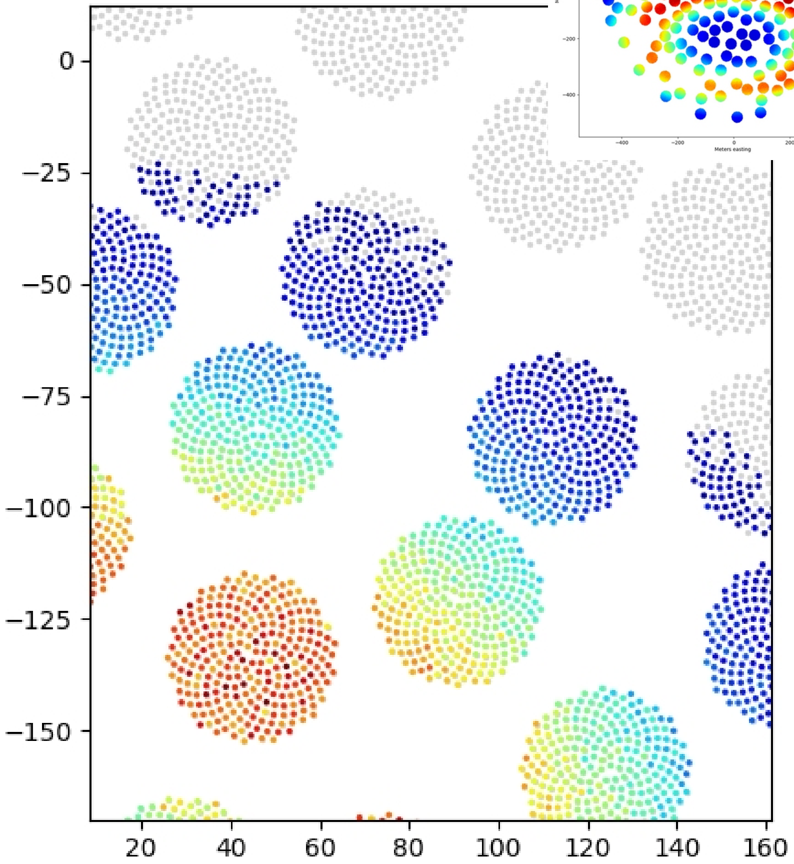
SKA antenna layout

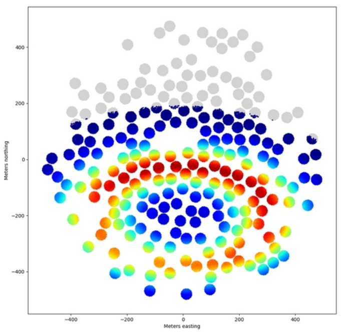




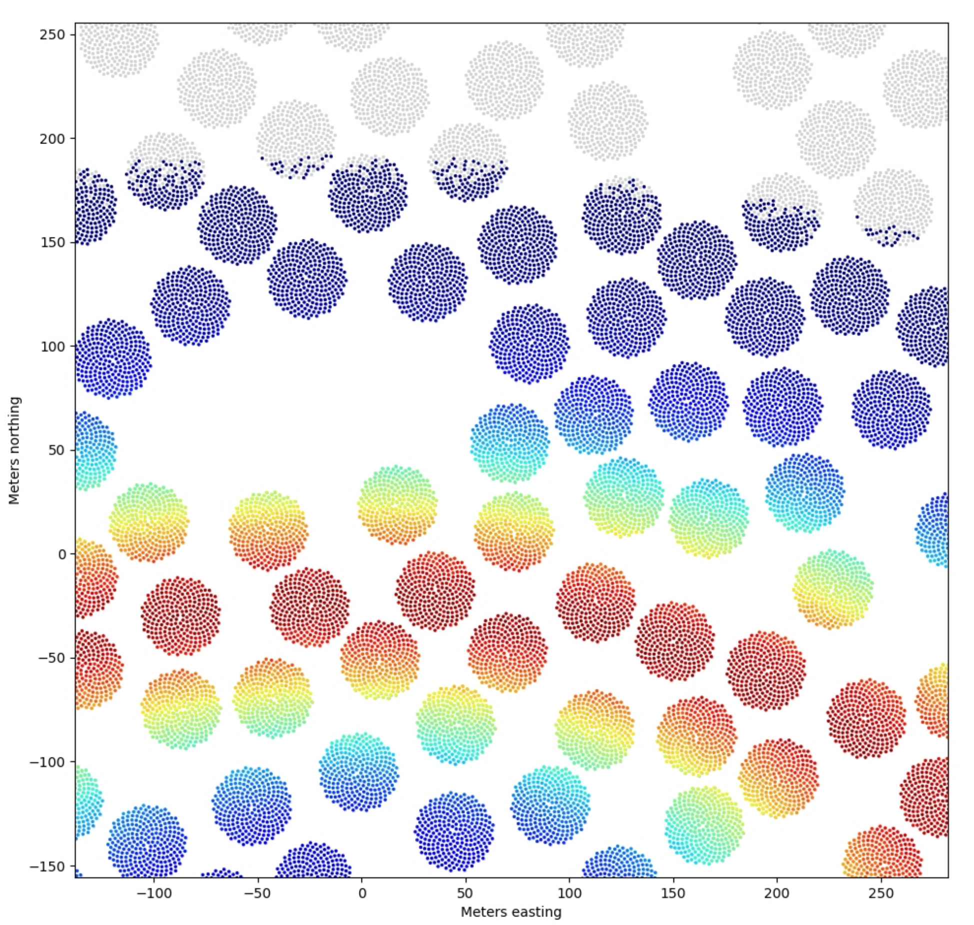
SKA-Low, a really dense array!







SKA-Low, a really dense array!

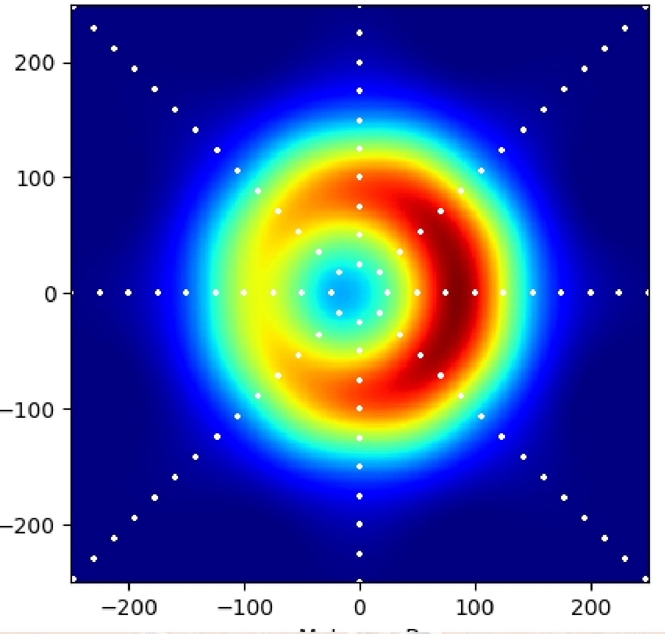


So, simulate 60,000 antennas??
(200 antennas takes 1.5 CPU-day)

Now what?

Interpolation from star-shape polar grid

(**50-350 MHz**, no antenna model)



Simulating 60,000 antennas is intractable

But: signals will not vary much across ~ 2 meters (redundancy)

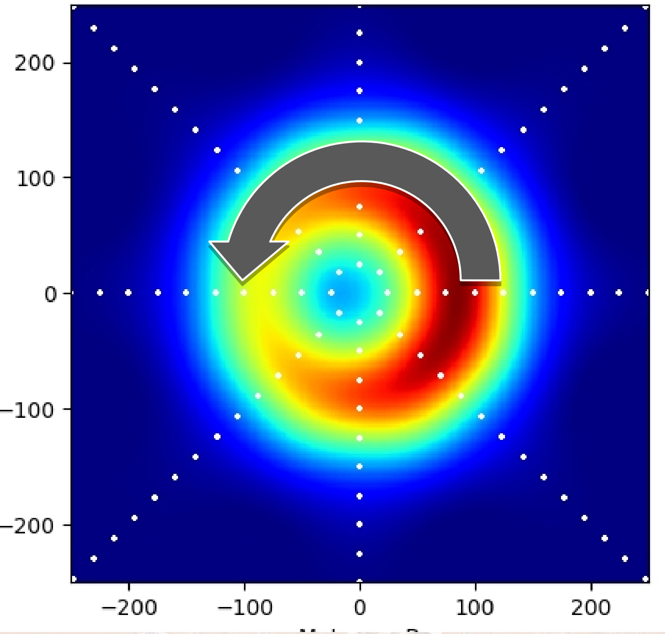
So, an **interpolation** routine would be helpful

Requires **high accuracy**
(in line with measuring with 60,000 antennas)

and **full signal traces**

Interpolation based on Fourier series

(**50-350 MHz**, no antenna model)



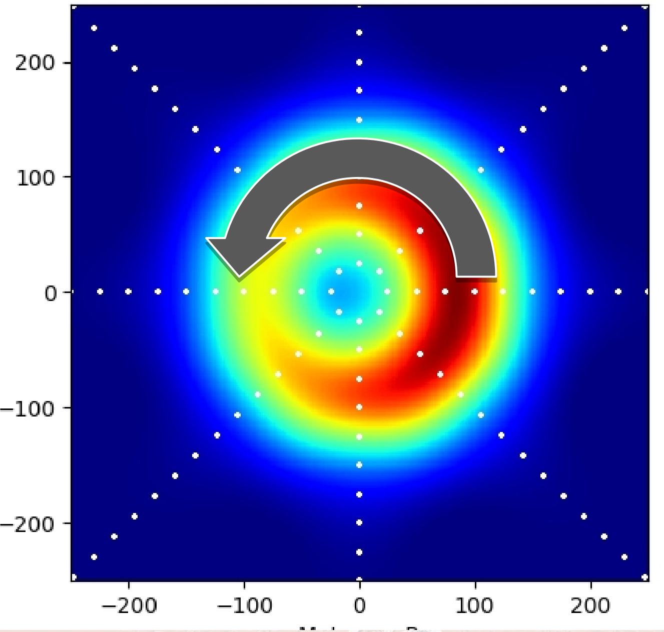
Idea:

- At each radial position, use Fourier series (FFT) to describe the angular variations
  - To a large extent: ~ cos(phi)
  - If purely sum of geomagnetic and charge excess, ampli f(x, y) ~ 1 + C cos(phi), C = charge excess fraction
  - Energy: $f^2(x, y) \sim 1 + \frac{1}{2} C^2 + 2C \cos(\phi) + \frac{1}{2} C^2 \cos(2\phi)$

- Express as sum of cos & sin for clarity

Interpolation based on Fourier series

(**50-350 MHz**, no antenna model)



Idea:

- At each radial position, use Fourier series (FFT) to describe the angular variations
  - To a large extent: ~ cos(phi)

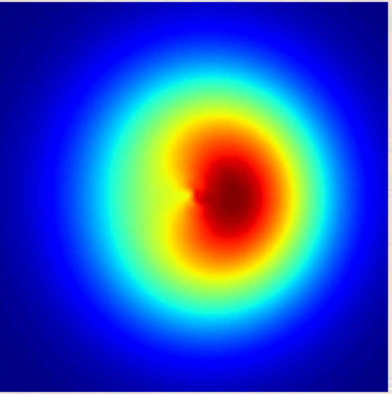
- Interpolate radially ALL the **8** components of the Fourier series
- Polar coordinates on grid, **r** gives Fourier components, evaluate at **phi**

- At each point, you have a sum
  $I(r, \mathrm{phi}) = \mathbf{I_0\,(r)} + \Sigma\, \mathbf{c_k(r)} \cos(k*\mathrm{phi}) + \Sigma\, \mathbf{s_k(r)} \sin(k*\mathrm{phi})$

- Use **cubic splines** in radial direction on the components, i.e. $\mathbf{I_0(r)}$, $\mathbf{c_k(r)}$, and $\mathbf{s_k(r)}$.

