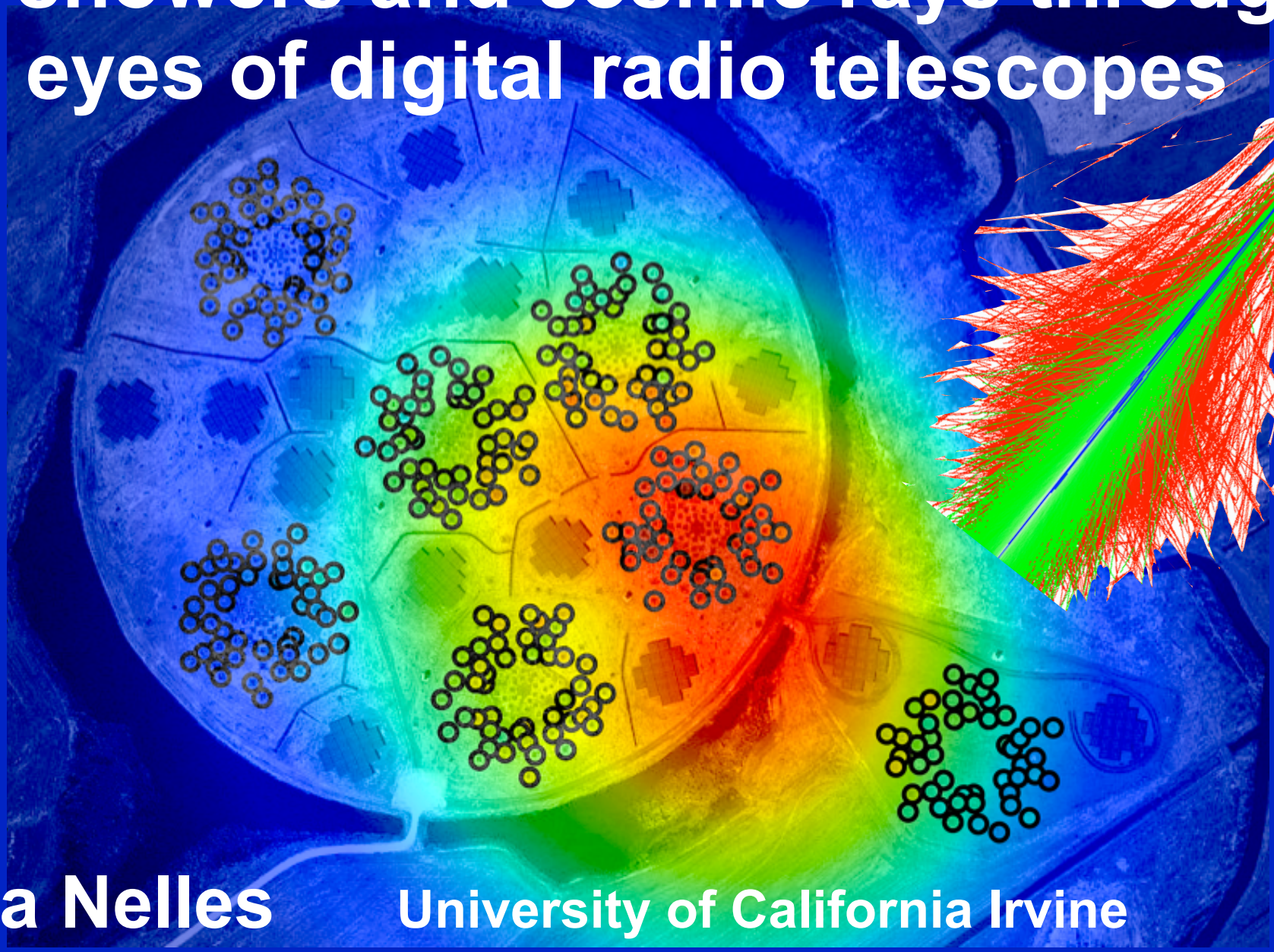
Air showers and cosmic rays through the eyes of digital radio telescopes



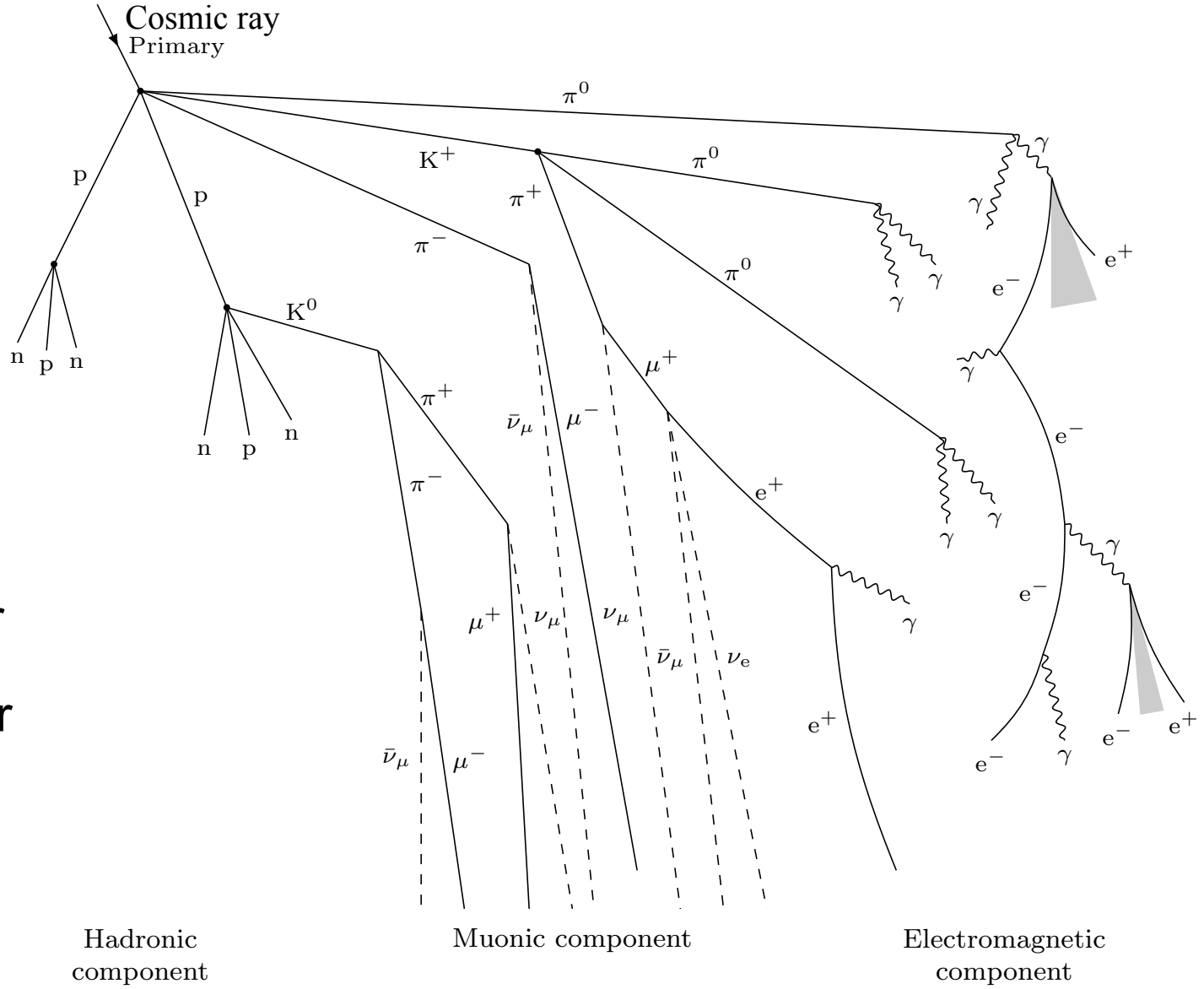
Anna Nelles **University of California Irvine**

LOFAR Key Science Project: Cosmic Rays

A. Bonardi, S. Buitink, A. Corstanje, H. Falcke, J.R. Hörandel, P. Mitra, K. Mulrey, J.P. Rachen, L. Rossetto, P. Schellart, O.Scholten, S. ter Veen, S. Thoudam, T.N.G. Trinh, T. Winchen

Cosmic rays and air showers

- Cosmic rays of energies > 10^{14} eV are not observed directly on Earth
- Flux decreases with energy, 1 particle per m^2 per hour to 1 particle per km^2 per year at highest energies
- Extended detectors needed



