Measuring high-energy cosmic rays at SKA-Low

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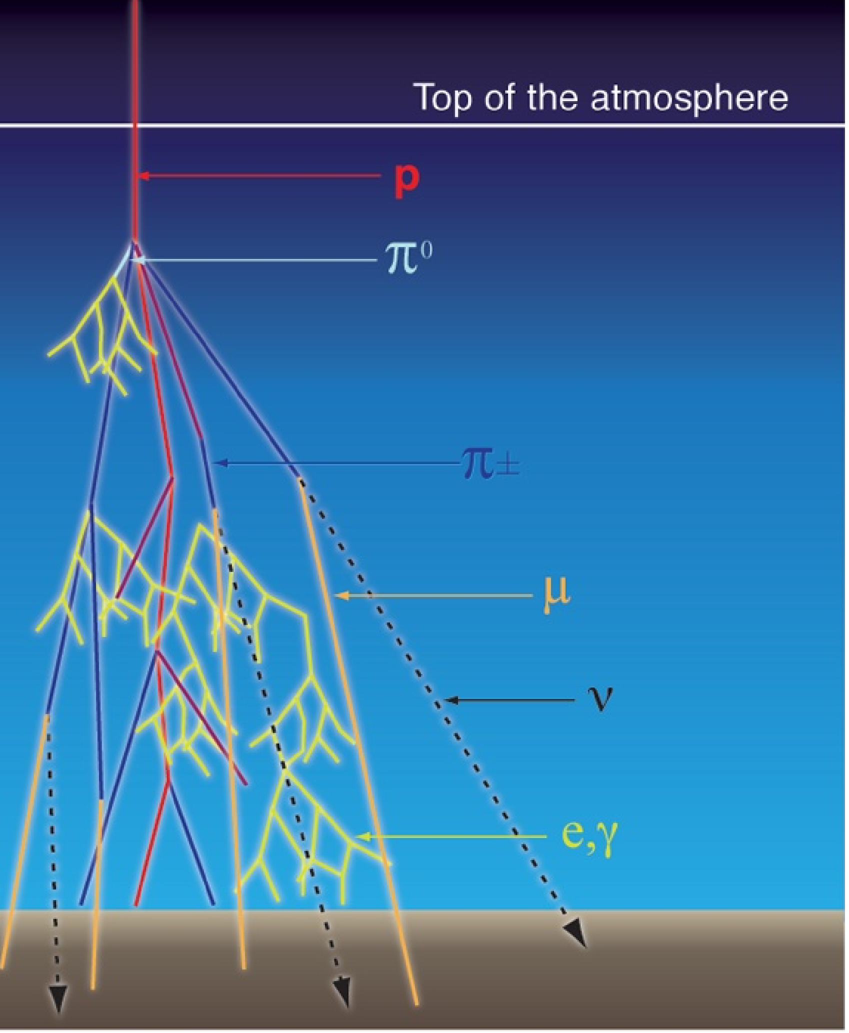
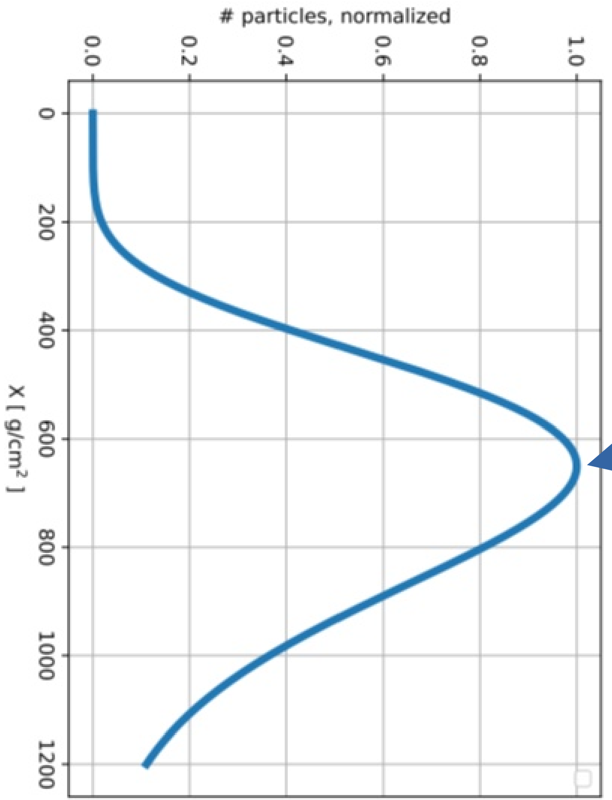