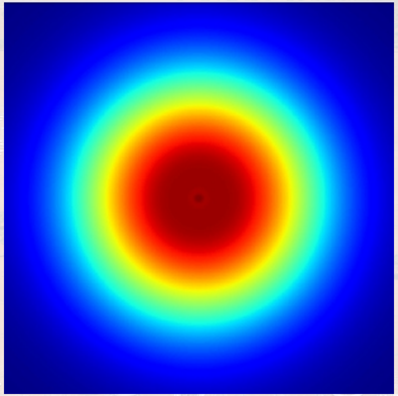
Decomposition in angular Fourier modes

CR Footprint



=

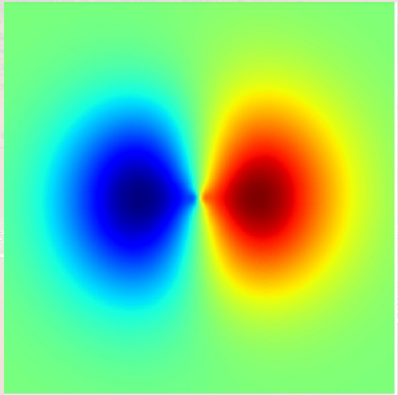
(100 %)



“monopole”

\+

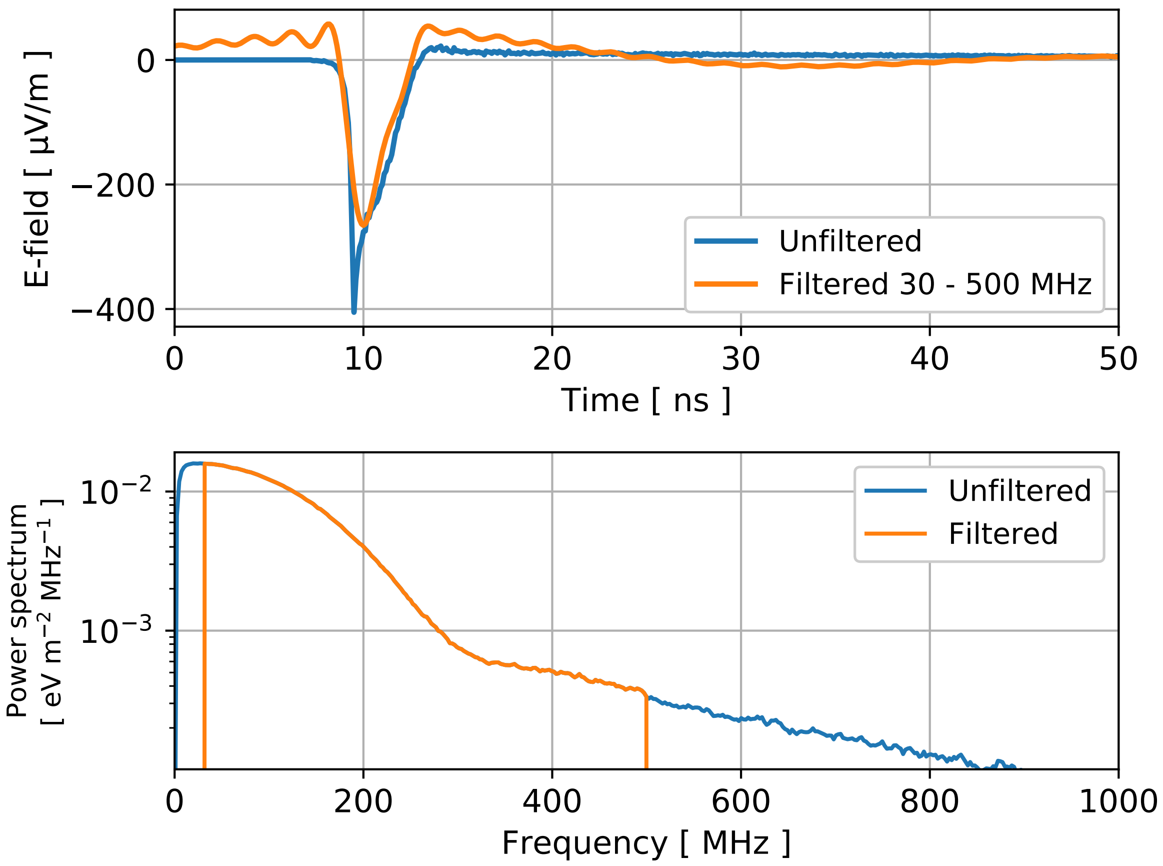
~ 20 %



“dipole”

\+ Higher order terms ~ 2 %

Interpolating full traces: Amplitude spectra

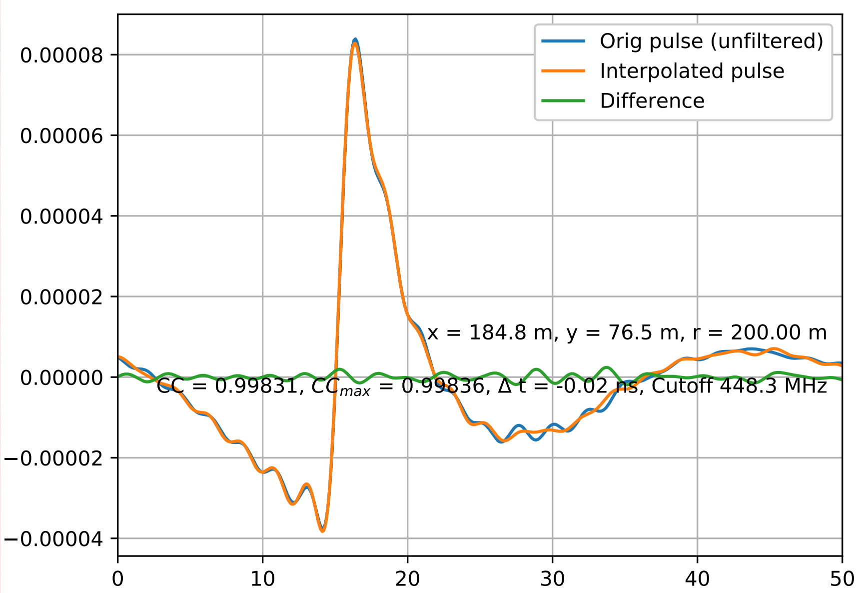


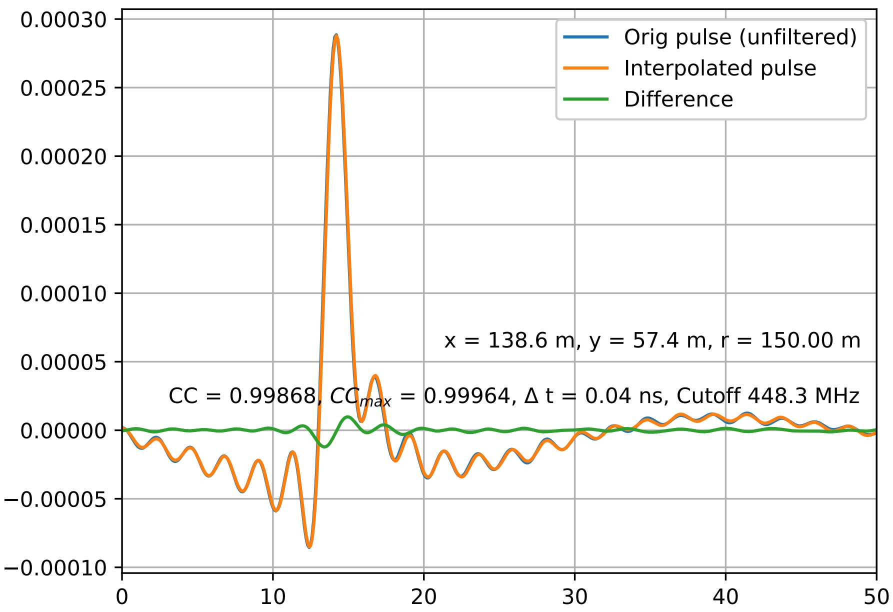
Each single-valued function at an antenna location can be passed into the interpolator (!)
For example:

- Arrival time
- Amplitude at frequency **f**

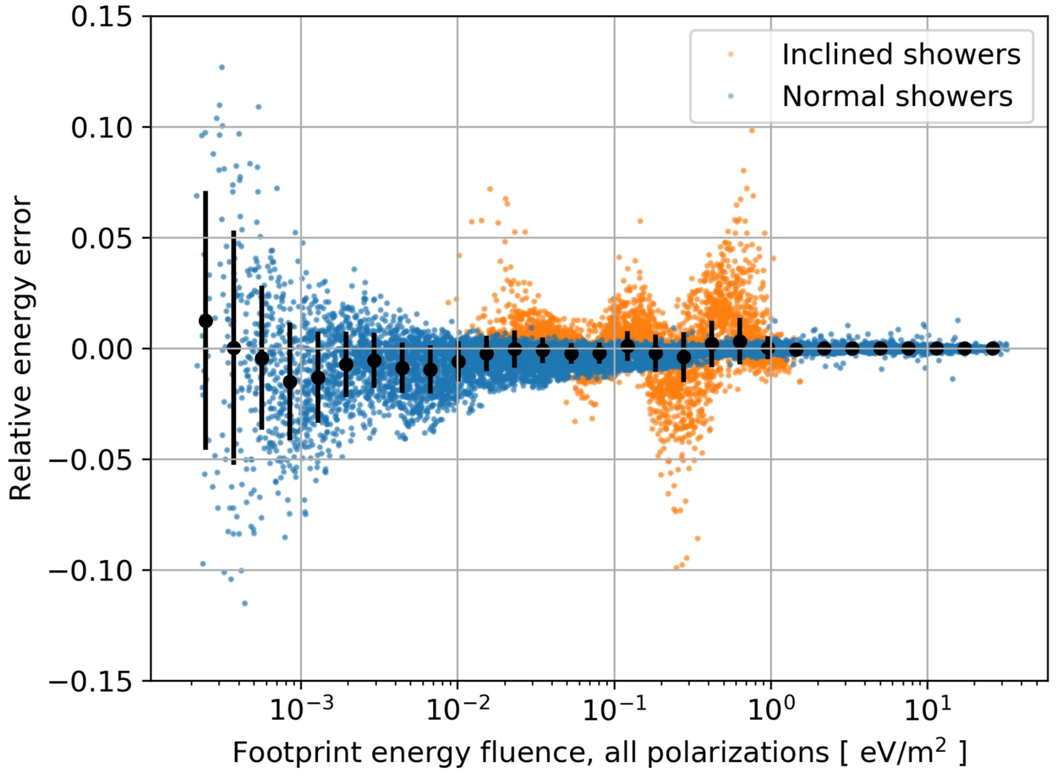
Performance results: pulse traces

30 to 500 MHz;
differences hard to see





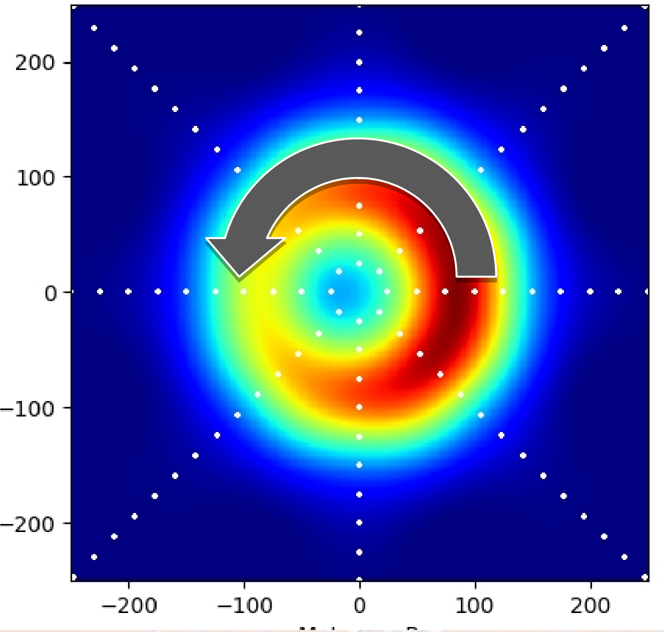
Performance results: fluence accuracy



- 30 to 500 MHz
- Accuracy better than 1 %, < 0.1 % for strong pulses
- Inclined showers had sub-optimal simulated antenna coverage
- When accuracy degrades, thinning artifacts etc become important
- “SKA-worthy” accuracy

Interpolation method

(**50-350 MHz**, no antenna model)



- Paper:
  Corstanje et al., JINST 18 P09005, 2023
  arXiv: 2306.13514

- Code:
  github.com/nu-radio/cr-pulse-interpolator

- Simulate 208 antennas, interpolate to ~ 60,000 (takes ~ 3 hours)

What makes SKA-Low unique for CR measurements?

- Very high antenna density, found nowhere else

  - e.g. Auger, GRAND etc. focus on highest energies, need very large area: antenna spacing ~ 50 – 200 m

- Wider frequency band than LOFAR, Auger/AERA

- Measuring air showers at the highest level of detail
  - Energy range 10^{16} to 10^{18} eV
  - More info on longitudinal distribution than just Xmax
  - Better constraints on proton fraction, mass composition
  - Reveals differences between hadronic interaction models at energies beyond LHC

The SKA layout

- The SKA antenna layout with particle detectors
- Placed quasi-randomly alongside antenna stations, respecting a 10 m distance to the nearest antenna

arXiv:**2504.16873**
submitted to Phys Rev D

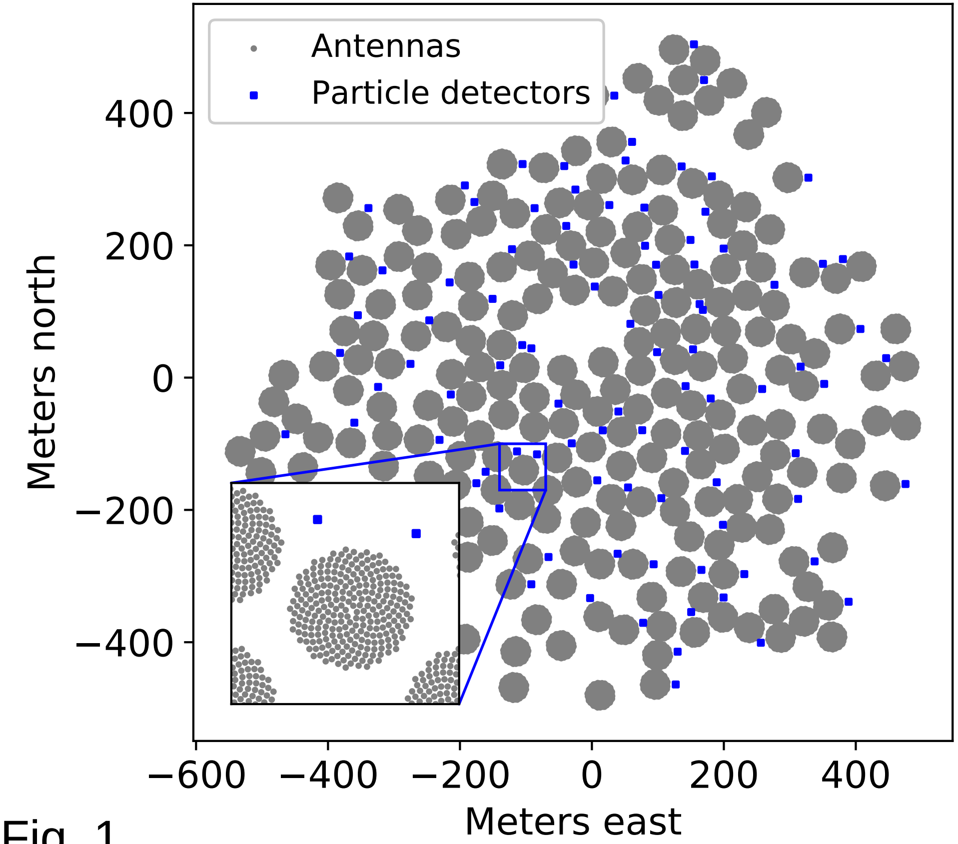


Fig. 1

Monte Carlo setup for SKA reconstruction

- Start from CoREAS traces
- Use pulse interpolation to get ~ 30,000 antenna traces
- Decimate number of antennas if desired (speed)

- Apply SKA Antenna model (NRR-SKALA4)
- De-disperse pulses (unit-gain filter)
- Add Galactic noise (NRR)
- Apply noise-whitening filter
- Measure fluence in **24** ns time window, **5 sigma** threshold

- Get fluence uncertainty from formula found using noise-Monte Carlo
  - No noise trials needed in simulated measurement
  - Still **memory intensive** with up to 30,000 antennas

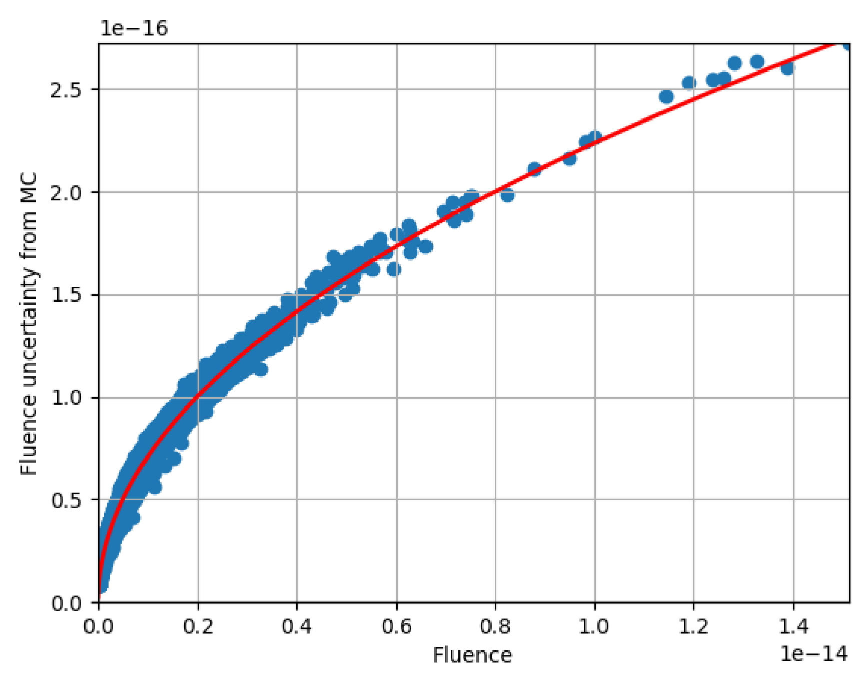
Fluence uncertainty versus (real) fluence

- Get fluence uncertainty from formula found using noise Monte Carlo
  - Determine fluence on simulated positions 1000 times with different noise realizations
  - For 30 showers
  - For 5 different energy levels to see different pulse shapes at various fluence levels etc

  - Formula: uncertainty = **sqrt(A * fluence + B)**

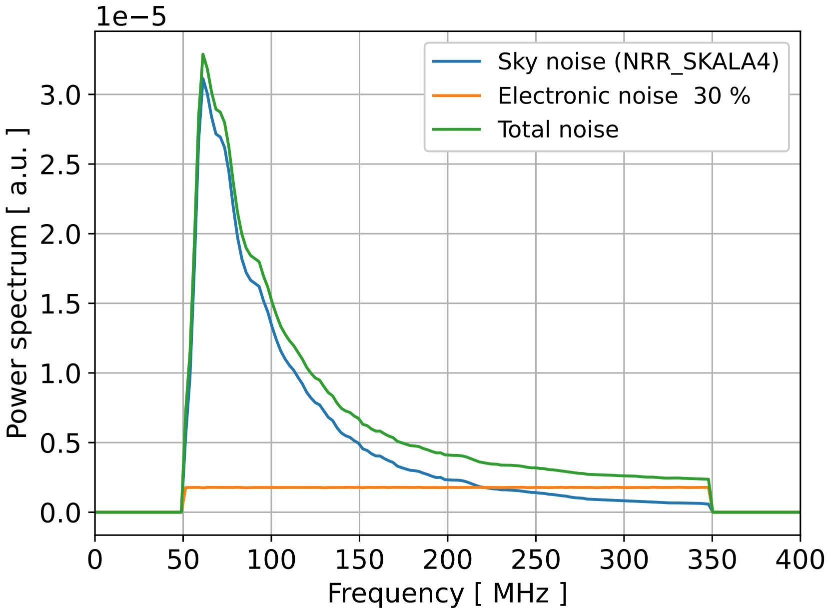
  - Gaussian uncorrelated noise:
    A = 4 sigma^2
    B = 2 N_s sigma^4