Radio emission of air showers

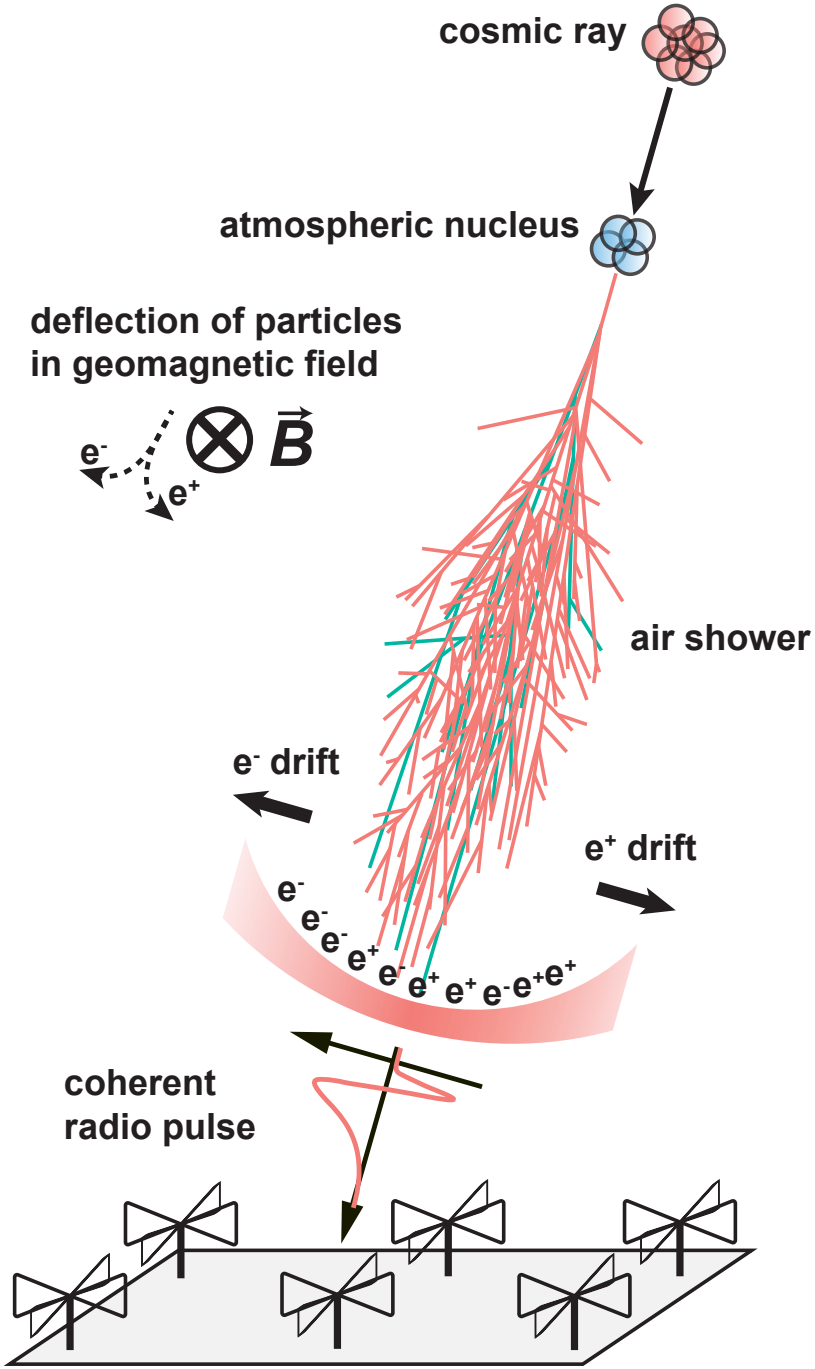
Electromagnetic component of shower responsible for radio emission

Emission arises from:

- e+ and e- are accelerated in geomagnetic field (geomagnetic effect)
- more e- than e+ in the shower by collecting e- from atmosphere (charge excess)

Emission is affected by:

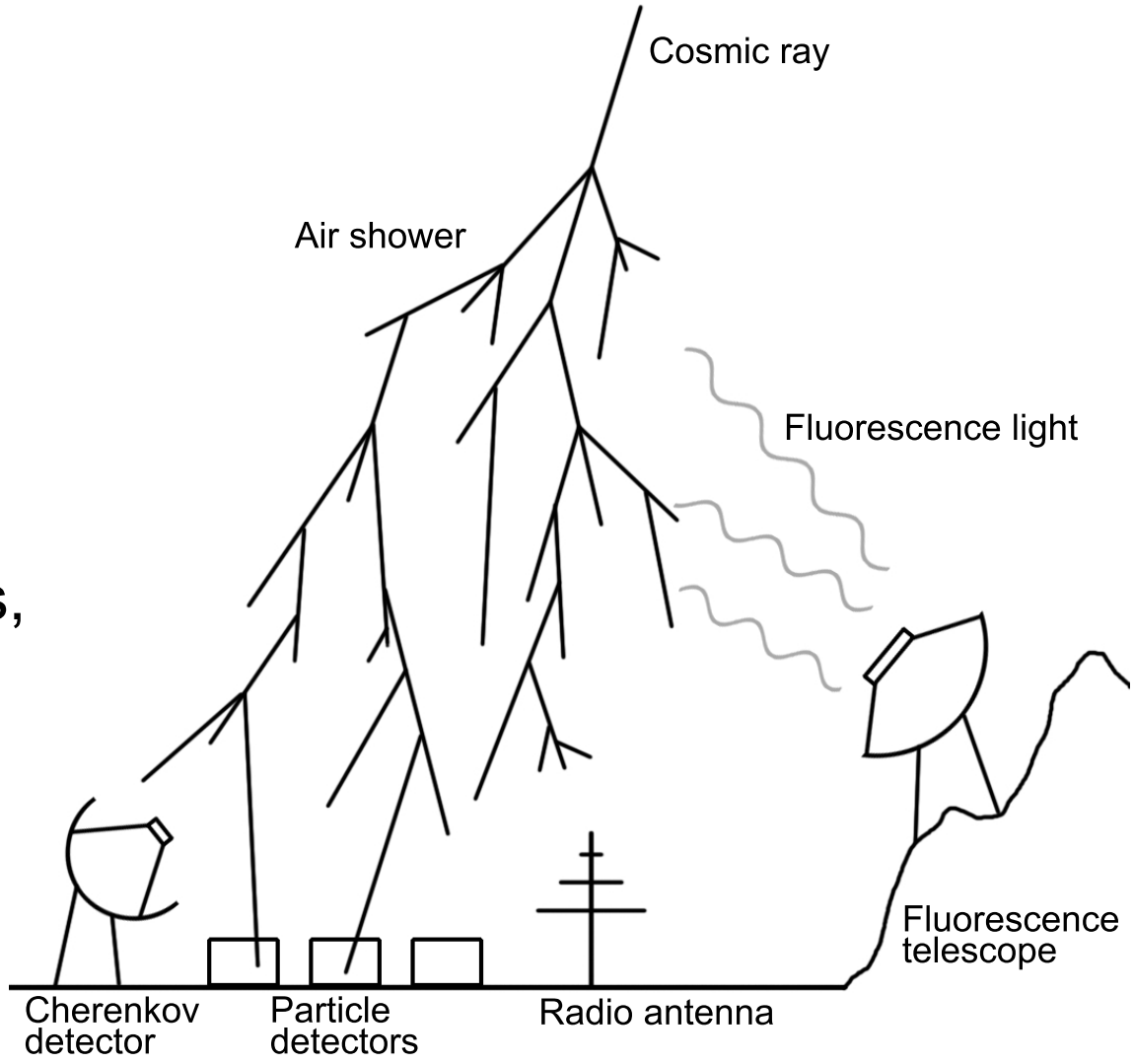
- Superposition of emission
- Cherenkov effects



Traditional methods & radio detection

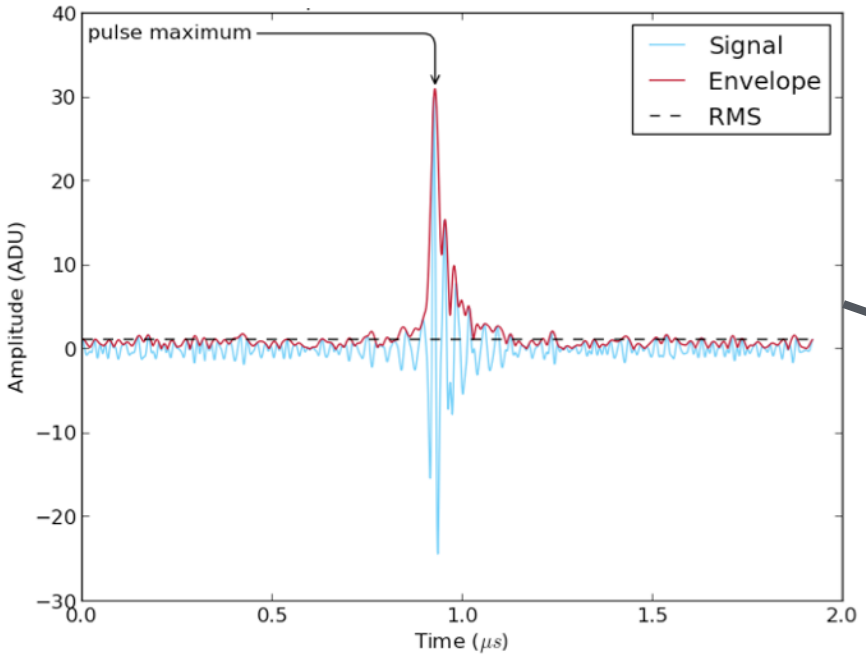
Air showers can be detected in many ways