Extensive air showers

Longitudinal profile of number of particles

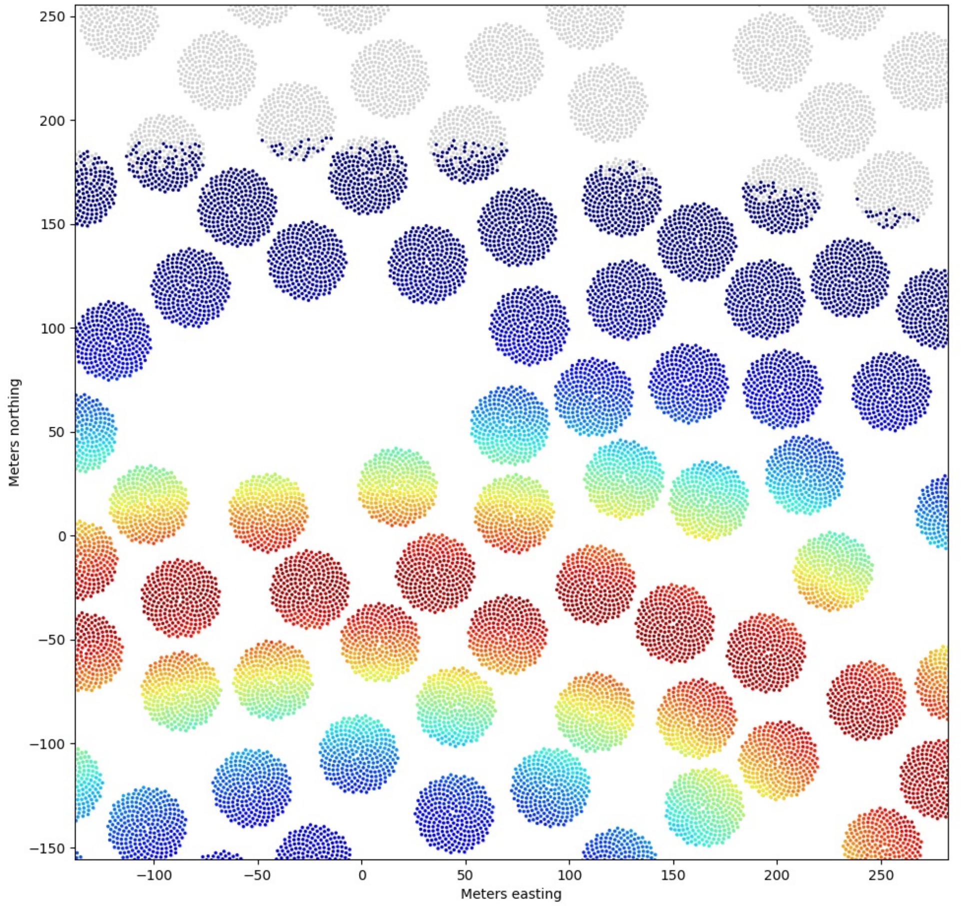


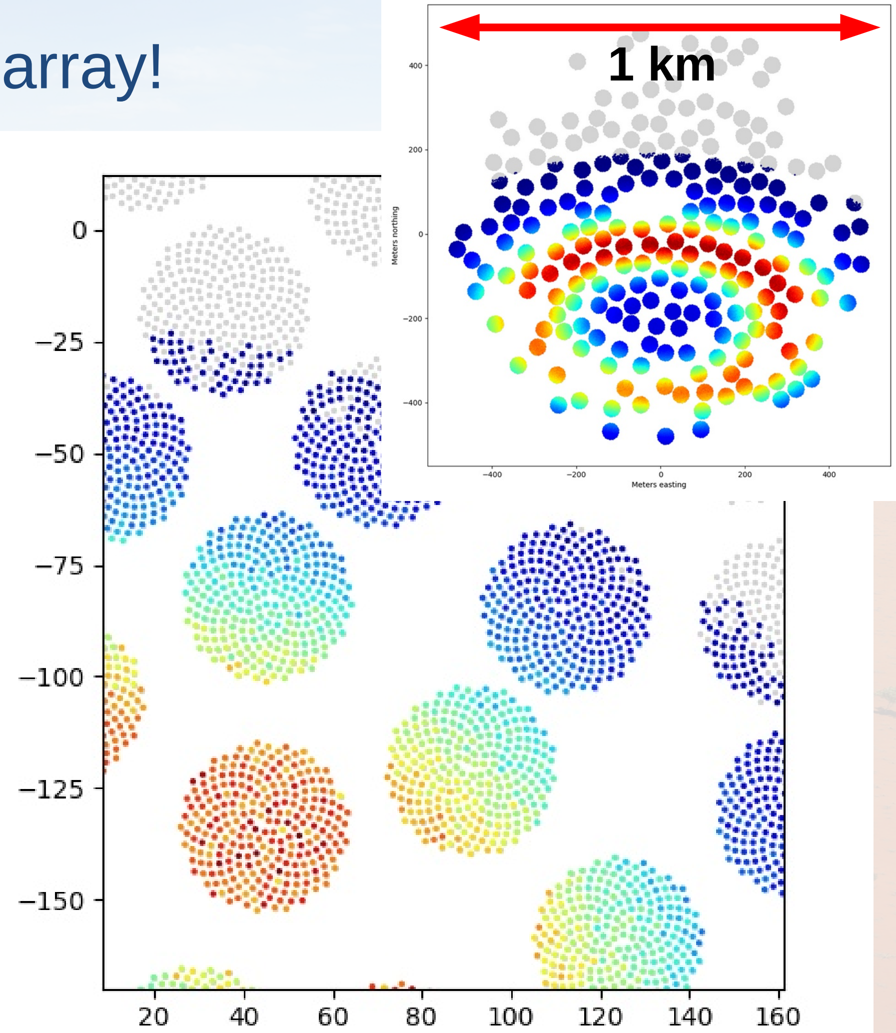
Shower maximum ***X*$_{max}$** varies with primary particle mass

- on average
- in distribution

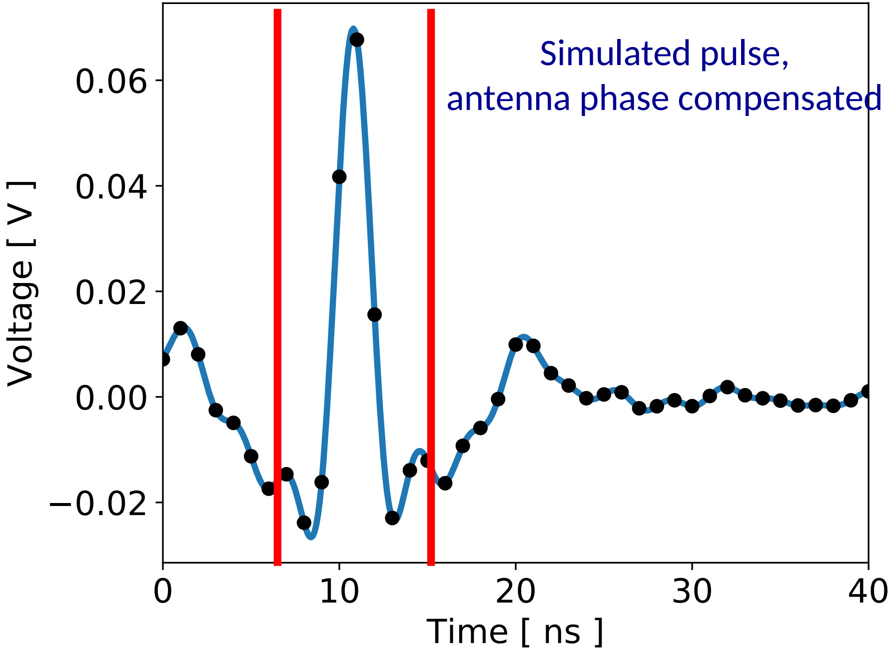
X_{max}

SKA-Low, a really dense array!





Pulses in SKA-Low antennas



Integrate ‘power’ in a time window

- Width of time window not too large (noise)
- Same in data as in simulations

- Pulse contains more information:
  shape, polarization, timing

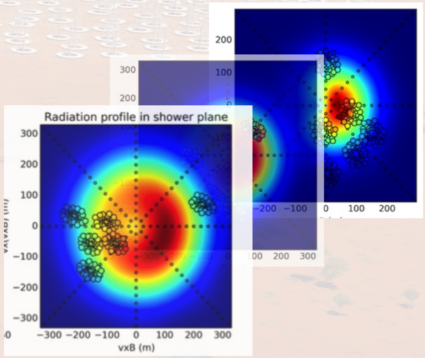
Monte Carlo setup for SKA reconstruction

- Mimic LOFAR-style measurement & X_{max} reconstruction

- Create 140 CoREAS simulated showers
- Apply SKA Antenna model
- Add realistic level of sky noise
- Trigger threshold **4 or 5** sigma

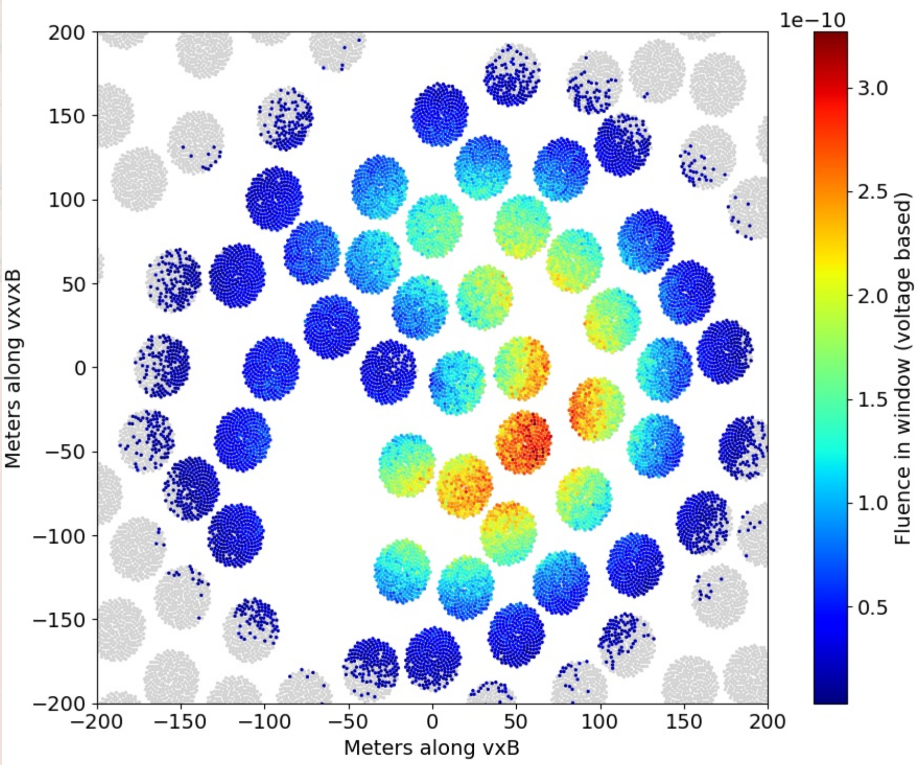
- For each SKA antenna, determine pulse energy fluence
- Store ‘measurements’ + uncertainties