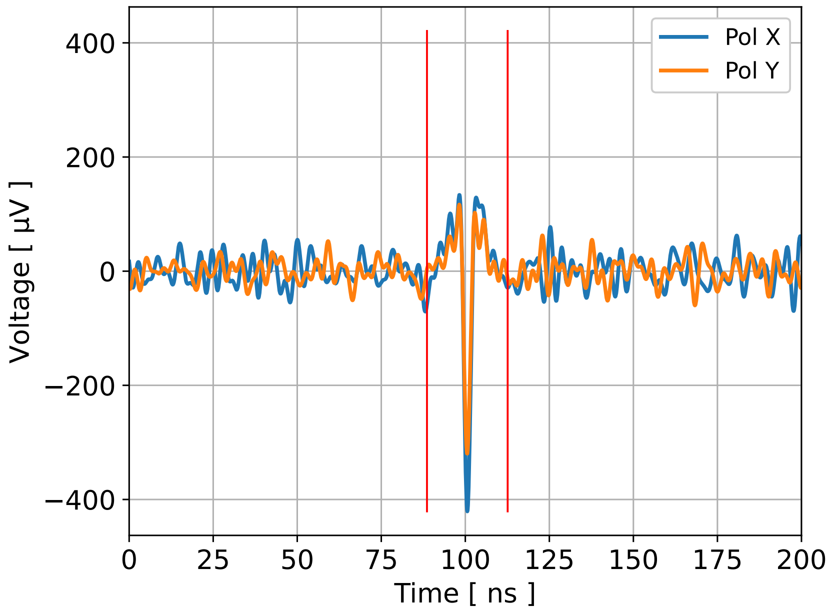
    N_s = number of samples in window
    sigma = stddev of noise



Noise spectrum and example time trace

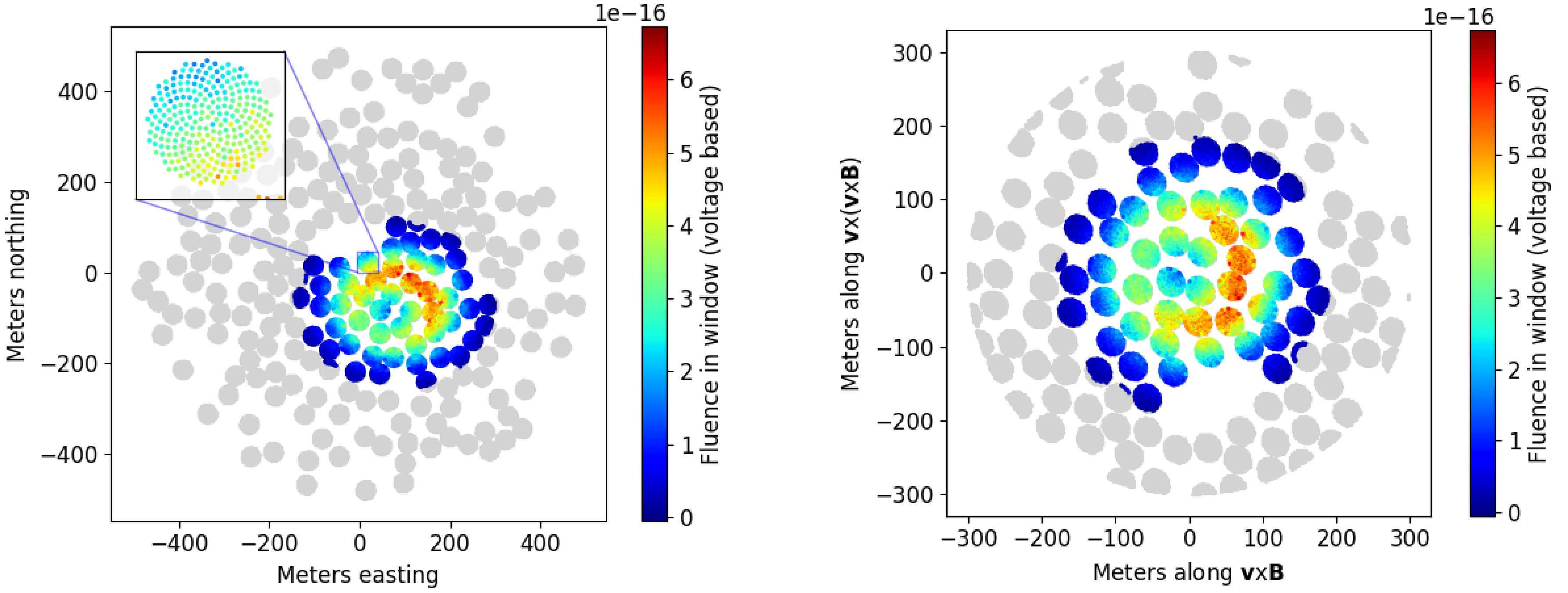
- Noise spectrum from the Galaxy, plus flat-spectrum thermal noise at 30% of Galactic noise energy
- Time trace of a pulse, after phase-compensation filter (hence symmetric)





Example footprint on ground and in shower plane

- Footprint of a zen 30 degree air shower

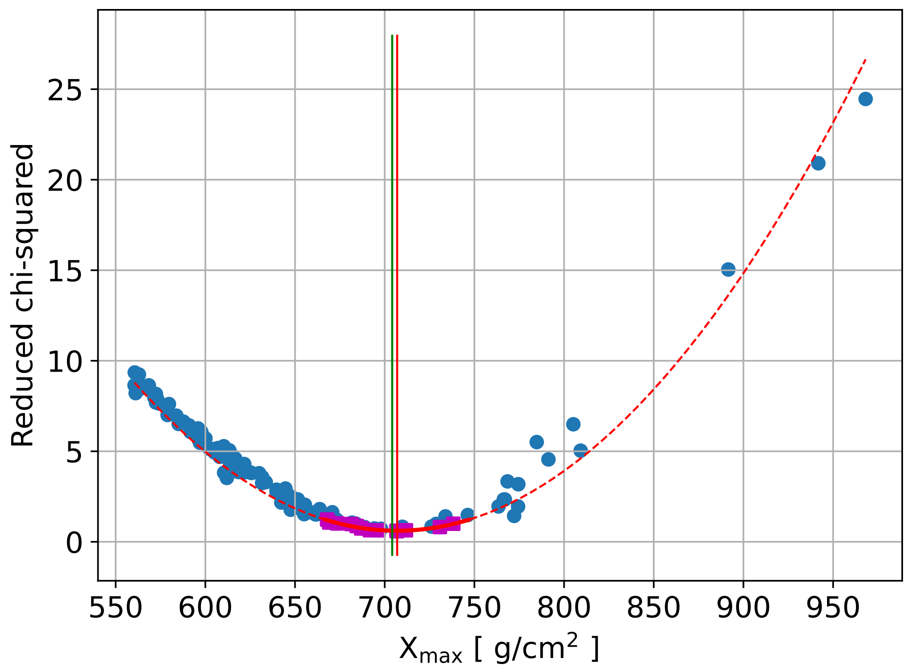


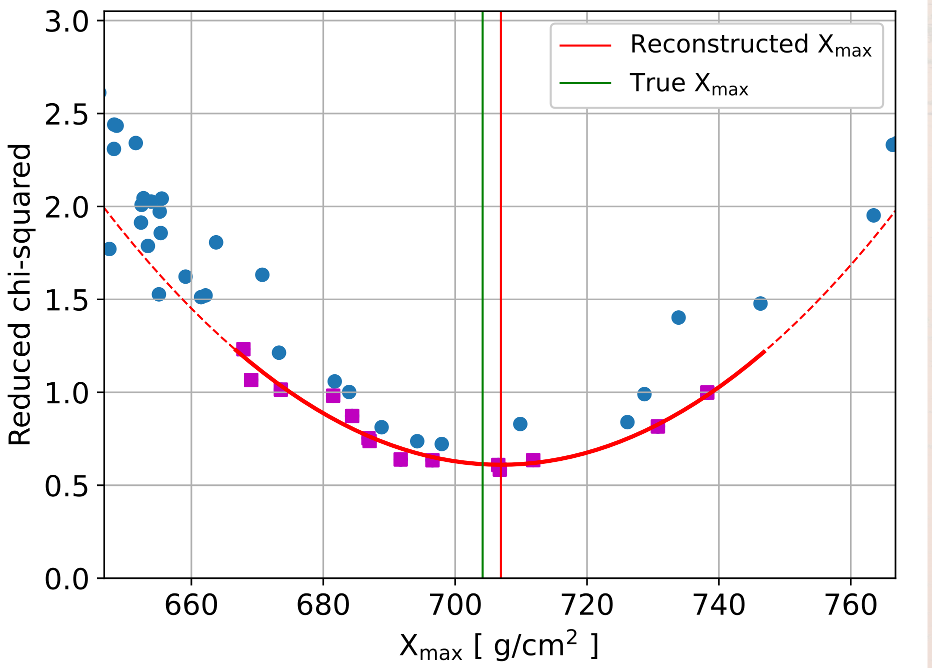
Simulation ensemble

- **140 showers** each: 50 p, 20 He, 20 C, 20 Si, 30 Fe
- From east; zenith angle 15, 30, 40 degrees
- Use one shower as mock data, use other 139 to reconstruct Xmax
- Do all showers in turn as ‘data’
- Determine reco-Xmax minus true Xmax
    - Average error: **bias**
    - Stddev error: **precision**

Fit quality, chi-squared vs Xmax

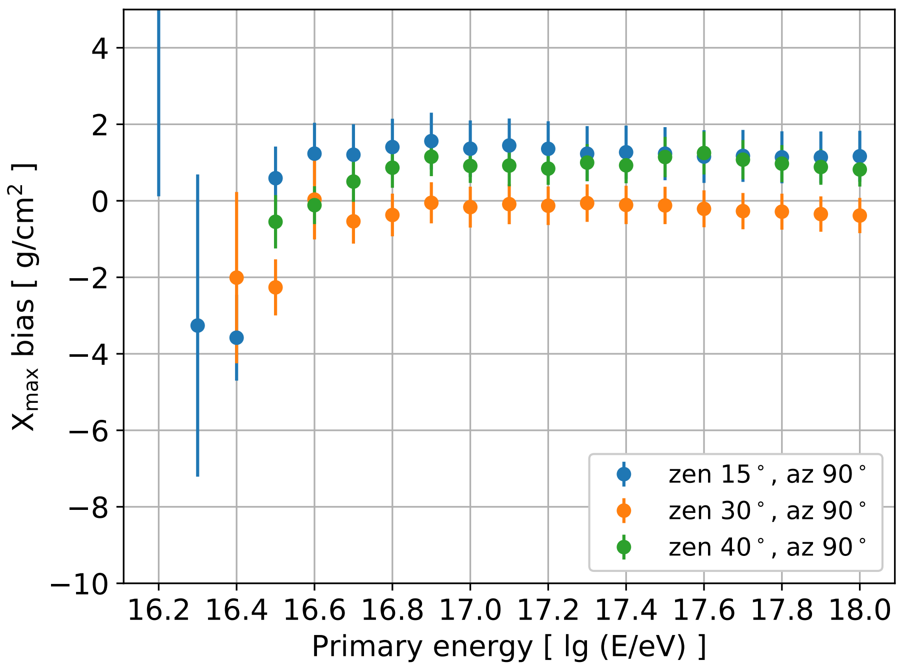
- Example fit quality plot, with Xmax reconstruction (parabola fit)