- **Particle detectors**:
  100% duty cycle
  little sensitivity to primary particle
- **Cherenkov and Fluorescence detectors**:
  10% duty cycle and high quality observing conditions, sensitive to primary
- **Radio detectors**:
  > 95% duty cycle and sensitive to primary particle

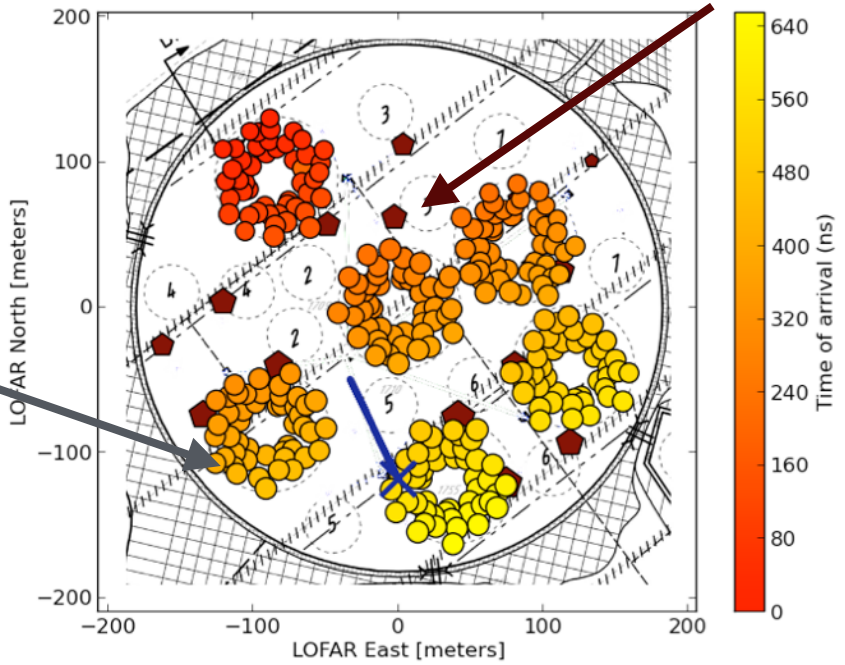


Detection at radio telescopes

Single antenna data LOFAR 30-80 MHz

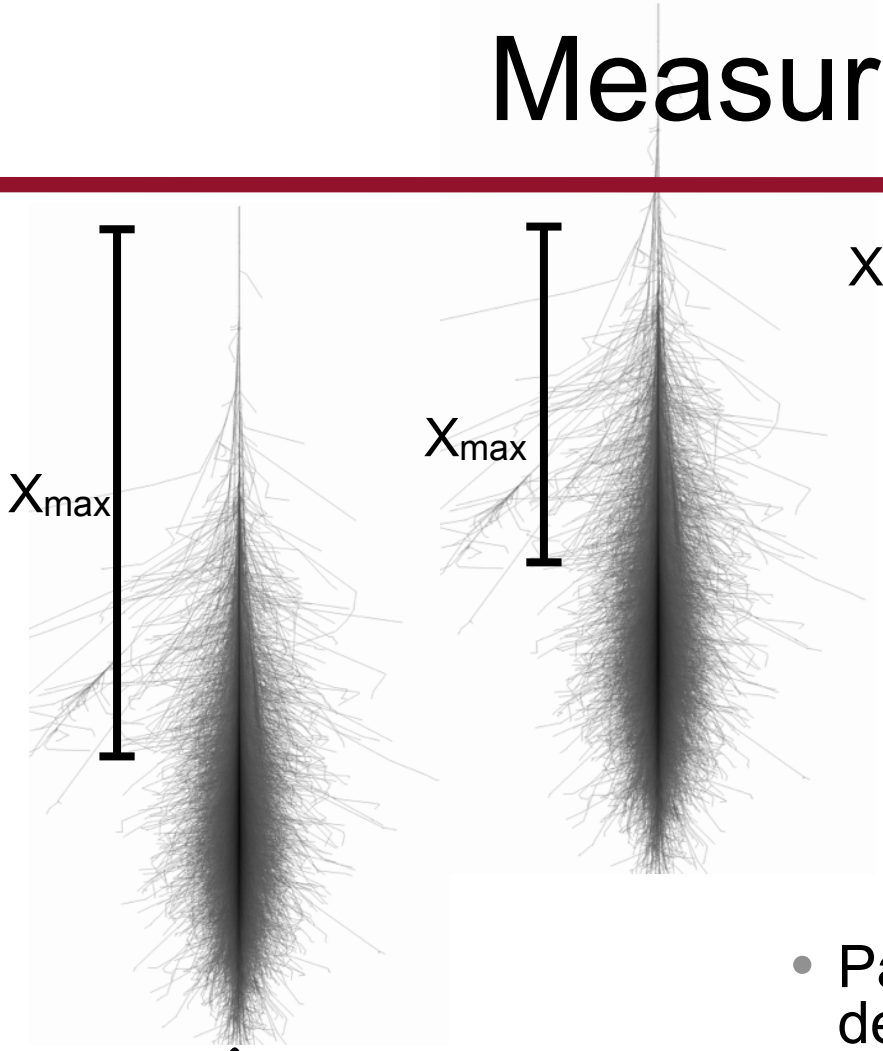


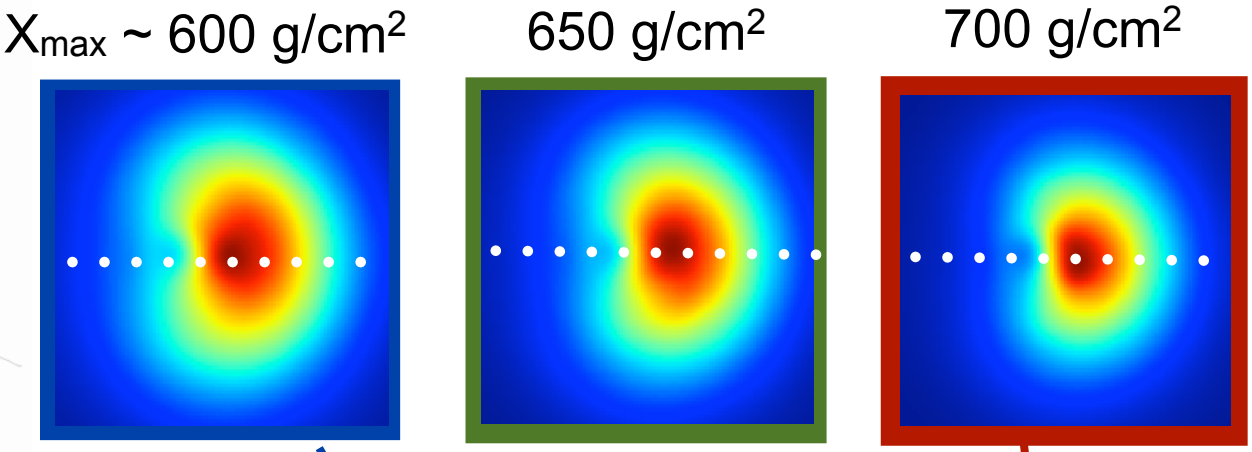
Particle detectors provide trigger

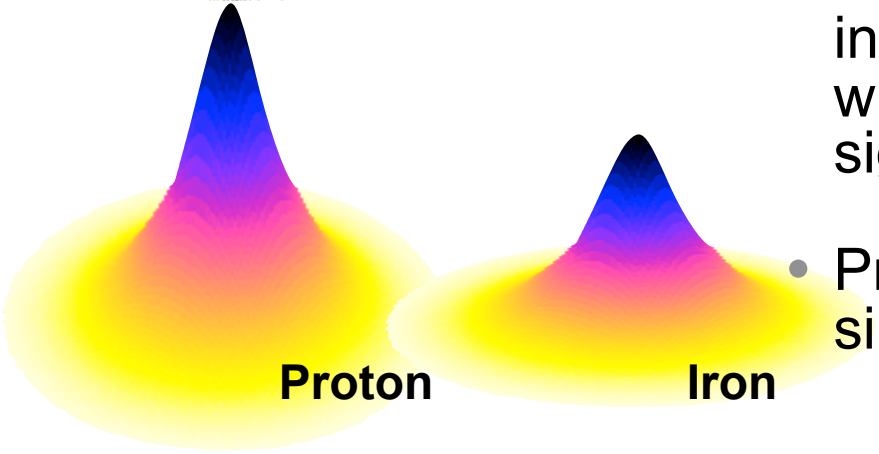


- Signals are short non-repeating broad-band pulses
- Need access to raw voltage data
- full frequency range: 10 - 300 MHz, about 50 nanoseconds
- Arrival times in antennas determined by shower arrival direction, source in atmosphere