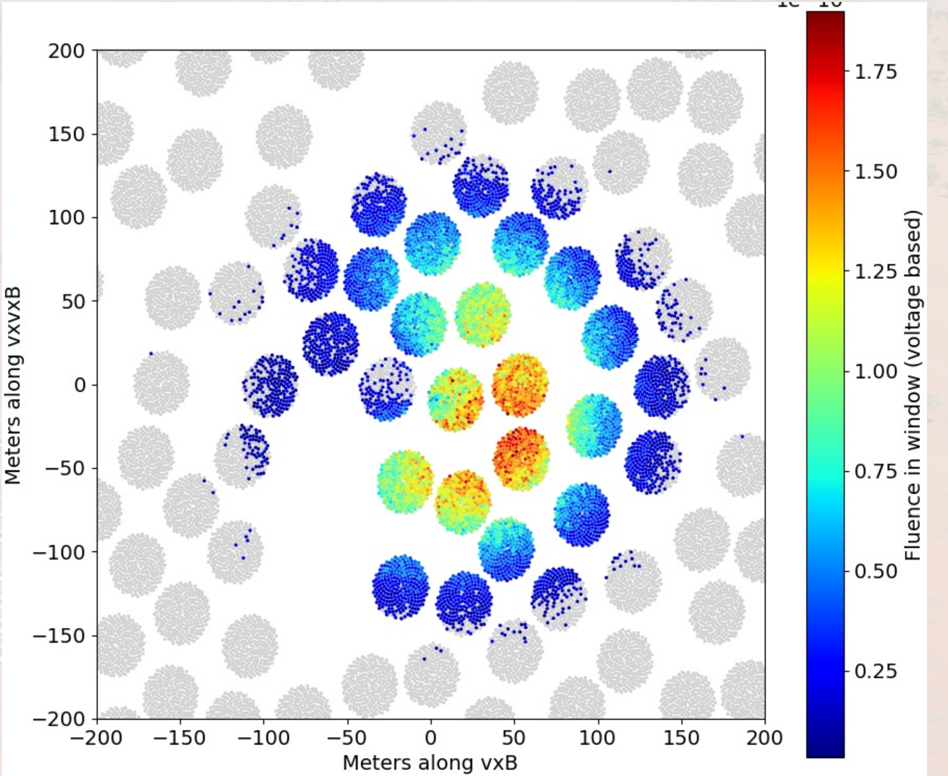
- Simulated ensemble of **140** showers, use each in turn as ‘data’
- Run reconstruction pipeline
  - Chi-squared fit of energy fluence footprints, sim vs ‘data’



Measured footprint

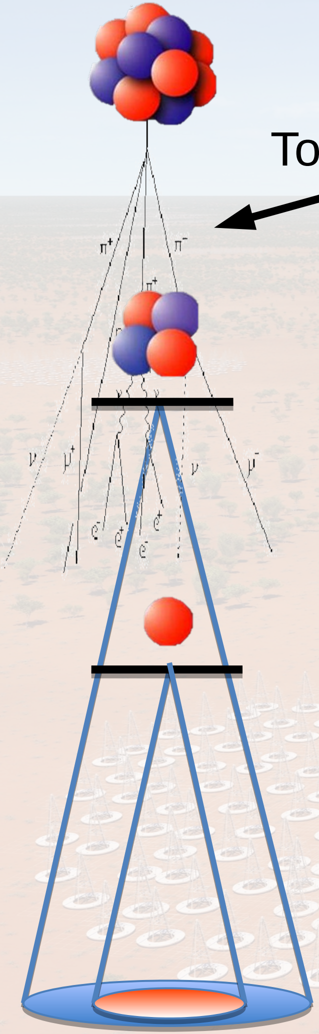
- Scatter in measured energy from noise
- Size varies, even for the same incoming direction (X_{max} sensitive)



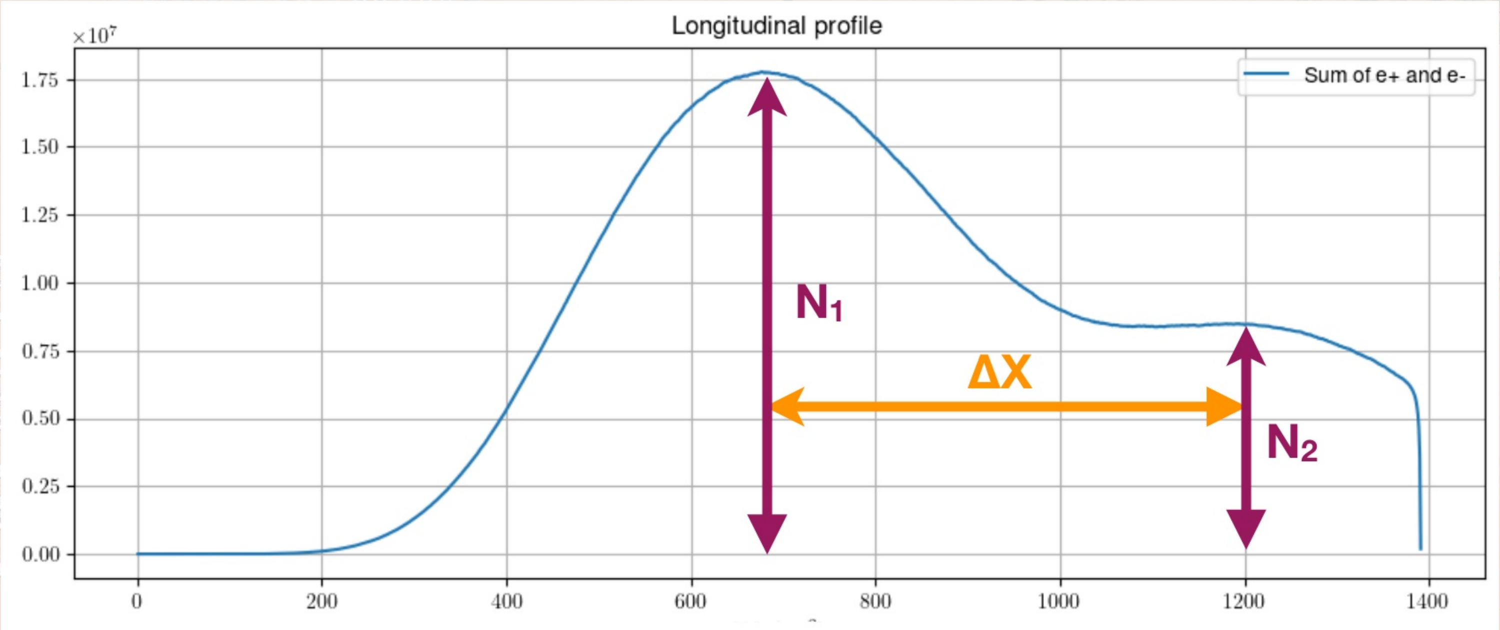


Outlier showers, ‘double bumps’

