INVESTIGATING

DOUBLE BUMP AIR SHOWERS WITH THE LOFAR

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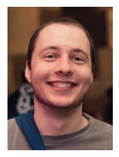


Link to proceedings

What goes on in the transition region?

Cosmic rays originating from between the knee and ankle stem from the transition region where sources shift from Galactic to Extra-galactic.

There might also be a secondary Galactic component, possible contributors include [1]:

Re-acceleration at a Galactic wind termination shock.

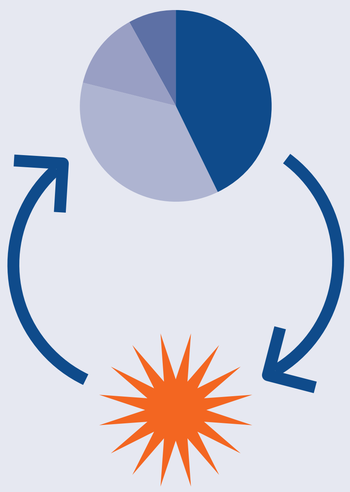
?

Acceleration in strongly magnetized shocks from Wolf-Rayet supernovae.

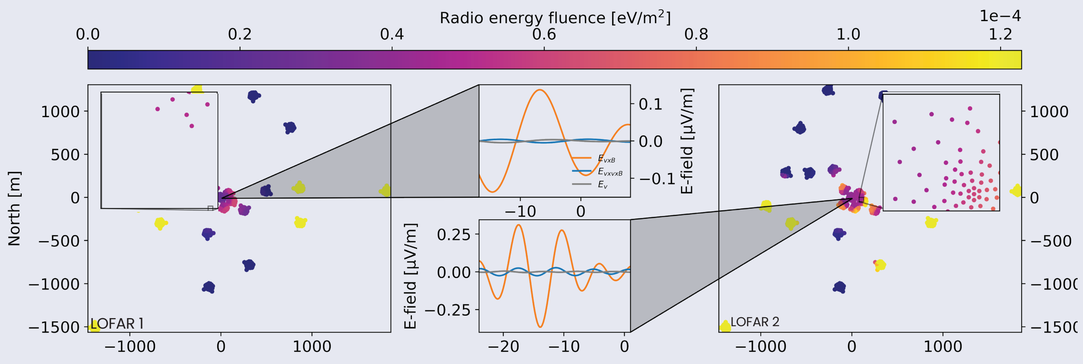
To find the onset of the Extra-galactic component and possible secondary galactic sources we need precise mass compositions.

We want
mass composition

We need
hadronic interaction models



We are stuck in an endless loop of **interpretation** and **extrapolation**.



The most precise radio-based air shower detector is LOFAR. Compared to this, the upgraded LOFAR 2 will have:

LBA and HBA antennas measuring at the same time.

A larger bandwidth of 50-180 MHz compared to 30-80 MHz.

This will enable the most accurate radio-based air shower reconstructions ever made.

Both the traces and radio footprint show much more complexity.

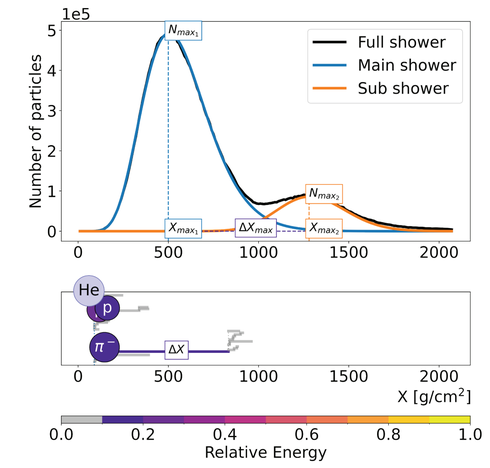
A study on the X_{max} resolution and mass composition capabilities of SKA-Low has recently been published [3].

What if a special type of shower can break this loop?

Anomalous development:

- Some shower particles carry a significant fraction of the total energy.
- At least one of these particles travels a long distance before interacting.

This will form a subshower deep in the atmosphere. The likelihood of this occuring depends on the hadronic cross-section.