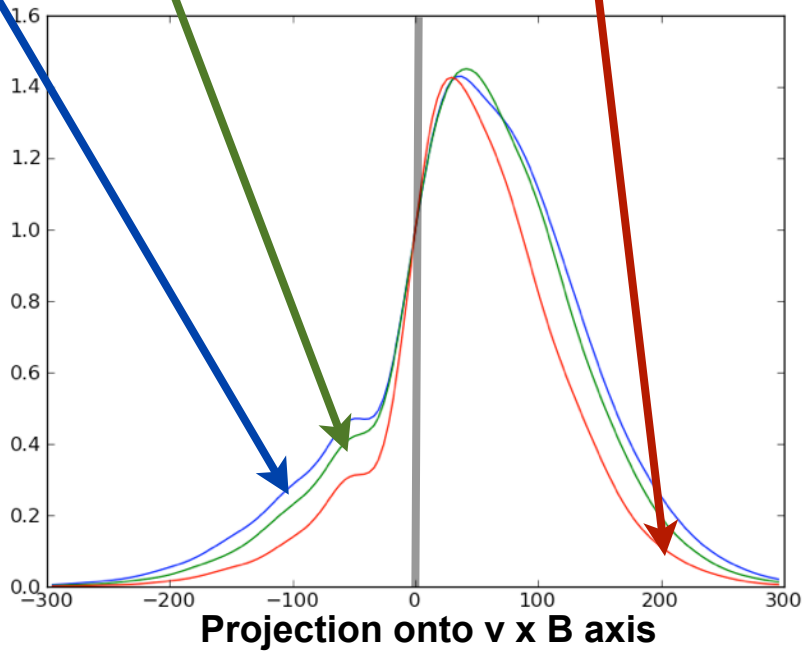
Measuring composition





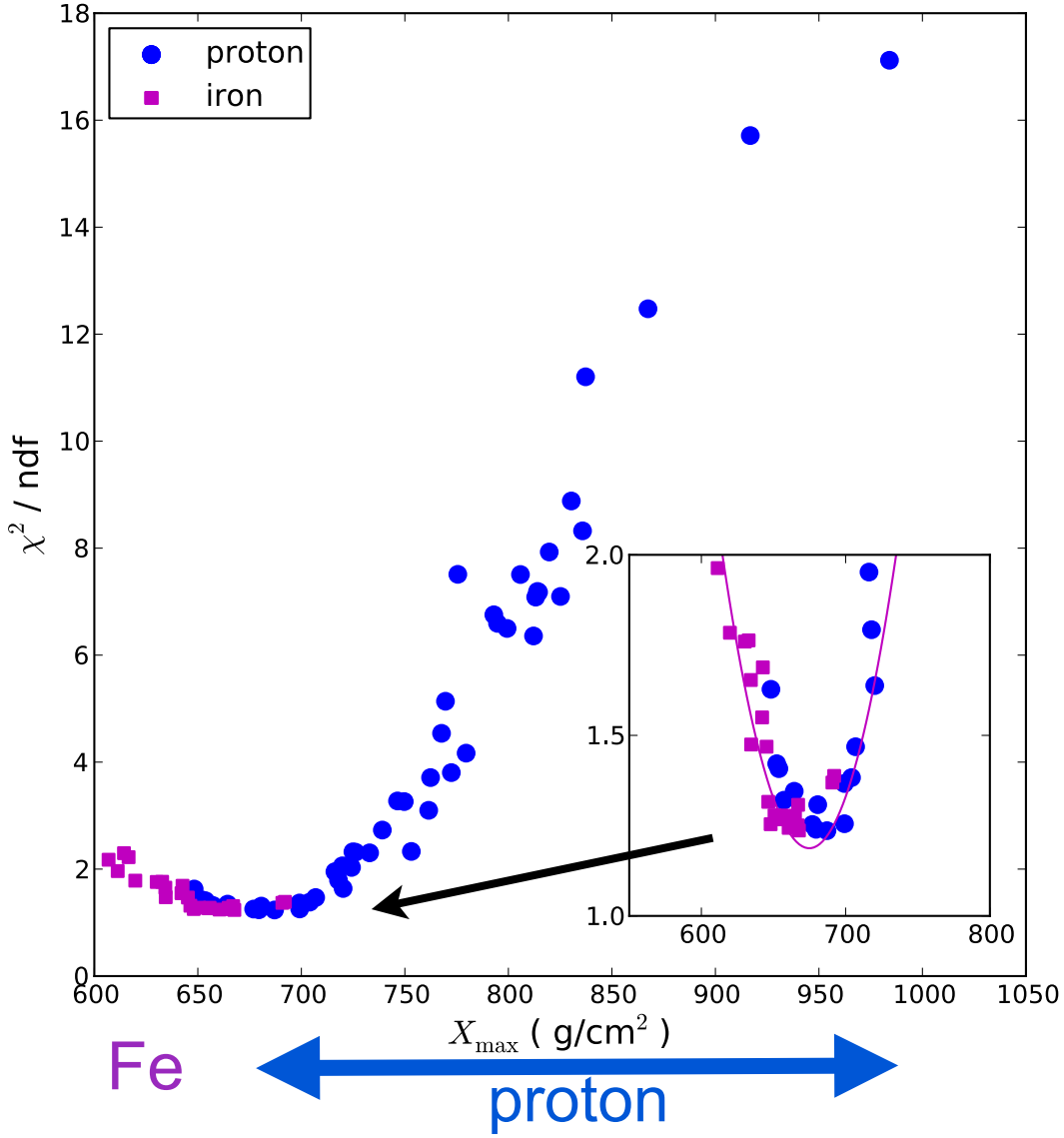


- Particle type determines interaction height, which determines signal distribution
- Prediction can be simulated



Measuring composition

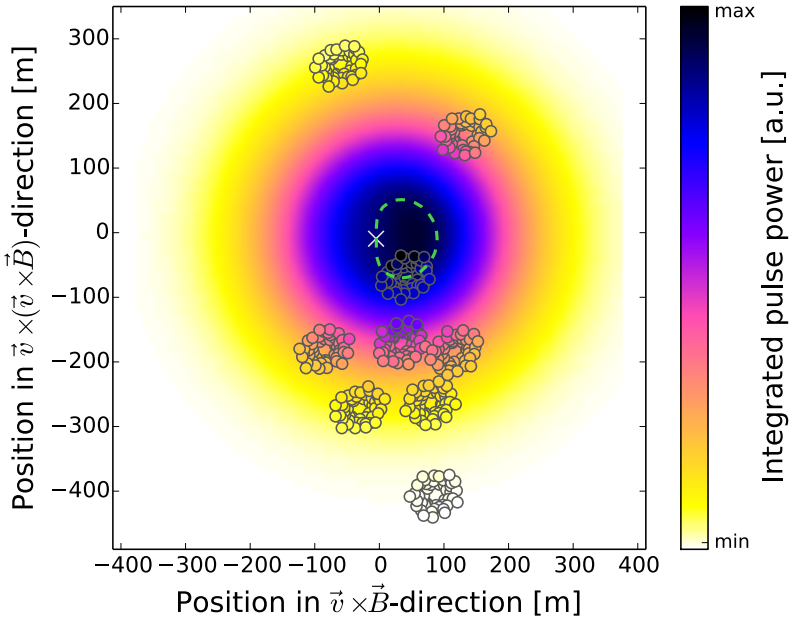
Buitink et al., Phys. Rev D, 2014

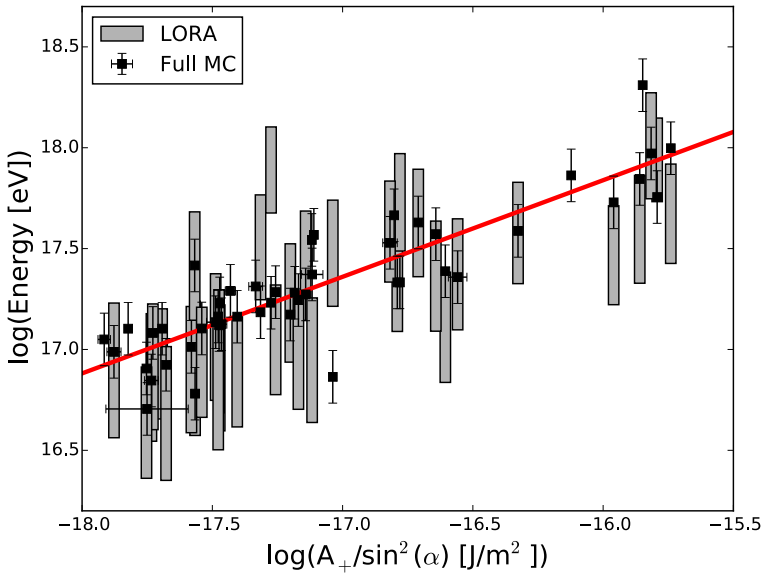


- Fit quality of simulated pattern to measured data, determines most probable value for shower height
- LOFAR data is extremely precise, often better than 20 g/cm^2, which is current standard of field
- Detailed measurement of single shower only possible with radio
- Examples: Proton and Iron simulations