Toy model



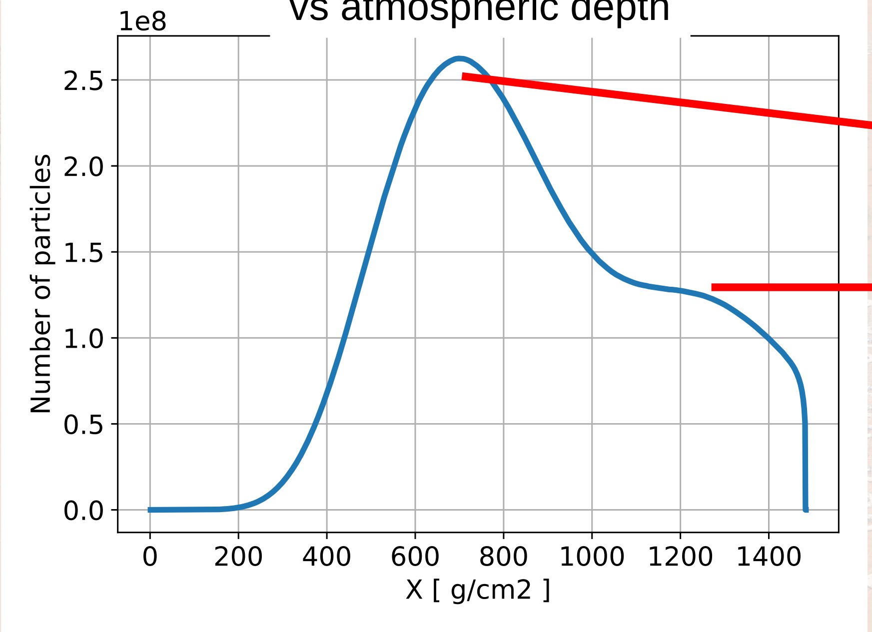
- Sometimes, one nucleon takes away a lot of energy after first interaction
- May take time before interacting again: starts ‘second shower’



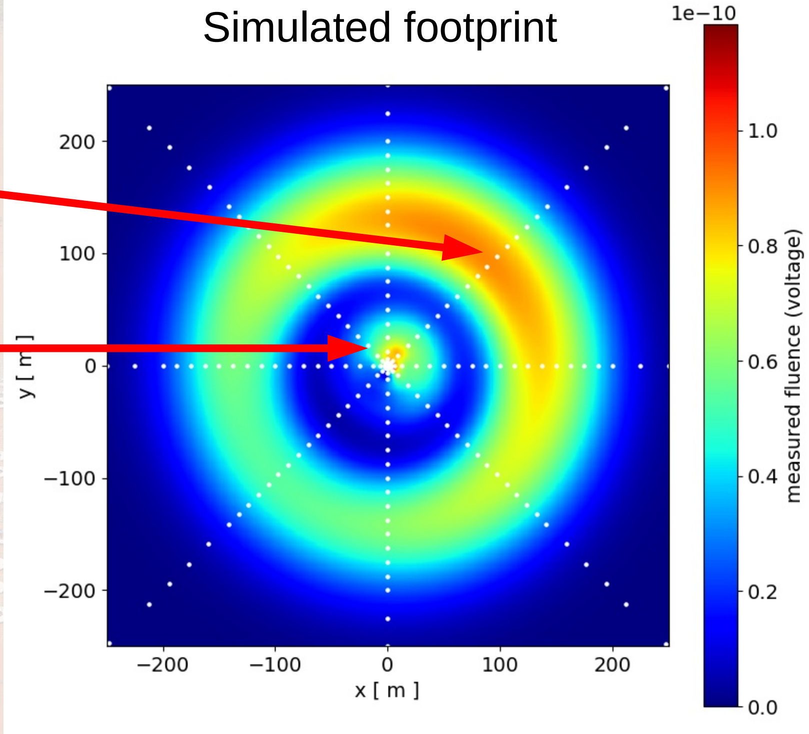
Outlier showers, ‘double bumps’