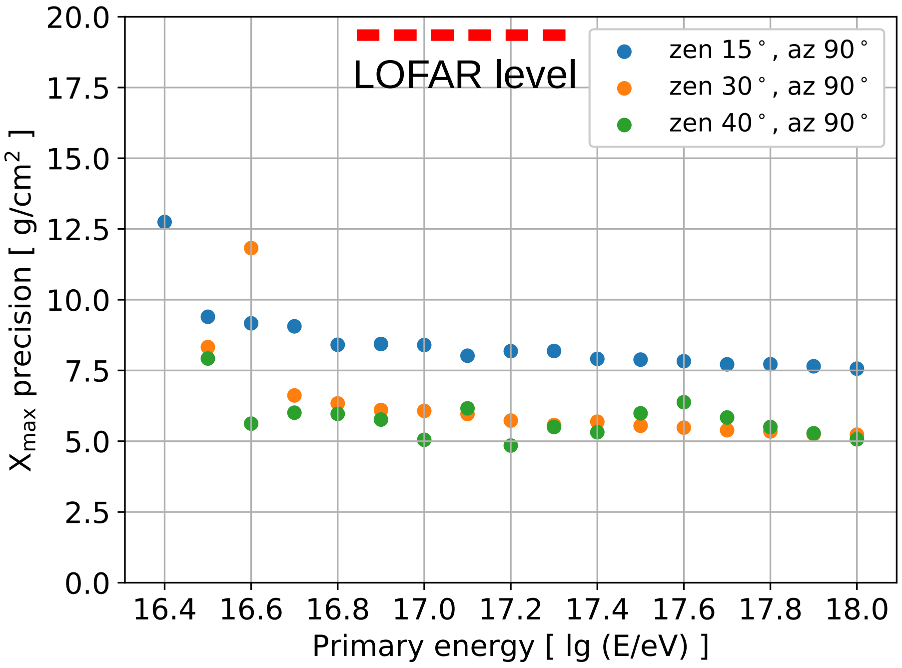




Bias and precision of Xmax reconstruction

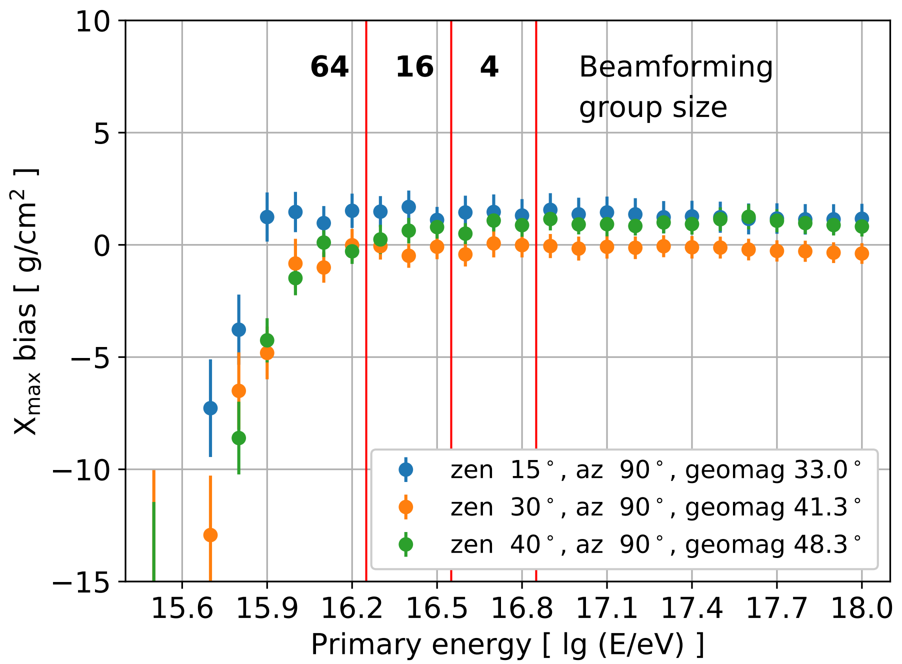
- Versus primary energy, with 1 in 4 antennas as “full array”
- Compare to 20 g/cm^2 precision on average with LOFAR

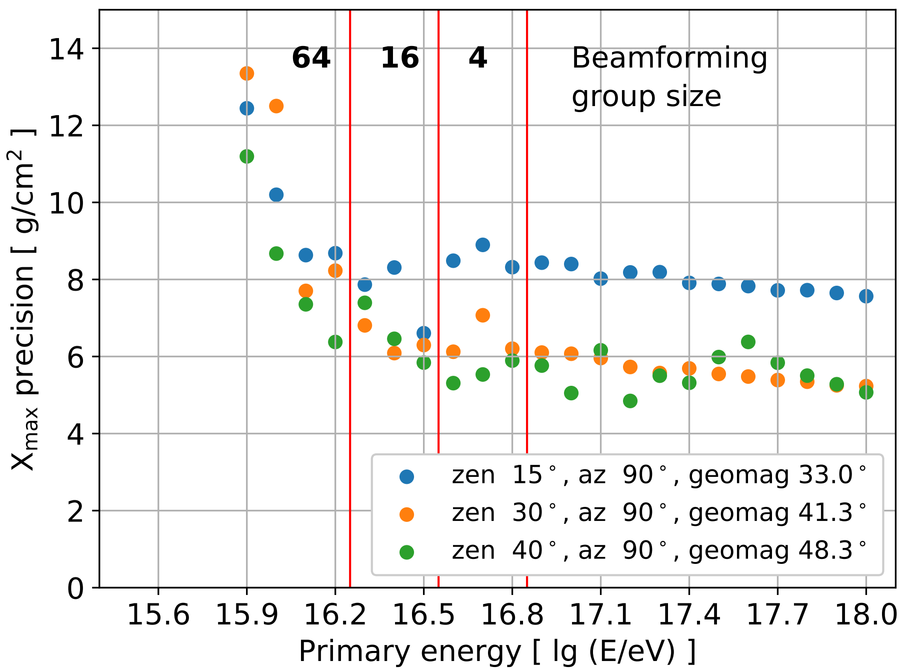




Bias and precision of Xmax reconstruction with (pseudo-)beamforming

- Results stay good down to 10^**16.0** eV
- Again taking 1 in 4 antennas as “full array”

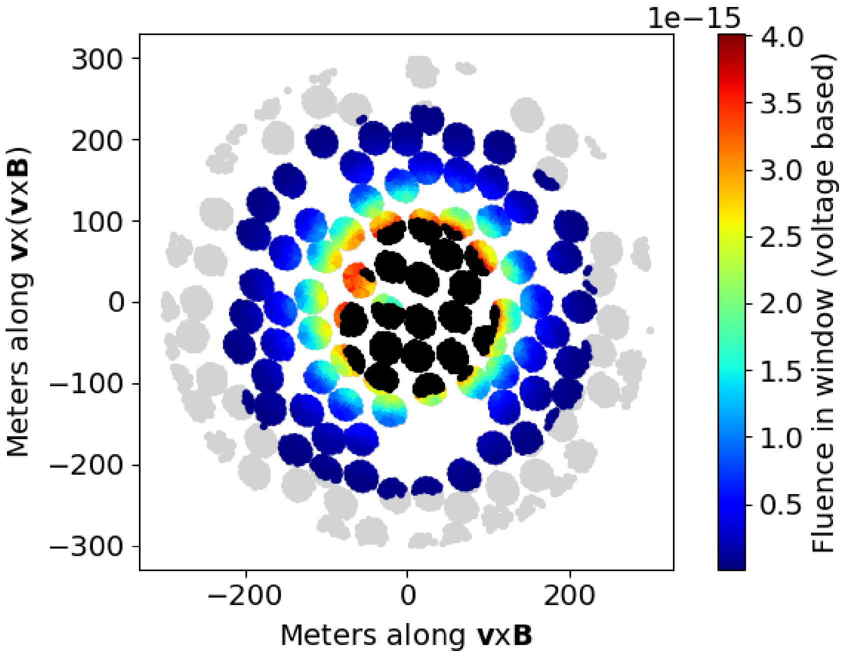




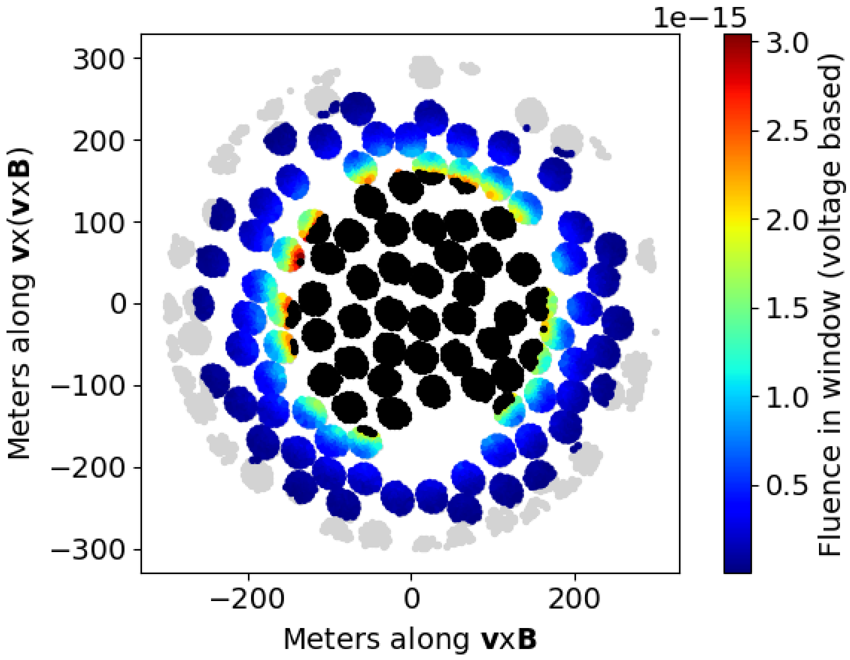
Example footprint with max dynamic range 32 sigma