Measuring energy

Nelles et al. JCAP 2015



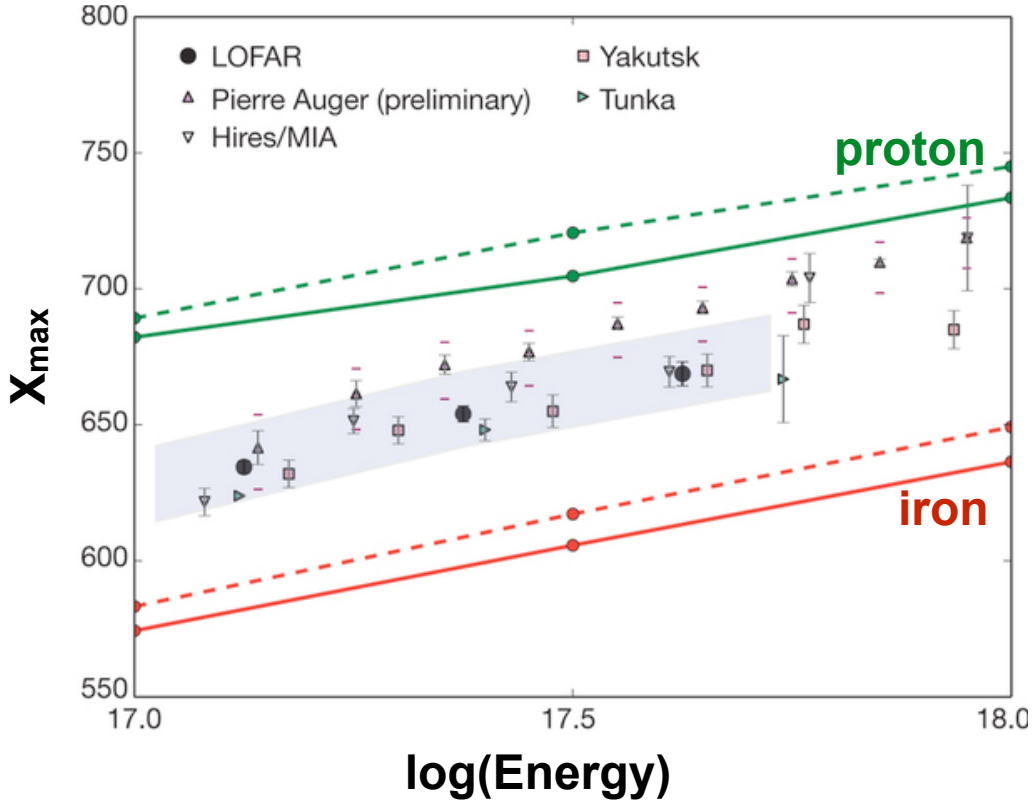


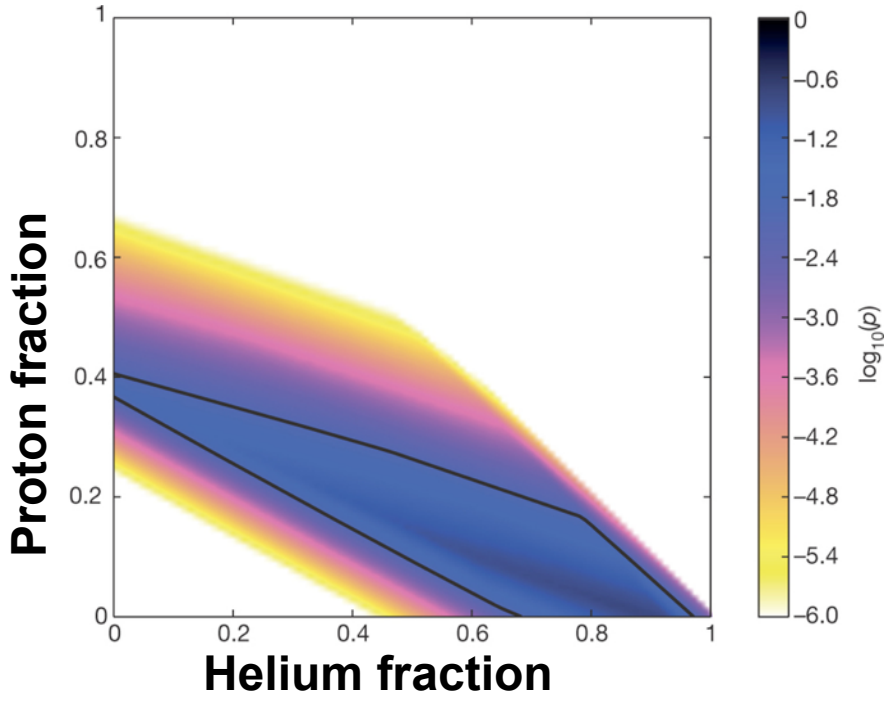
- Radio emission also excellent in determining energy
- Fitted intensity pattern is directly proportional to energy of the shower
- Energy resolution better than particle detectors
- Very small systematic uncertainties

- **With energy and composition we can do Astrophysics**

Astrophysical results

Buitink et al, Nature 2016



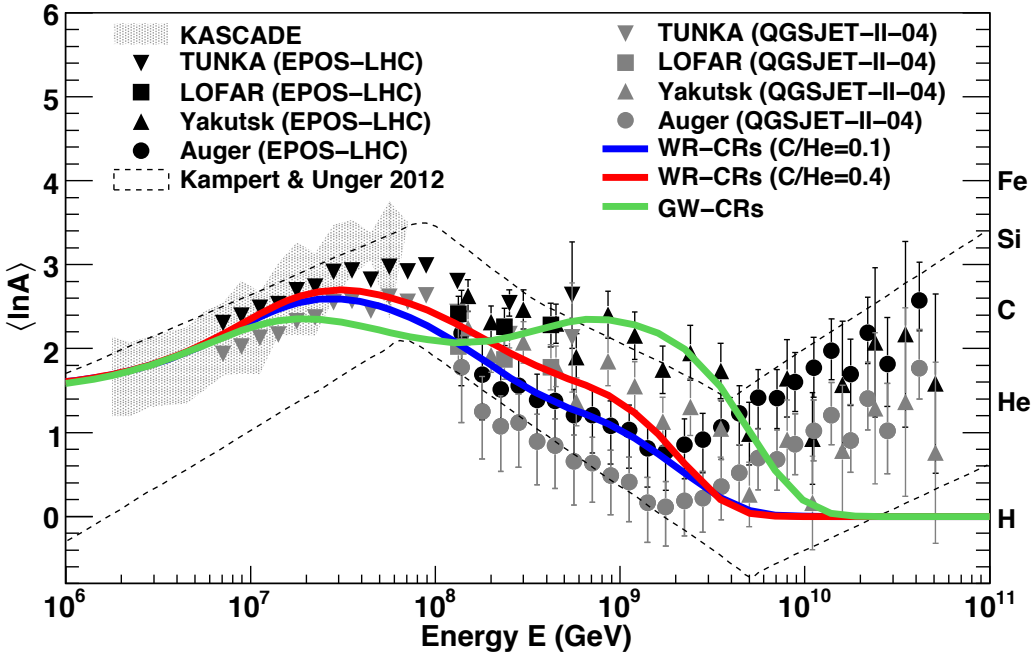


- Already with 100 showers, measurements competitive to other experiments in the field
- High precision measurements determine strong light component at transition energies of 10^{17} - 10^{18} eV

Astrophysical implications

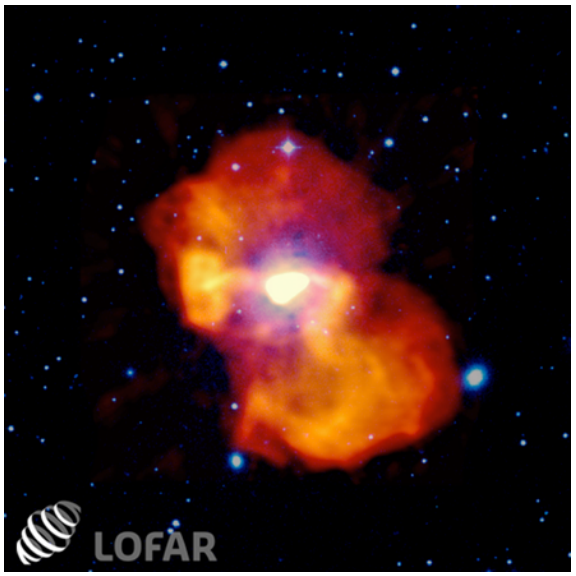
- LOFAR results already now put tension on theories:
- Strong light component argues against single type of source of Galactic cosmic rays after the knee, which suppresses protons
- Strong light component, but not purely protons, argues against imprint of pair-productions
- More likely a second Galactic component, caused by for example Galactic-Wind or Wolf-Rayet stars