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

Number of particles vs atmospheric depth

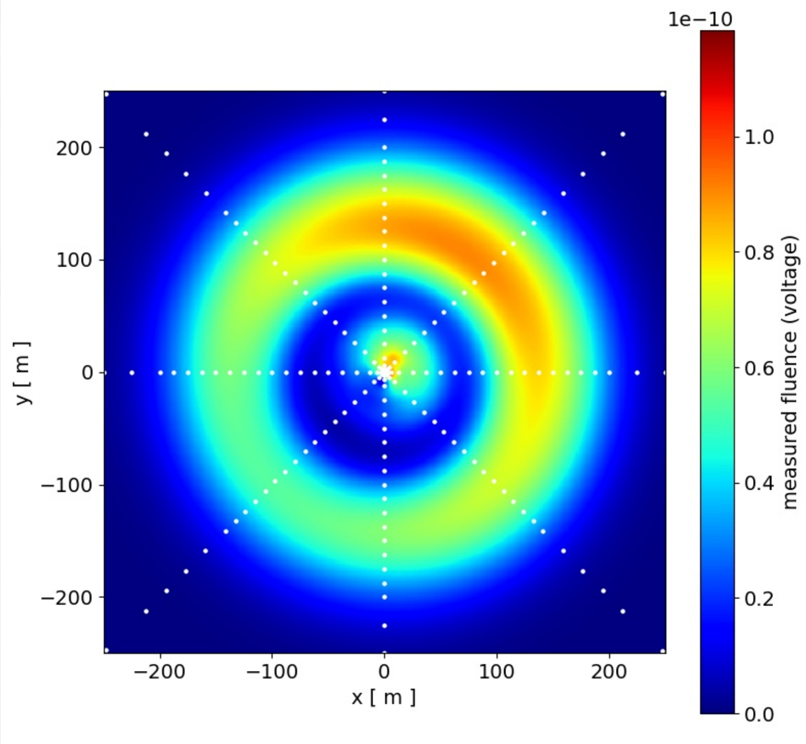


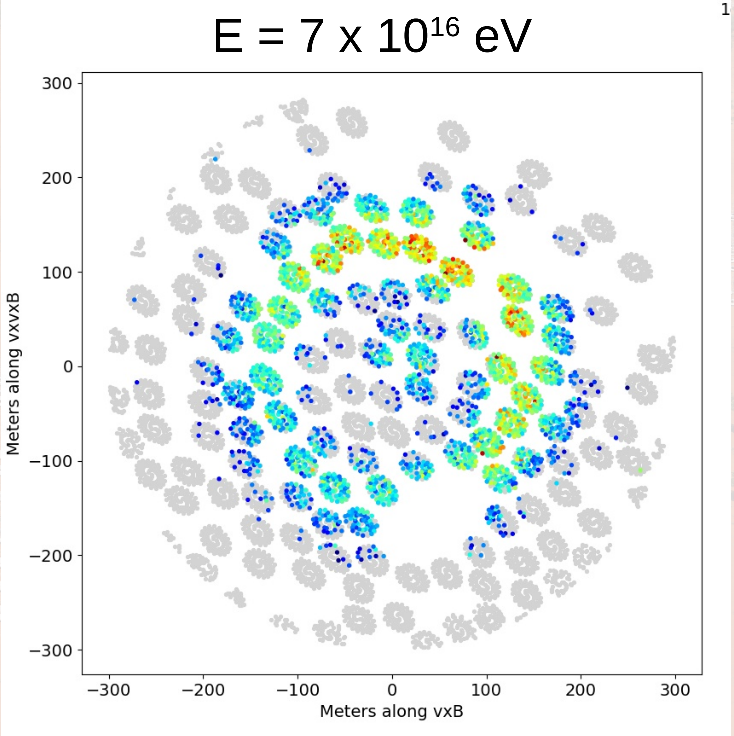
Simulated footprint



Outlier showers

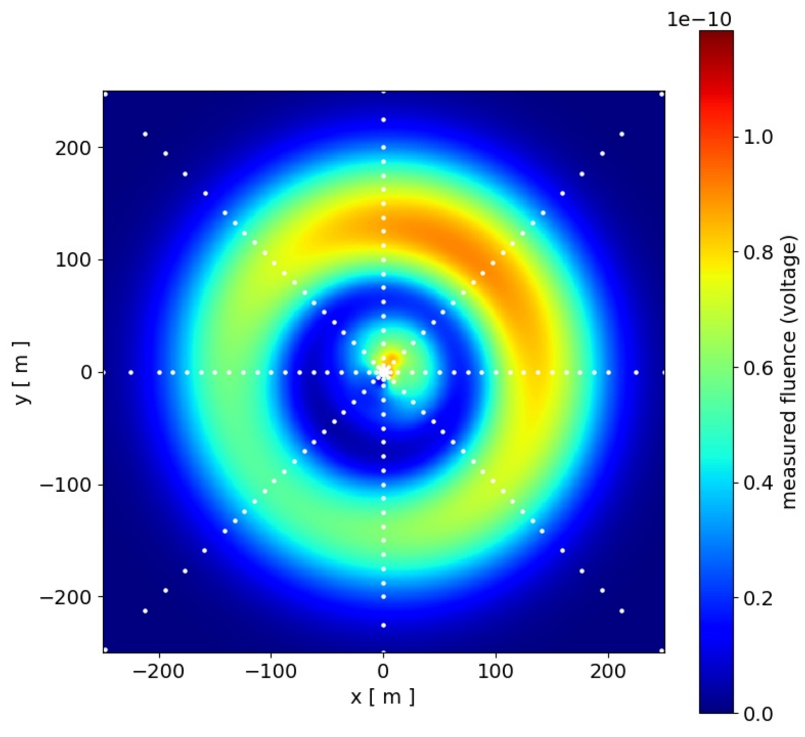
- Simulated measurement with noise
- SNR boost by a factor **2** from beamforming patches of **4** antennas
- Feature in the center is visible in the footprint!



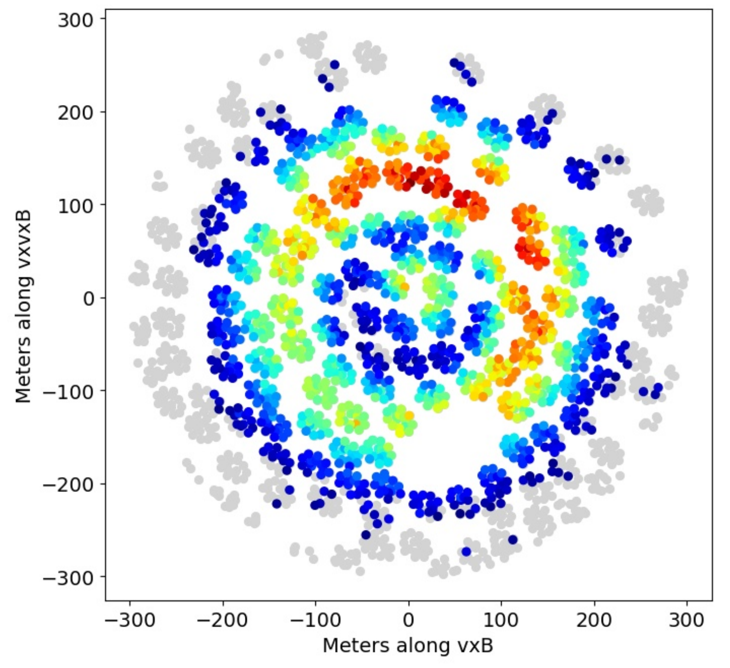


Outlier showers

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



E = 7 x 10^{16} eV

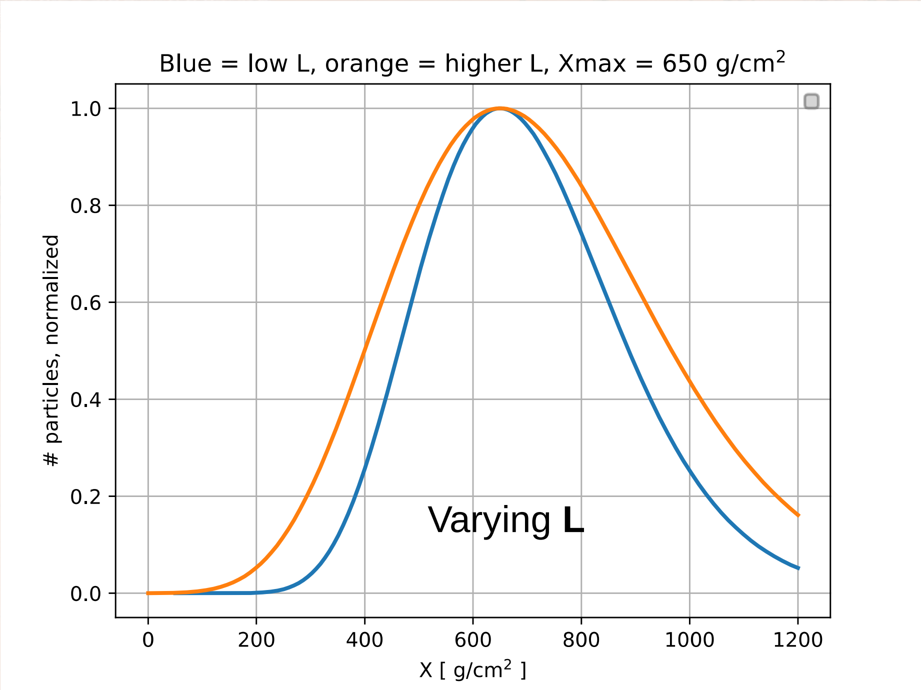


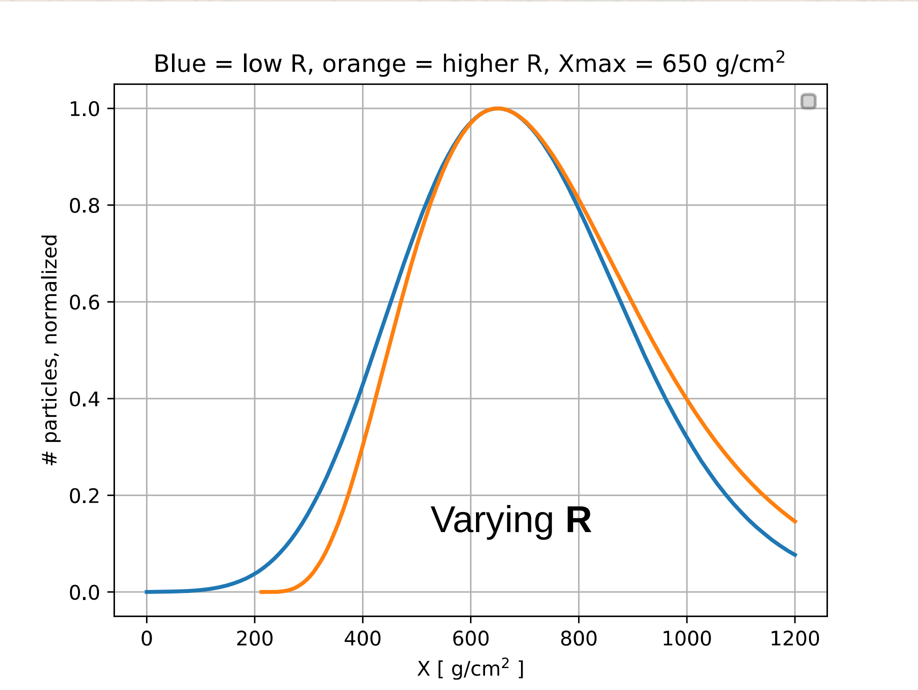
Beyond Xmax: Longitudinal distribution of particles