- Cutting out all antennas where >= 1 polarization saturates the range

- 10^17.5 eV

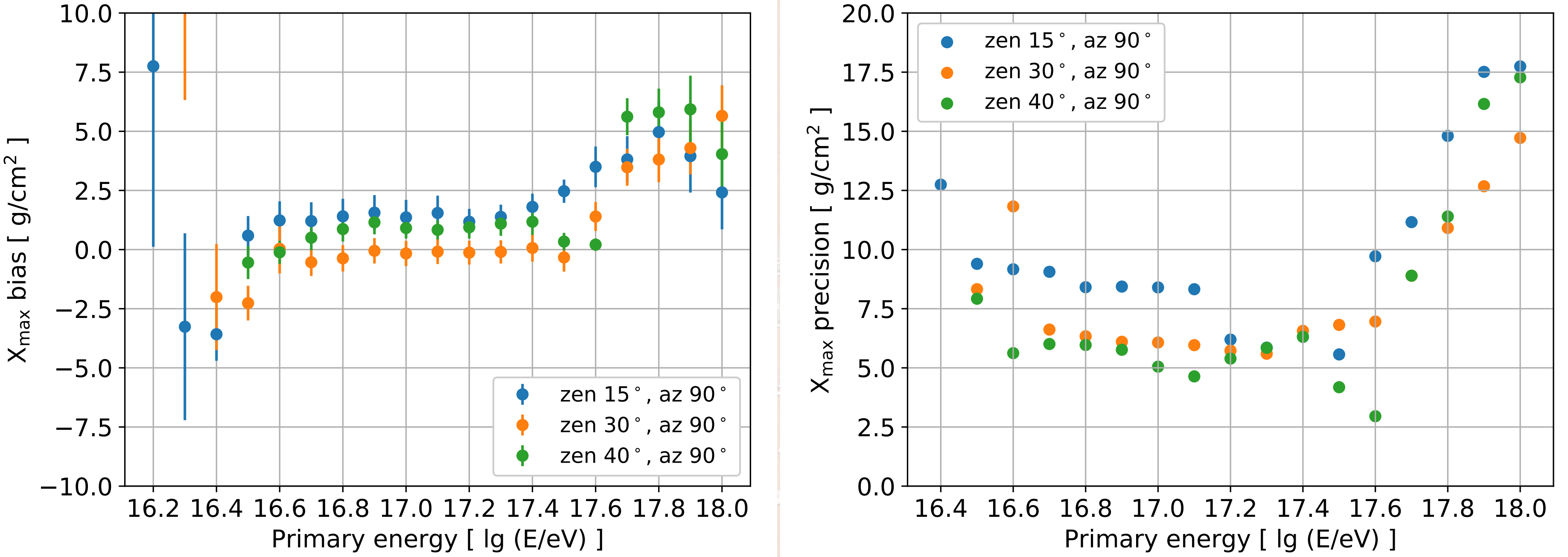


10^17.8 eV



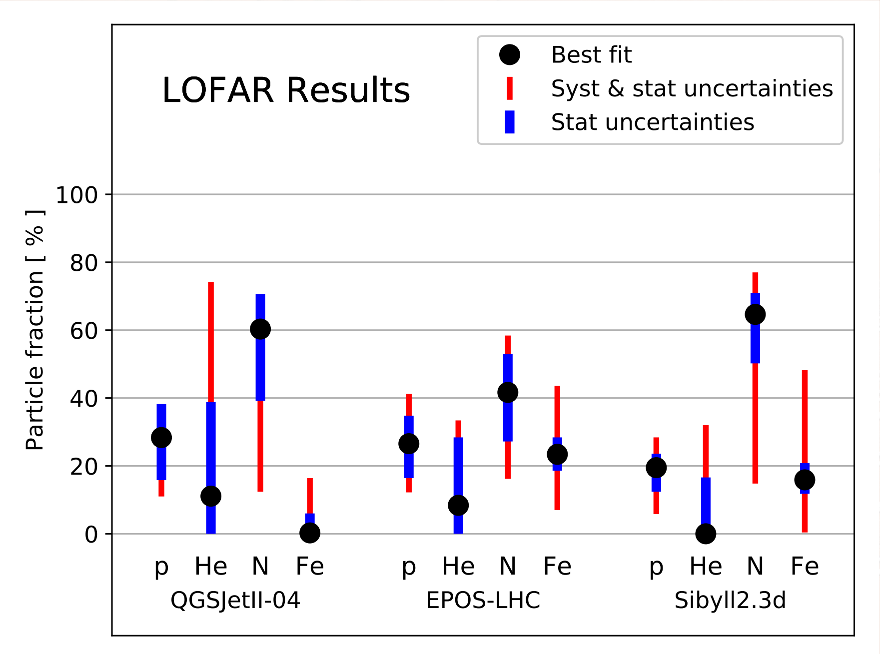
Bias & precision results with dynamic range 32 sigma

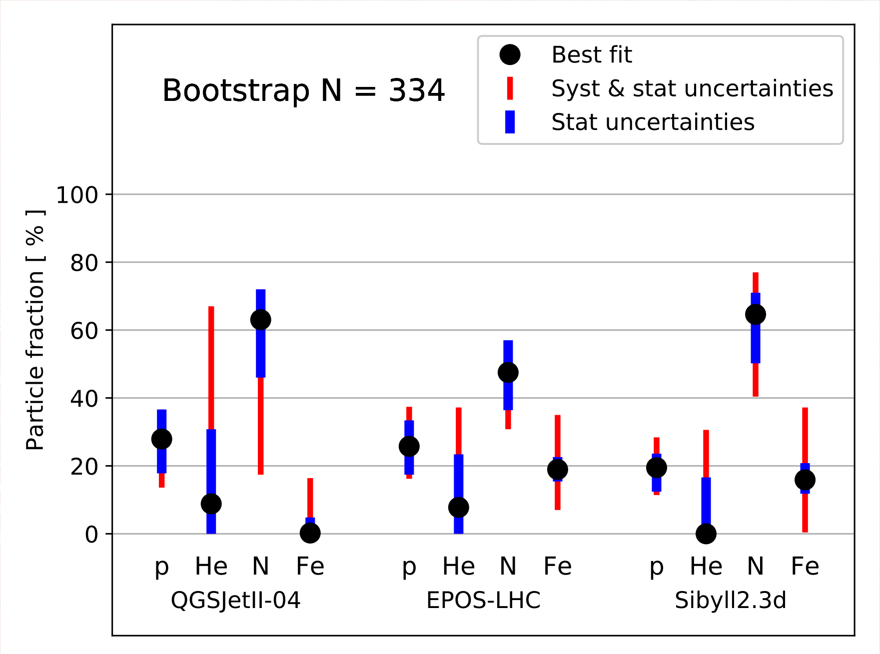
- Degradation at lg E >= 17.6
- Bias increases, has to be investigated (later, not here)
- Precision manageable, though newer analyses may be impacted more



Mass composition results

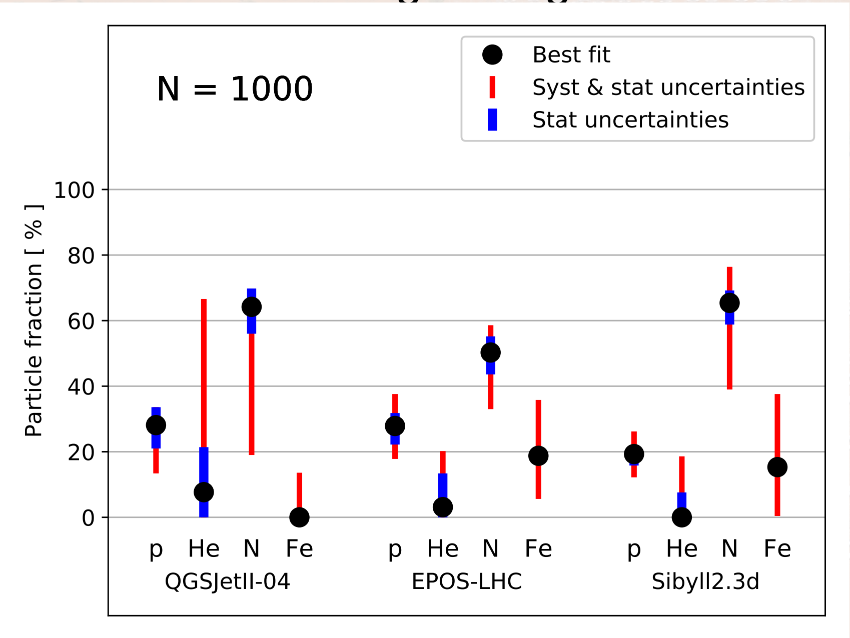
- How many showers needed to have:
  - Systematic uncertainties >> statistical uncertainties
  - A mass composition in narrow energy bins, improving over LOFAR (2021)