Thoudam et al, A&A 2016

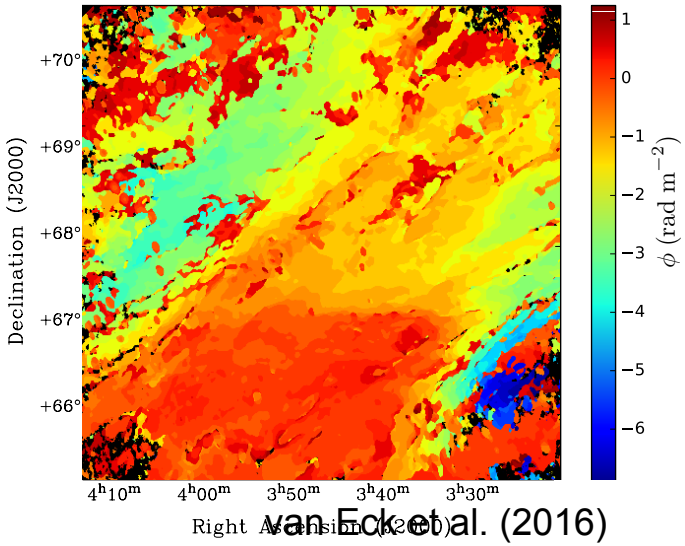


Synergies in astrophysics

Detailed source observations

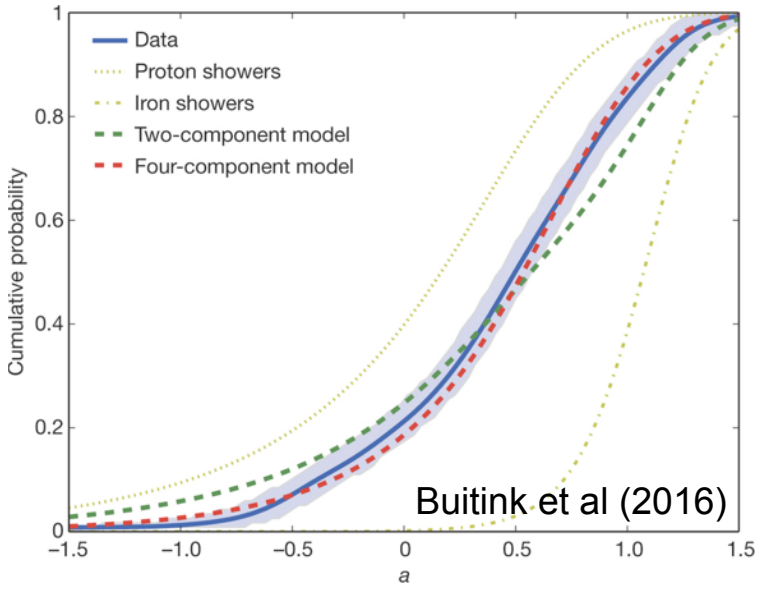


Magnetic field measurements and models



van Eck et al. (2016)

Improved composition and energy of cosmic rays



Buitink et al (2016)

better understanding of sources

better understanding of propagation

Synergies in calibration methods

Cosmic ray measurement

- Single antenna, raw voltage data
- no beamforming
- no time-integration

- Very detailed understanding of individual antenna needed

- Time-dependent monitoring of single antenna performance

- Absolute calibration on artificial sources

Astronomical observation

- Combined antenna signals, visibilities
- beamformed
- time-integrated

- Detailed understanding of station-beam needed

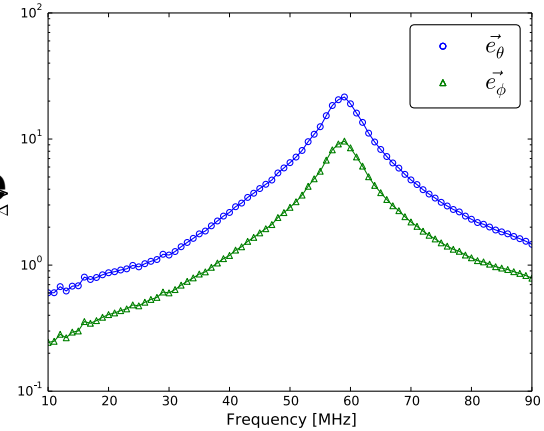
- Time-dependent monitoring of array performance

- Absolute calibration on astronomical sources and sky models

Antenna calibration

Flying reference source

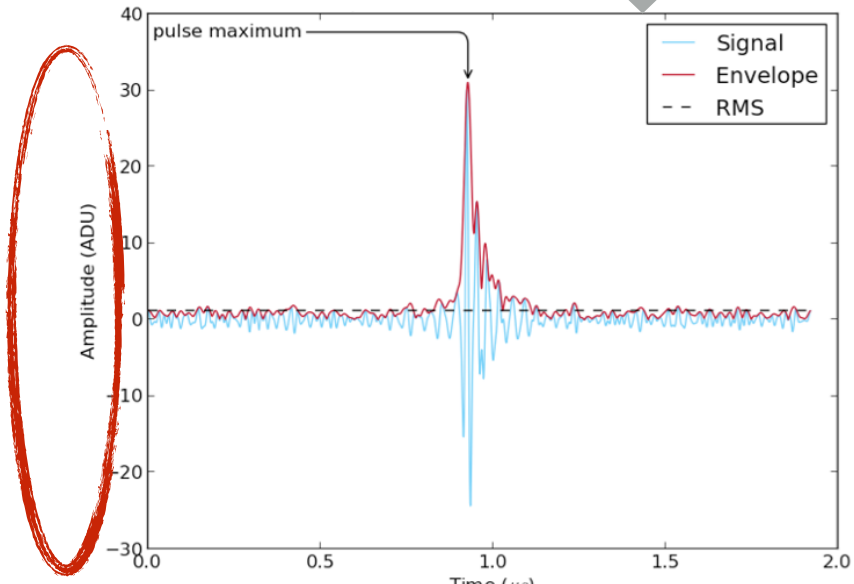
Model of the electronics and antenna response



Stationary reference source

iterative improvement

correction data

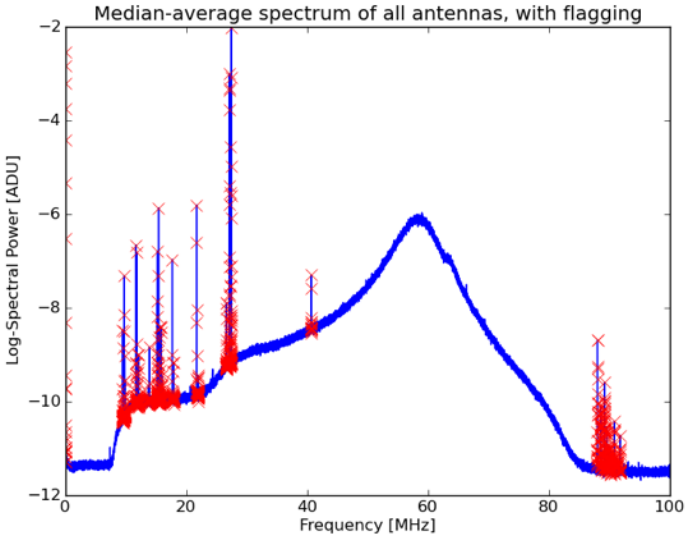


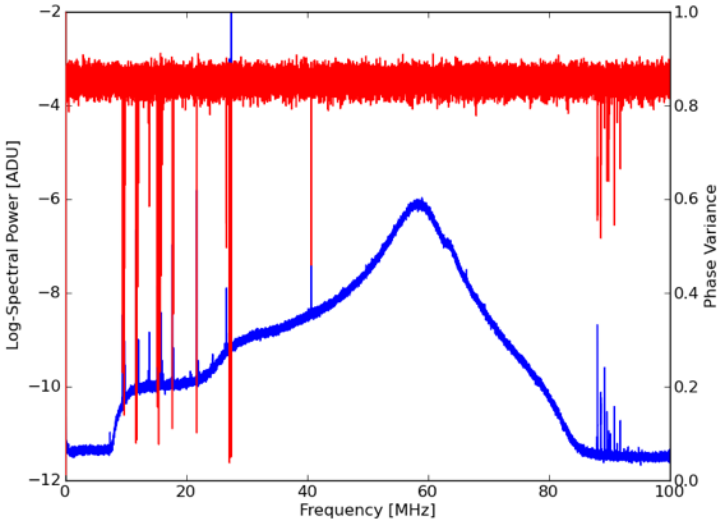
"real units"