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

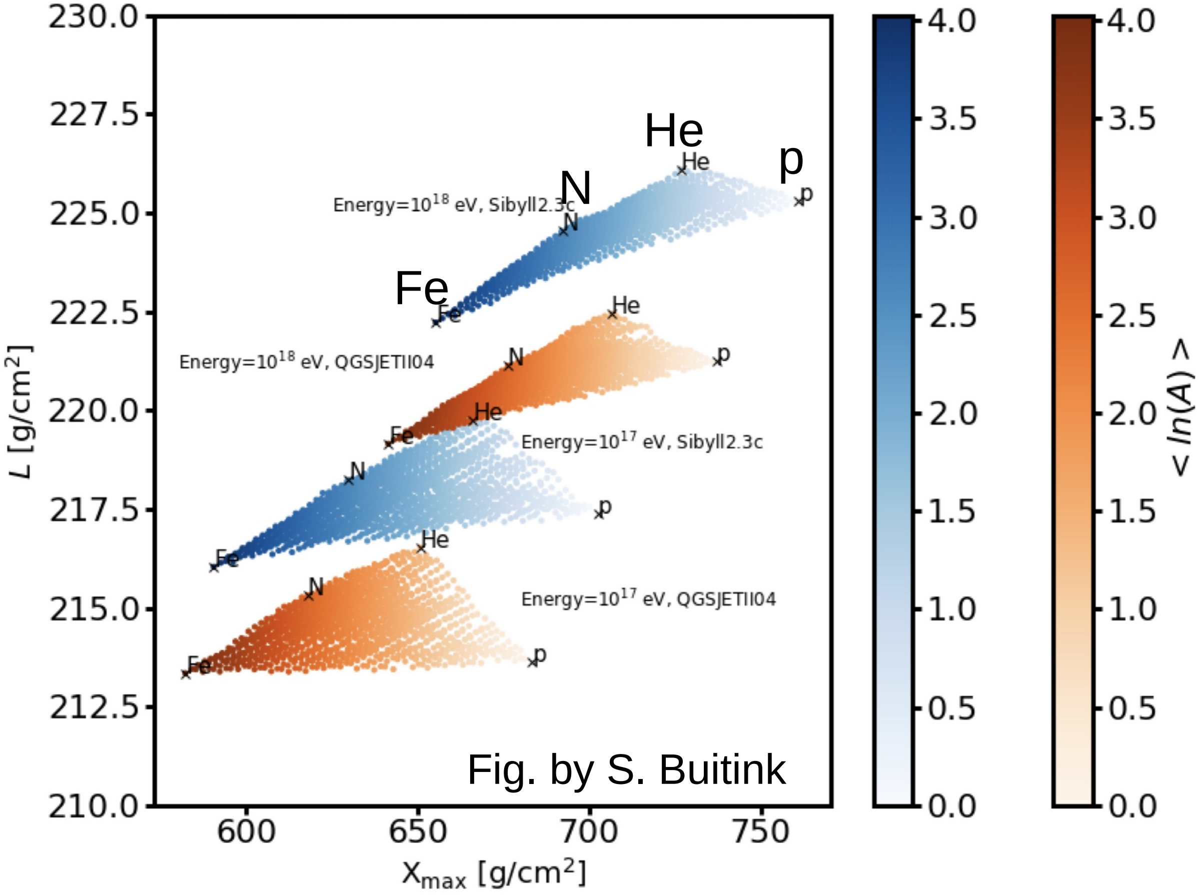
Parameter **L**: width (variance)

Parameter **R**: asymmetry (skewness)





Xmax and **L** vs mass composition and hadronic interaction models



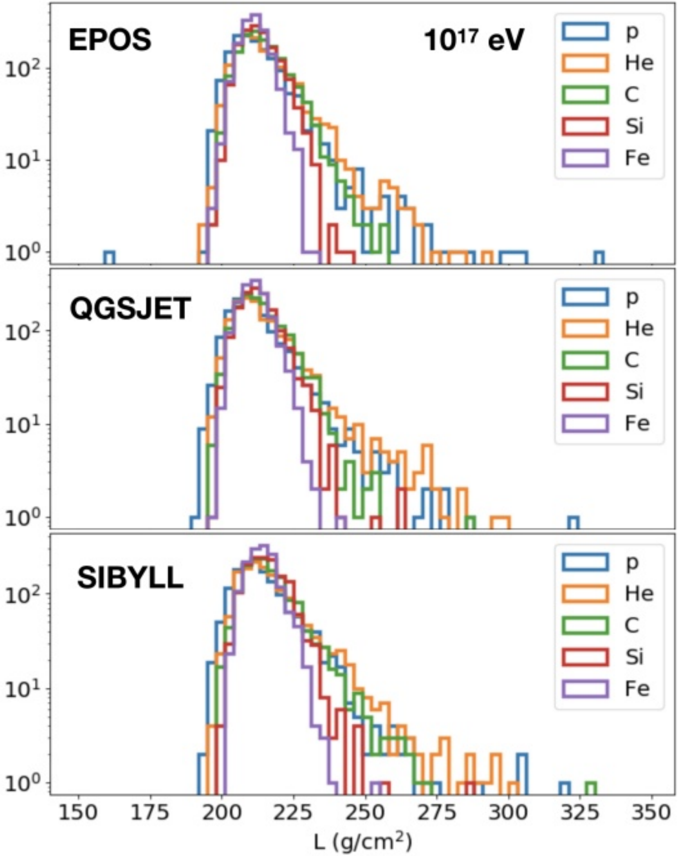
Average **Xmax** and **L** over 1000 showers

Varying mass composition

Blue = Sibyll 2.3c
Orange = QGSJetII-04

- Can distinguish between hadronic interaction models by measuring ***L*** !

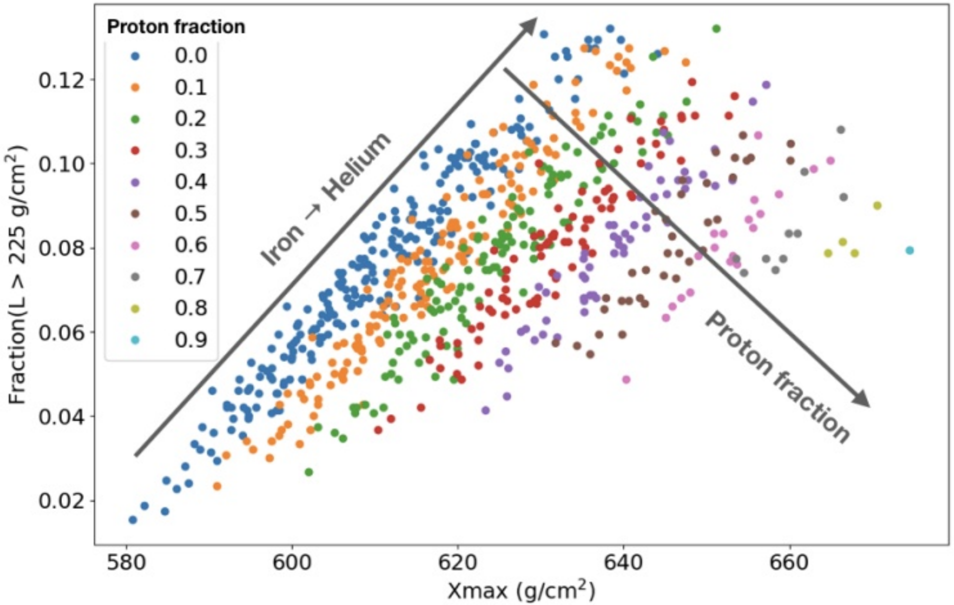
Distribution (tail) of L parameter: **proton fraction**



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

- Independent handle on proton fraction!