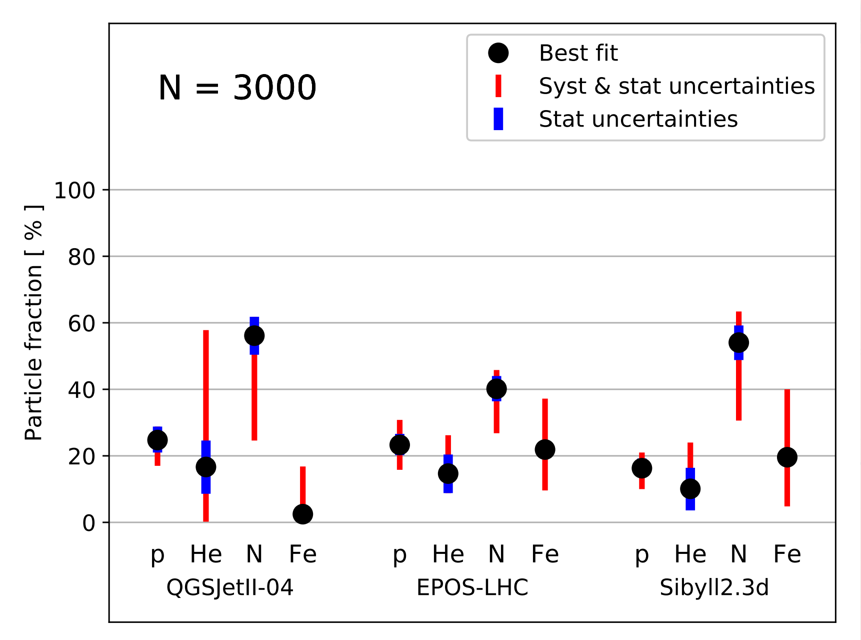




Mass composition results

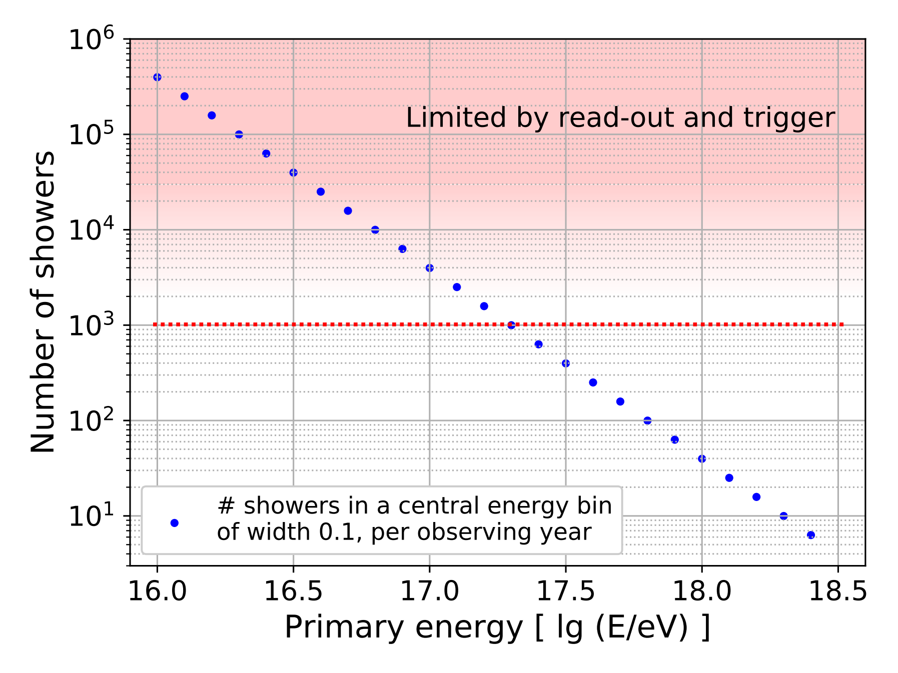
- Bootstrap: take best-fitting mass composition (LOFAR)
  - Do random drawing from Xmax distribution for that composition, add random Xmax errors +/- 7 g/cm2, account for syst errors +/- 9 g/cm2
  - Run that drawing through same mass composition analysis





Cosmic ray spectrum & expected event counts

- Event counts in an energy bin of width 0.1 in lg E/eV
- Over 1 observing year = 1 year of CR-mode uptime
- Nature-limited above **lg E ~ 17.3**, tech/obs limited below



Next steps

- Results presented here are just the beginning!

- There is more to be measured than only Xmax and energy
  - Longitudinal distribution
  - Special showers (‘double bumps’)

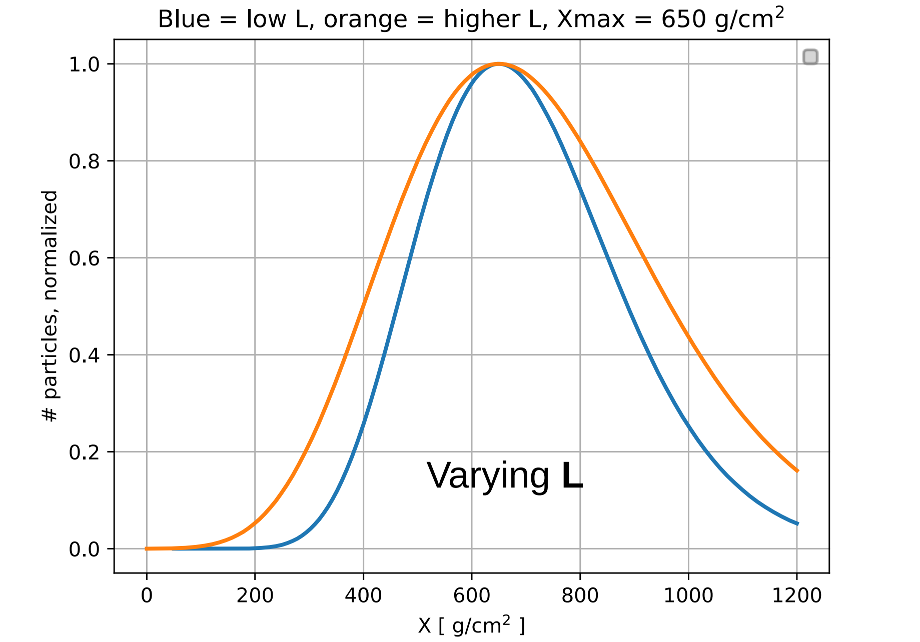
- New analysis techniques
  - Information field theory
  - Interferometry / beamforming
  - Other approaches that use timing, polarization, frequency spectra

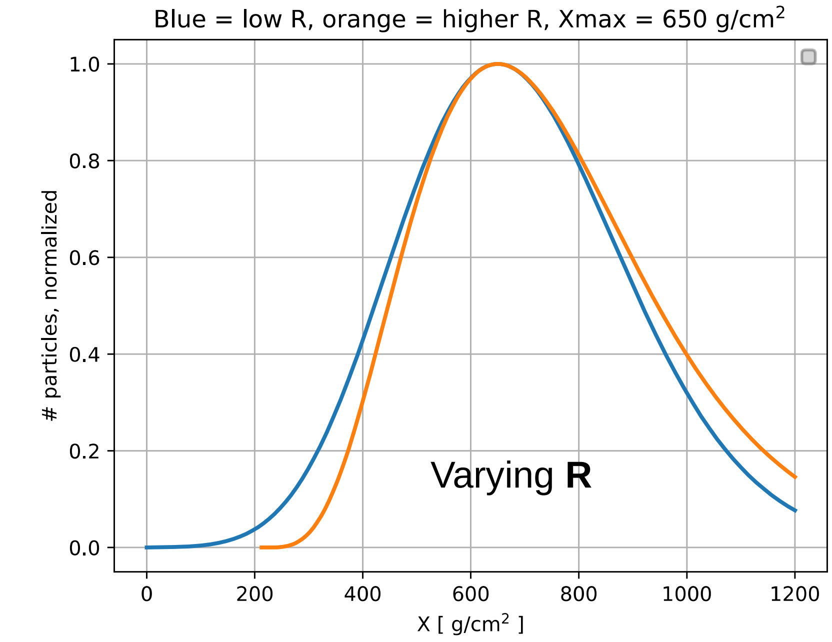
Beyond Xmax: Longitudinal distribution of particles

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

Parameter **L**: width (variance)

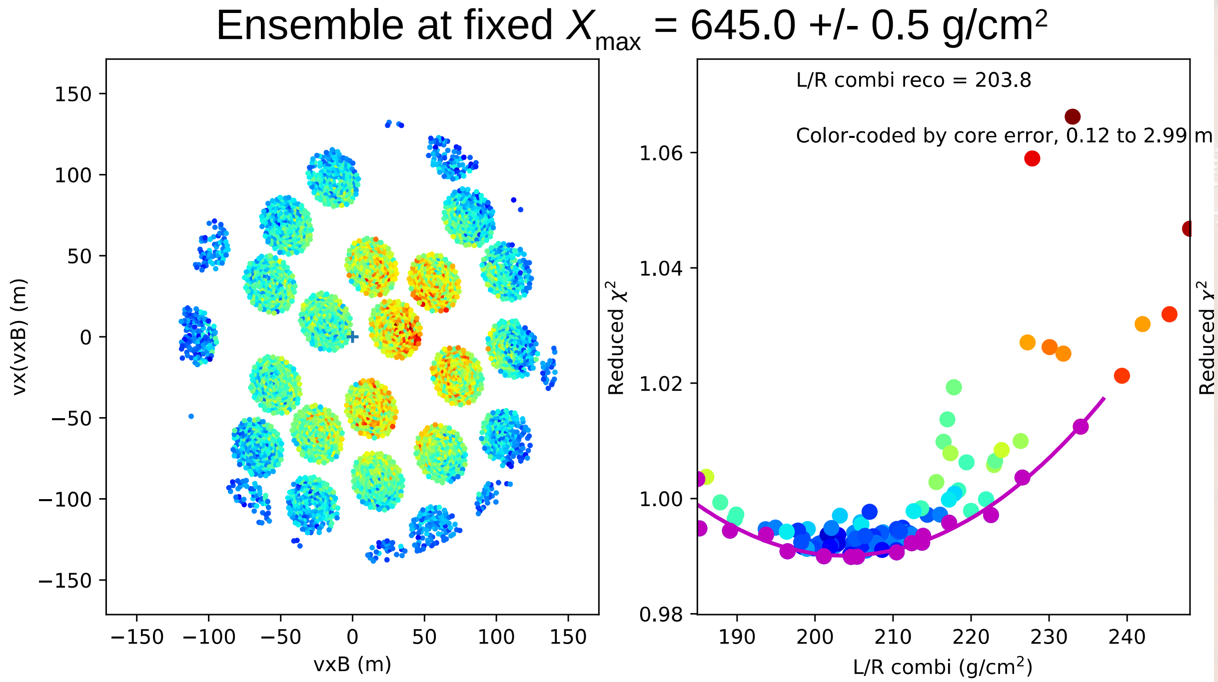
Parameter **R**: asymmetry (skewness)