- Totally independent from sky models, agreement provides confidence

Nelles et al. JINST 2015

RFI cleaning

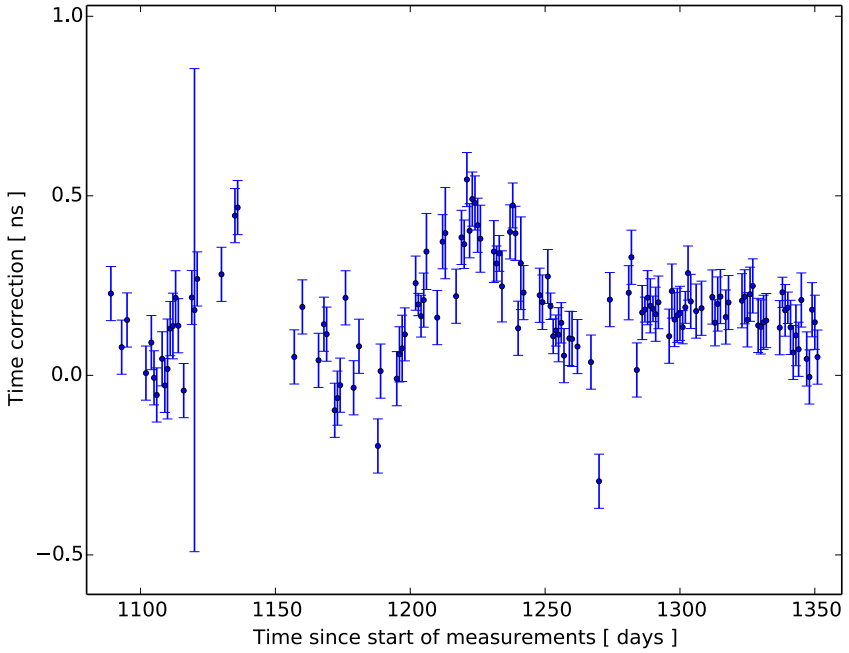


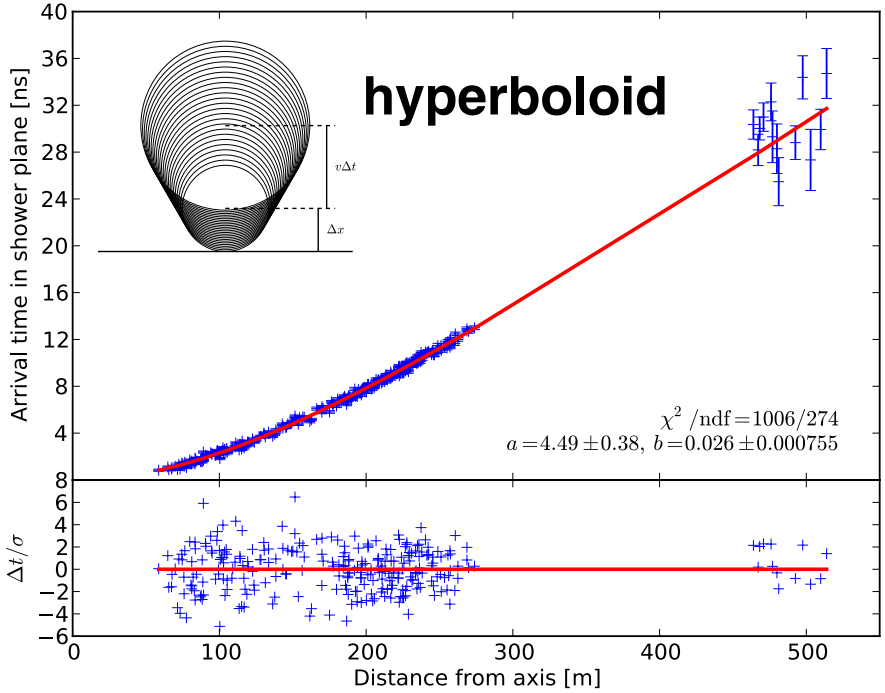


Corstanje et al. A&A 2016

- In raw voltage data: A stable phase difference between two-antenna pairs reveals RFI transmitter
- Data can be recorded and flagged offline
- Better accuracy than baseline fitting and continuous monitoring of RFI environment
- Phase difference also reveal timing stability of system

Timing calibration



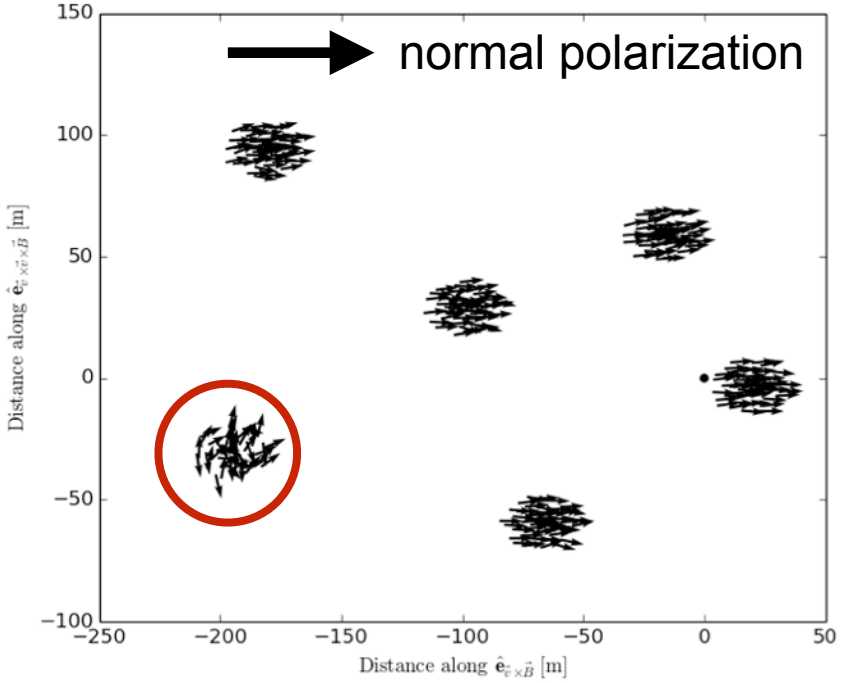


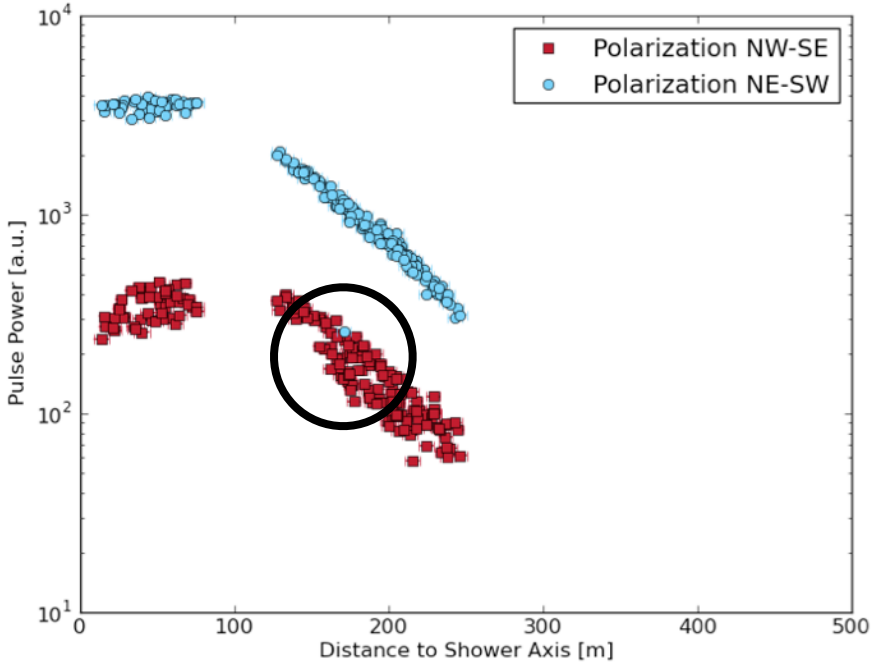
- Monitoring of phase differences shows that also LOFAR clock shows small drifts
- Larger jumps (sample shifts) are immediately recognized

- Cosmic rays signals arrive as hyperboloid with subnanosecond structure
- Perfect cross-check for system stability

Instrument health

- Any radio telescope can detect air showers, if there is access to raw voltage data
- Unexpected failures are easily identified in raw voltage data