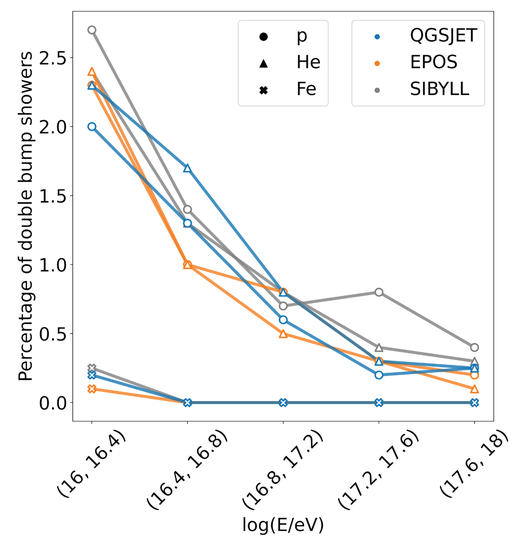


Scan to see if things are always this simple

We define a double bump shower as one where using the Akaike information Criterion (AIC) [2] a double Gaisser-Hillas fit returns a lower AIC value compared to a single one. The AIC value balances the goodnness-of-fit with model complexity.

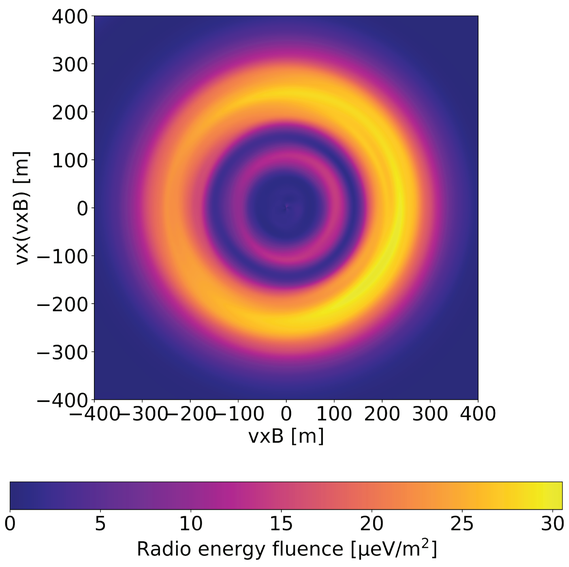
Apart from measuring the rate of double showers we also reconstruct ΔX and the energy in the secondary bump.

These parameters are sensitive to hadronic interaction models and mass composition.



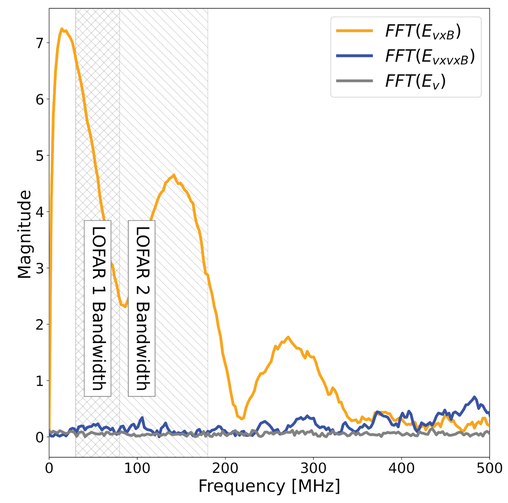
Filtered (200-250 MHz) radio-footprint. A double ring structure appears which might seem to correspond to the two shower components, but they are more accurately explained as interference maxima. At even high frequencies, this pattern can show three or more rings.

Scan to see if you can find more intriguing patterns



The interference is also clearly seen in individual antennas and is the case for all shower geometries.

Using the frequency minima caused by interference and the antenna position we can reconstruct X_{max_1} and X_{max_2}.



With the LOFAR 2 we will be capable of detecting these anomalous events. By studying them, we obtain a new handle on the cross sections of the hadronic interactions in air showers. This will open a new window on the hadronic models and potentially give us a new, mass-sensitive parameter.

(1) S. Thoudam et al. Astronomy & Astrophysics, 595 (2016)
(2) P. Stoica et al., IEEE, 21 (2004)
(3) A. Corstanje et al., PRD accepted arXiv:2504.16873 (2025)