Fig. by S. Buitink



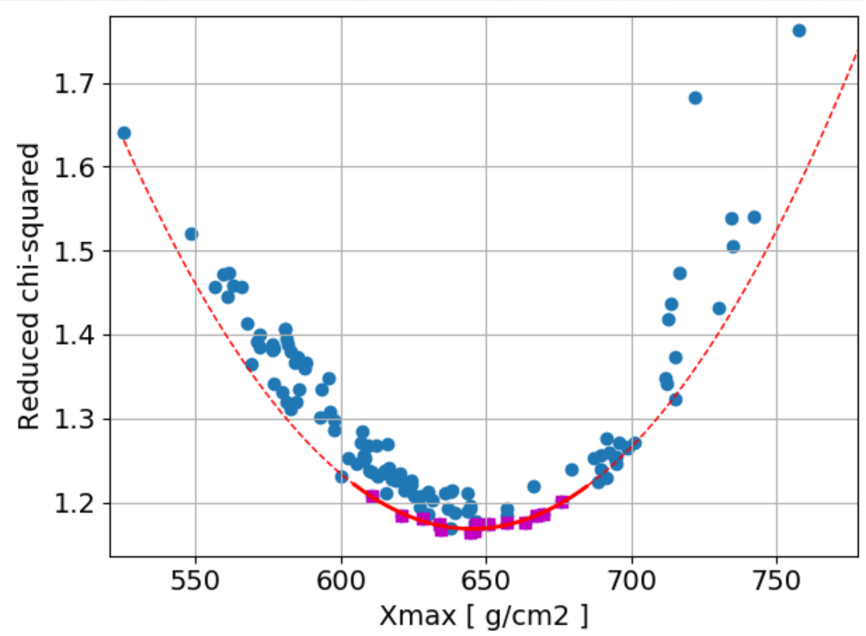
Reconstruction result for X_{max}

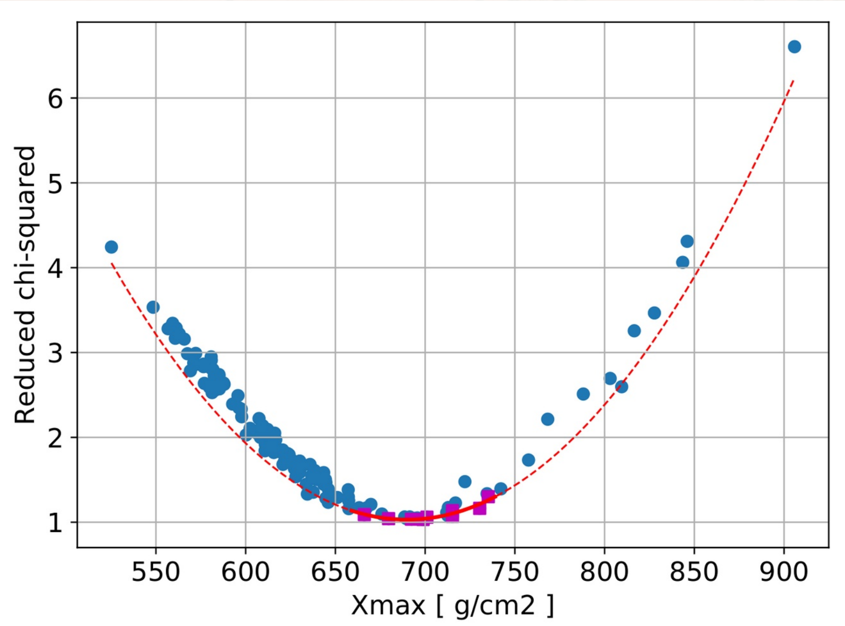
50 – 350 MHz

Primary energy 2 x 10^{17} eV, ~ 8000 antennas triggered

Minimum of enveloping parabola estimates X_{max}

Resolution **6-8 g/cm²** (current state of the art 20 g/cm²)

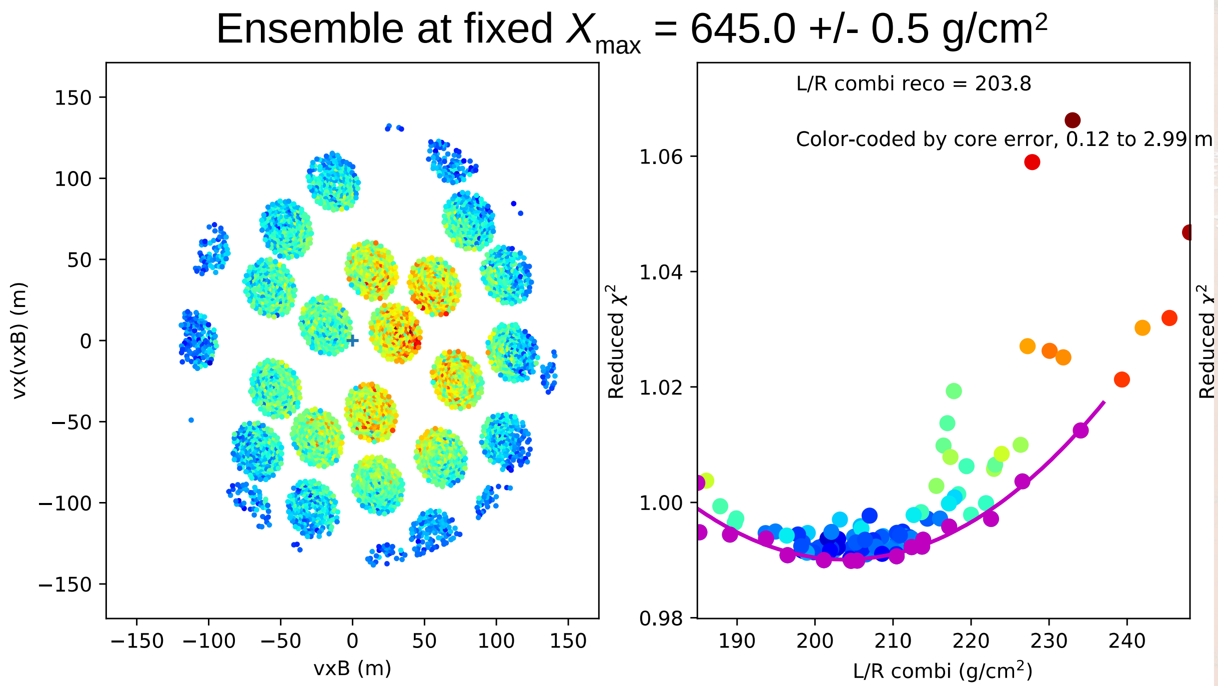




Reconstruction result for L/R

(higher-order particle distribution parameters)