Reconstruction result for L+R combination

50 – 100 MHz



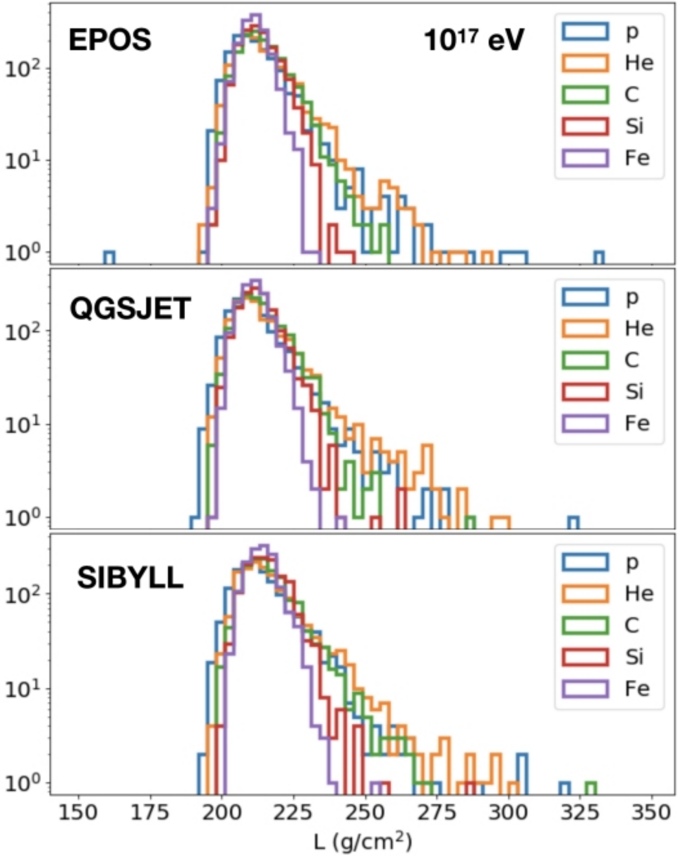
~ 5000 antennas triggered

Reconstructed "L+R" = 203.8 g/cm²,

True "L+R" = 204.2 g/cm²

Reconstruction Xmax, and L+R together still to do

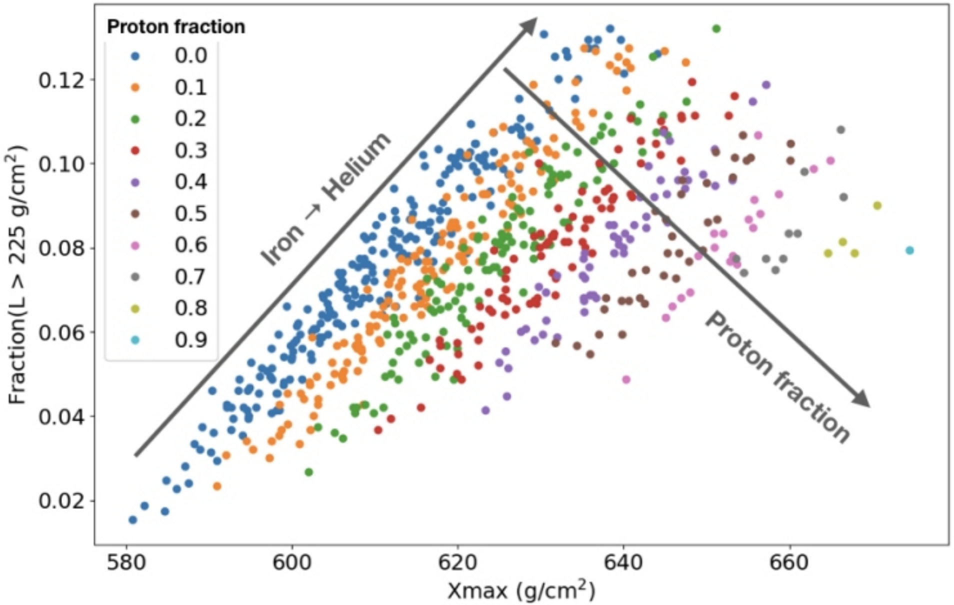
Distribution (tail) of L parameter: **proton fraction**



Tails are highest for **helium**, not protons

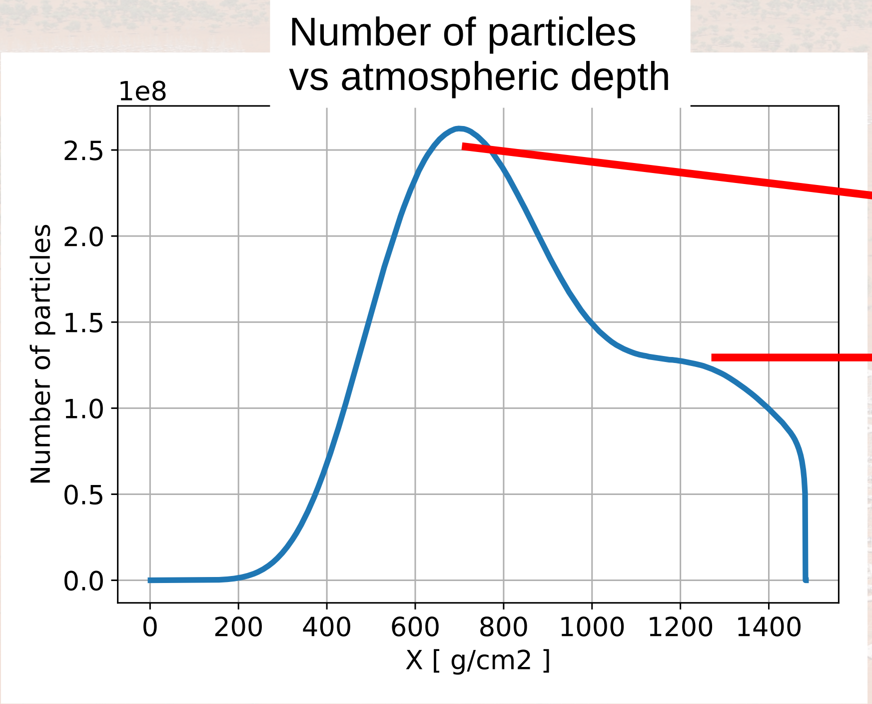
- Independent handle on proton fraction!

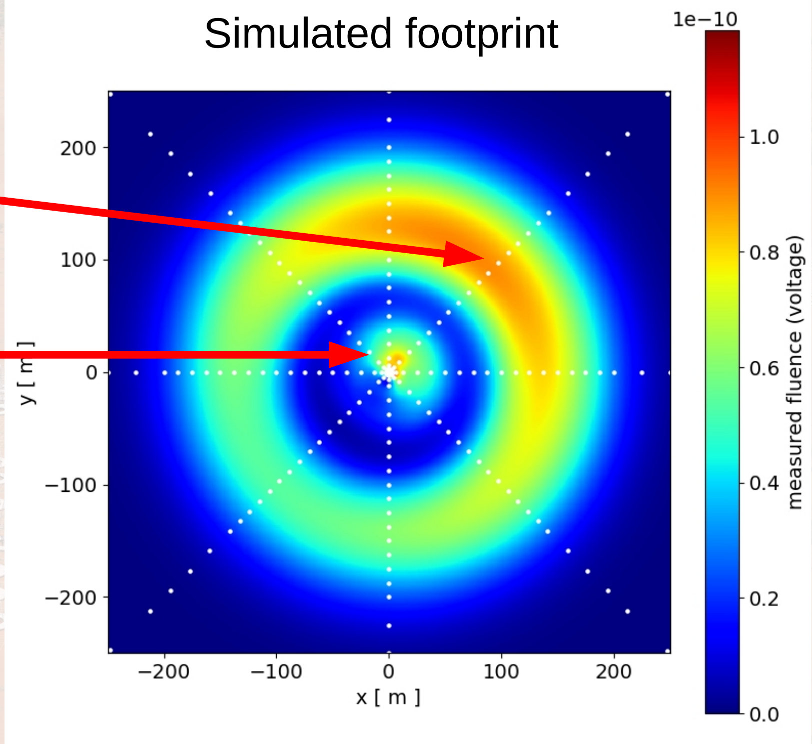
Fig. by S. Buitink



Outlier showers, 'double bumps'

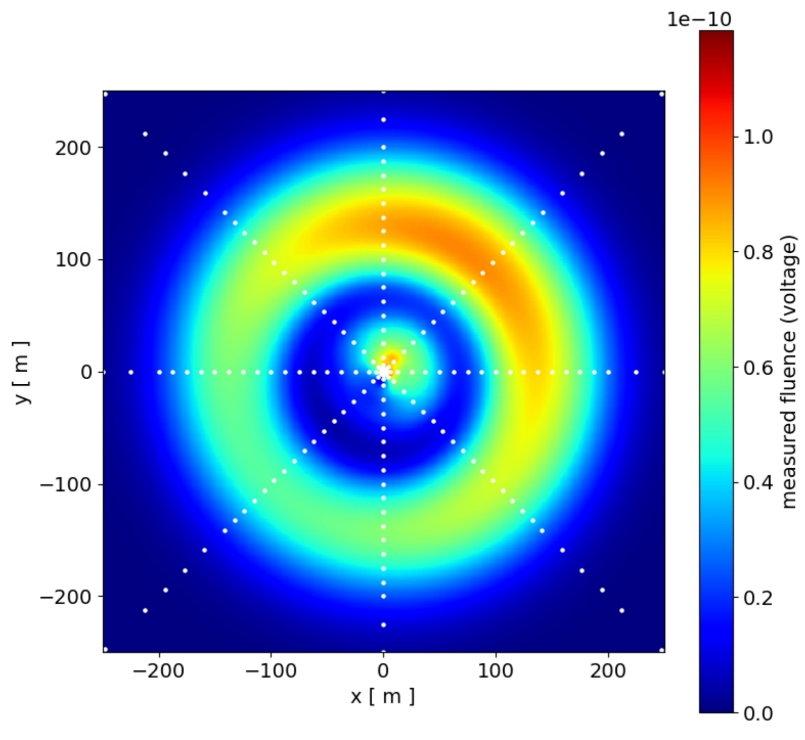
- Filter to 150 – 350 MHz band for sharper features
- Secondary shower visible separately (though uncommon)



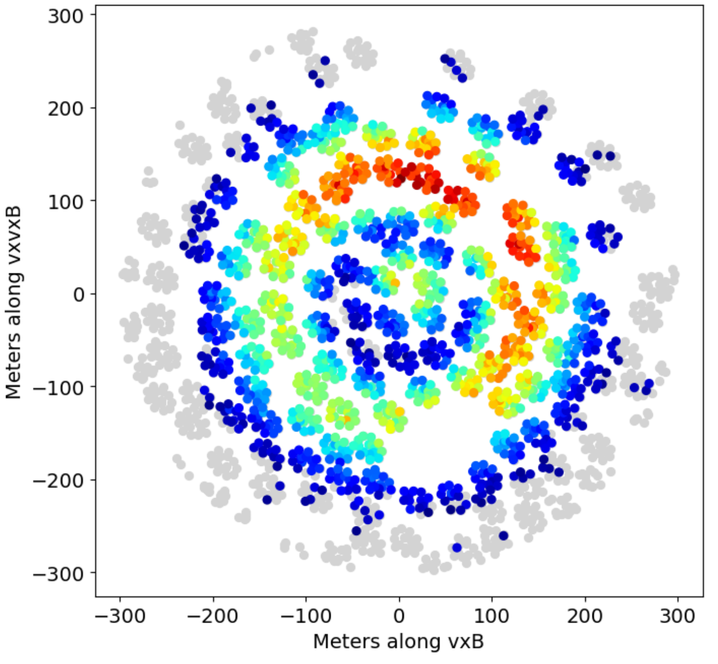


Outlier showers

- SNR boost by a factor **4** from beamforming patches of **16** antennas
- Further enhancement; clearly detectable double structure



E = 7 x 10^{16} eV



Summary

- SKA is the ‘ultimate’ dense radio array for cosmic-ray detection

- Using established techniques developed for LOFAR,
  precision on Xmax is 3x better than LOFAR, using known techniques
  (may improve later, measuring full shower evolution)

- Energy range extended to lower energies, **10^{16}** to **10^{18} eV** now available
- Mass composition analysis in narrow energy bins will be possible,
  for low energies quite soon

- New techniques promise to add new, independent information
  - Mass composition (p/He separation)
  - Hadronic physics

Backup