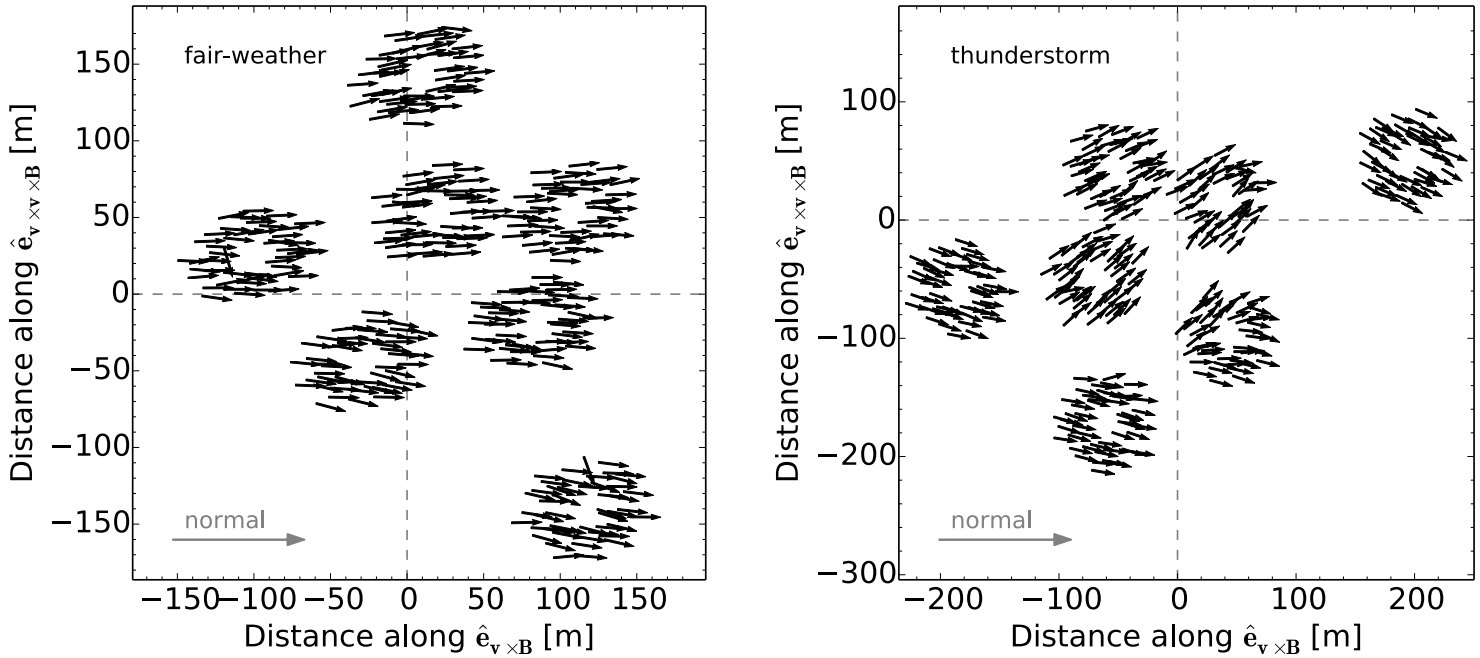


- Timing instability shows in **polarization** reconstruction
- No monitoring run needed

- Swapped cable in raw data
- Identifiable without analysis

Thunderstorms

Schellart et al. PRL 2015, Trinh et al. PRD 2015, Scholten et al PRD 2016

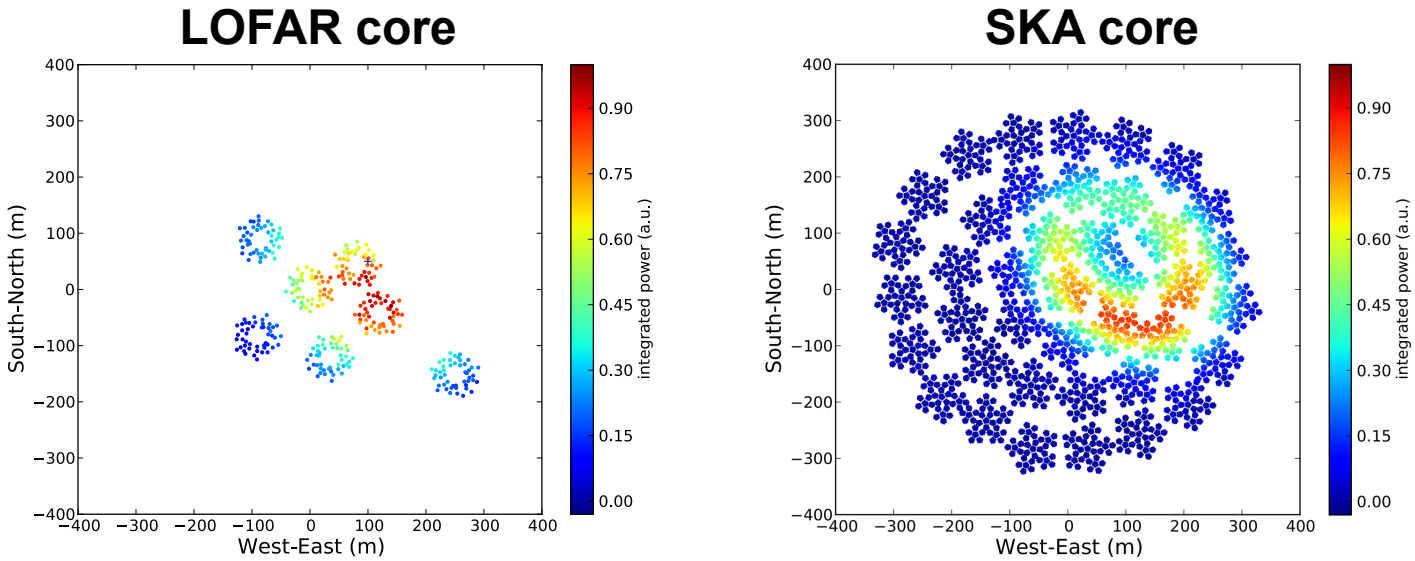


- Cosmic rays during thunderstorm show unique polarization signature
- Traces the strength and the height of electric fields
- Cosmic rays radio signals are a surprising tool to study thunderclouds

Future plans

- LOFAR will continue to do high impact cosmic ray science, better statistics, higher energies, improved systematics
- Continued thunderstorm measurements — little statistics in the Netherlands

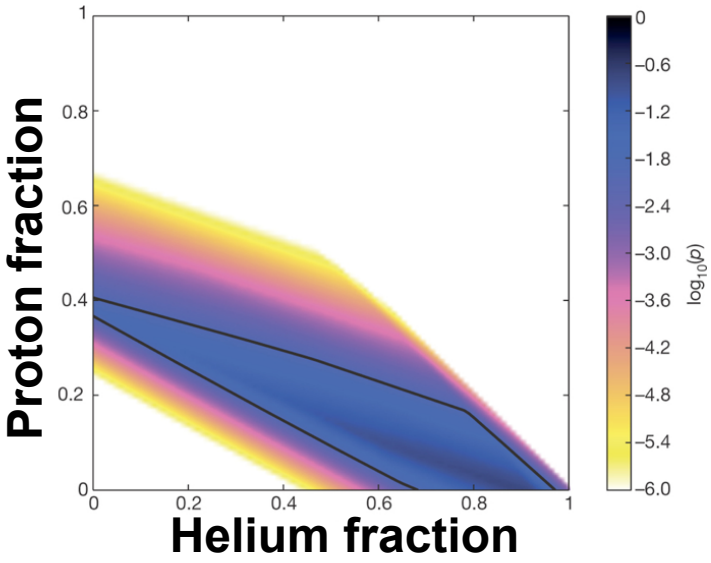
- Long-term effort: SKA - ultimate precision for cosmic rays and particle interactions in shower



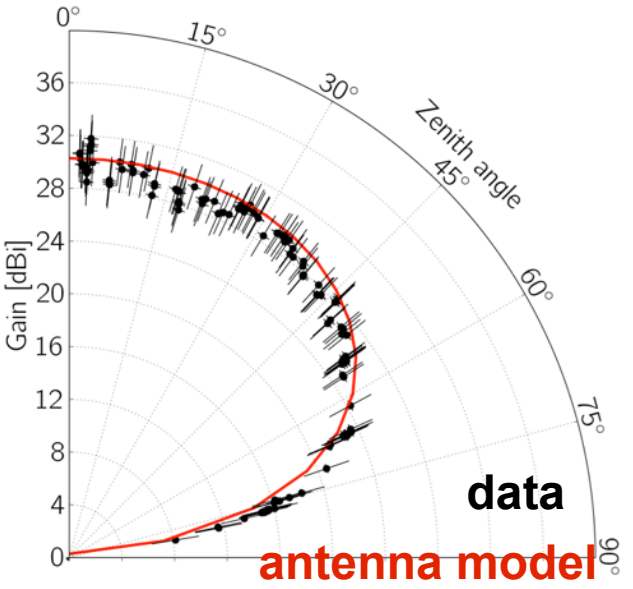
- Requires engineering change proposal, currently under discussion

Conclusions

- Exciting astrophysics with LOFAR
  - LOFAR can resolve shower maximum to better than 20 g/cm^2
  - good resolution reconstruction of cosmic ray particle type
  - will lead to improved understanding of sources and propagation



- Cosmic ray data is perfect monitoring tool
  - continous RFI monitoring
  - continuous timing-calibration and monitoring
  - in-depth study of antenna properties
  - absolute calibration without sky models



- Unexpected science such as studying electric fields during thunderstorms