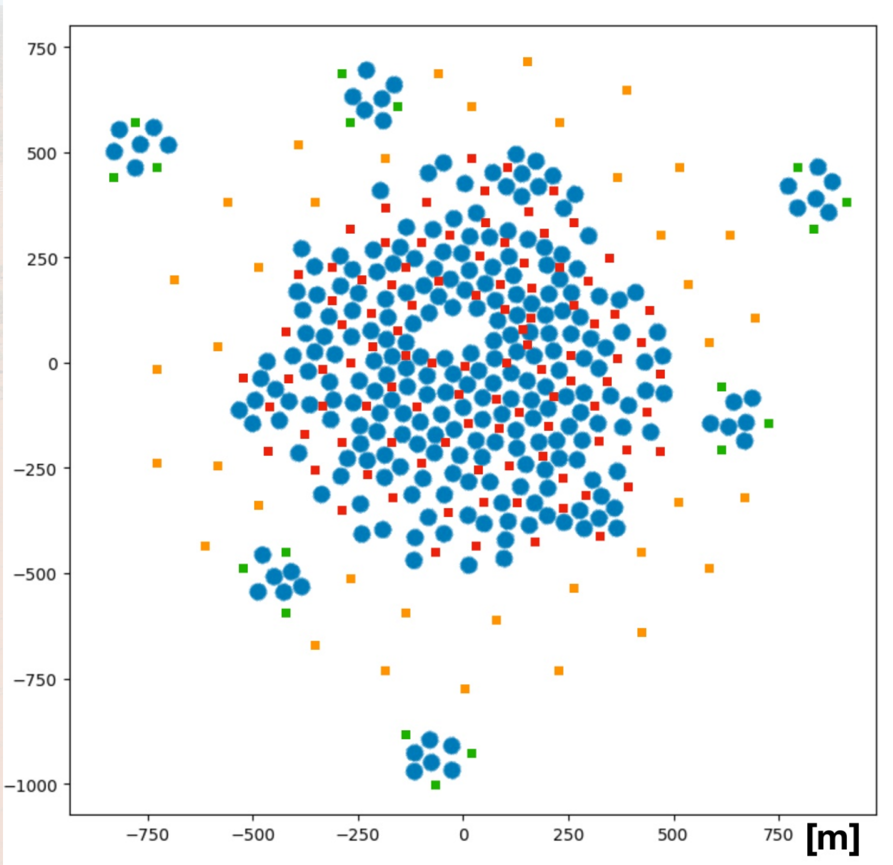
50 – 100 MHz



~ 5000 antennas triggered

- From 100 showers which all have the same X_{max}
- Reconstructing all together limited by number of simulations (CPU time)

Particle detector array at SKA-Low



- Particle array of ~ 100 detectors
- Scintillators from Kascade-Grande collaboration (KIT)
- Funding: 740k euro by FWO (Belgium)
- Test array of 8 prototypes being built

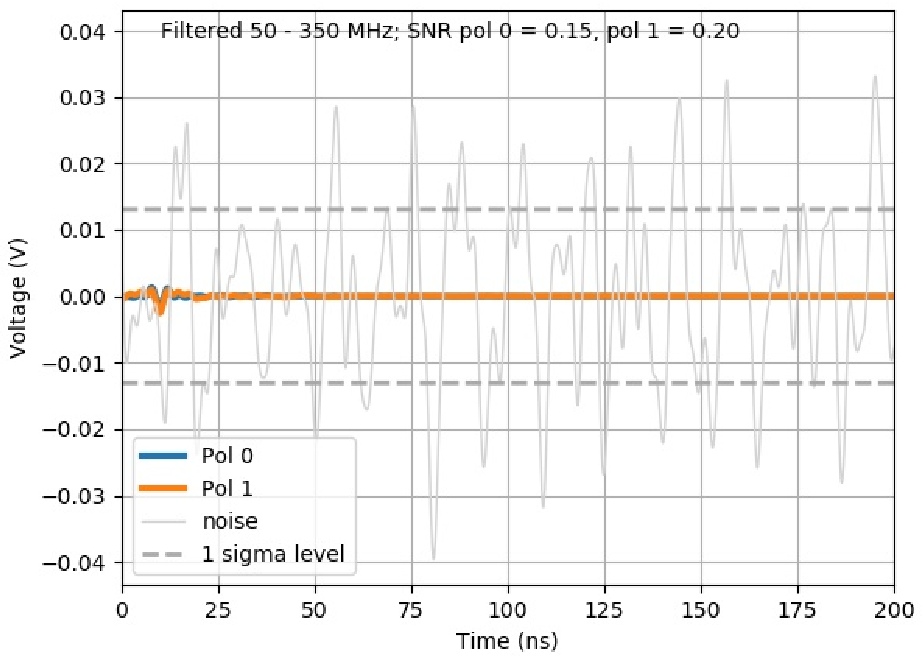
Prototype at Murchison Wide-field array site (next to SKA-Low)

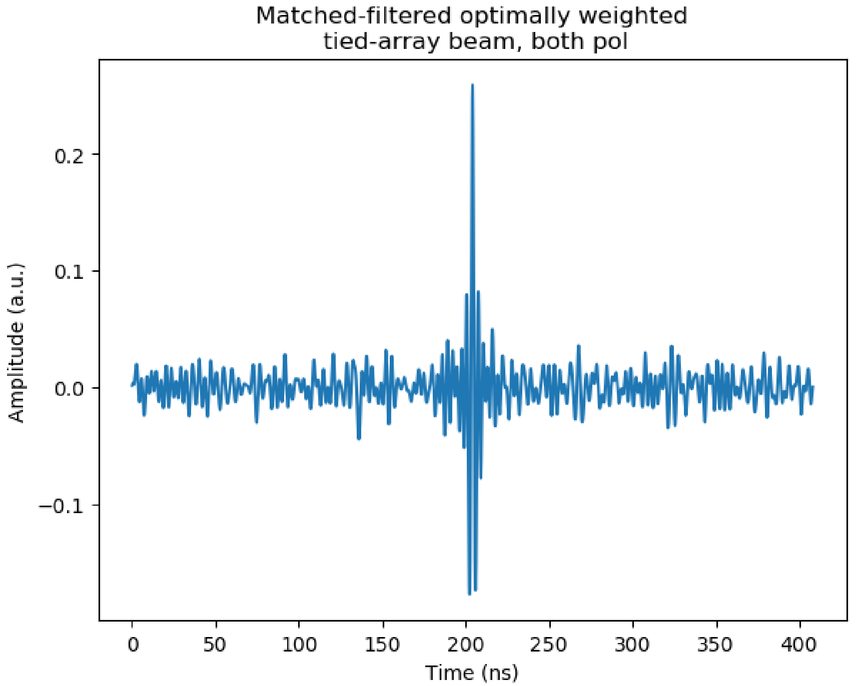
Design:
University of Manchester

Deployment:
Curtin University

Detecting PeV gamma rays?

- Detecting radio signals well below the noise in every antenna
  - interferometry/beamforming needed
  - Optimal (matched) filtering
  - External or online trigger??





Summary / On the science case

- Xmax resolution < **8 g/cm²**
  - Make the most detailed picture of individual air showers ever
  - Will reveal limitations in the models – including the hadronic interaction models at energies > LHC !

- Improve the mass composition measurements
  - Extra, independent information from longitudinal distribution
  - Better **H / He** separation, astrophysically relevant
  - Extends to lower energy range, <= **10^{16} eV**
  - Effective area ~ **x5**, hence better statistics

- Two similar observatories in North and South
  - LOFAR and SKA-Low
  - Same principles, same analysis methods, same code
  - Resolve tension Auger – LOFAR??