Radio detection of extensive air showers

Jörg R. Hörandel Radboud University Nijmegen http://particle.astro.ru.nl

Present Detection Methods

The Pierre Auger Observatory

Hybrid detection of extensive air showers

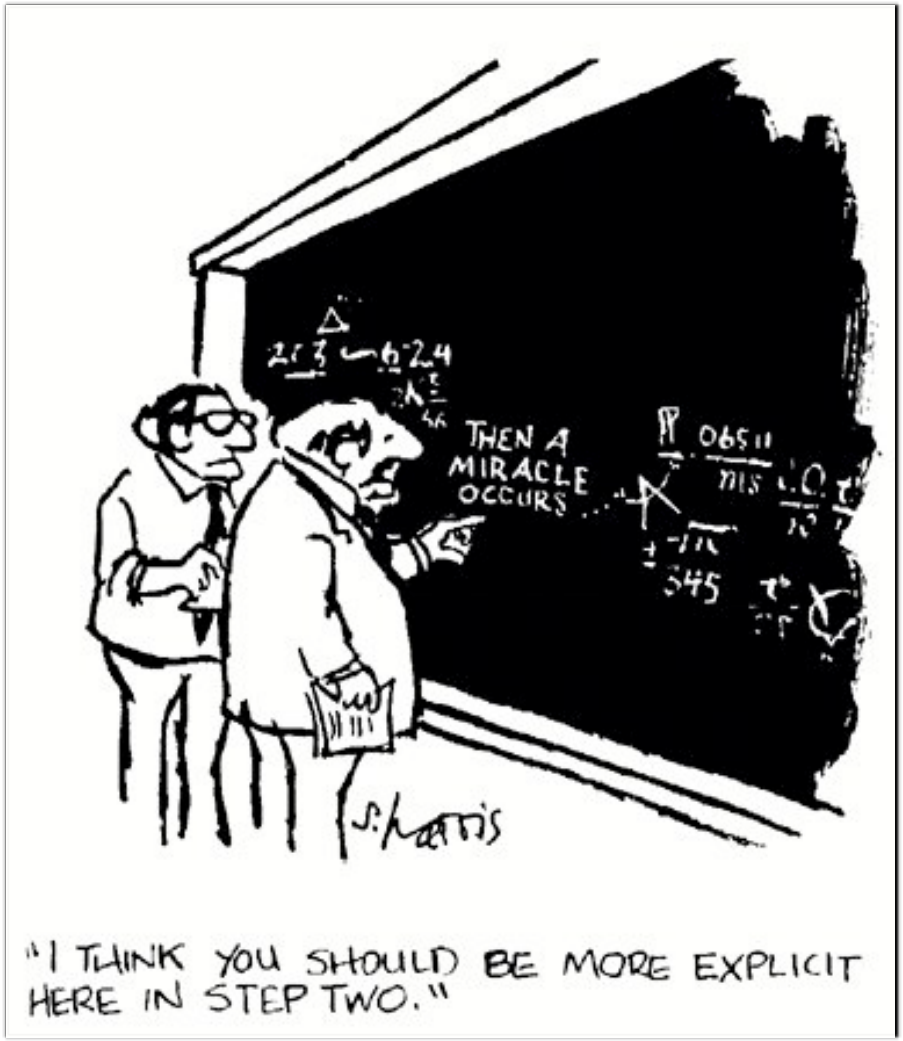
Water Cherenkov detectors

- **lateral distributions on ground level**
- **~100% duty cycle**

Fluorescence telescopes

- **longitudinal shower development**
- **~15 % duty cycle (moonless nights)**
- **light absorption by aerosols**

Radio Emission



"I THINK YOU SHOULD BE MORE EXPLICIT HERE IN STEP TWO."

Radio Emission in Air Showers

- Mainly: Charge separation in geomagnetic field

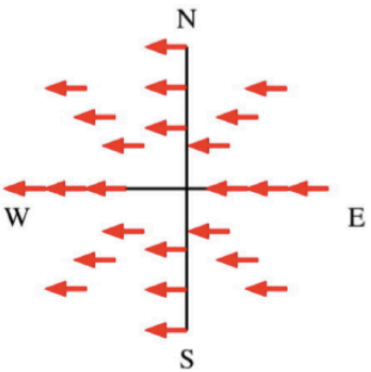
$$\vec{E} \propto \vec{v} \times \vec{B}$$

Theory predicts additional mechanisms:

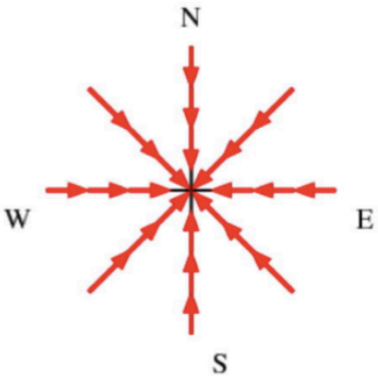
- excess of electrons in shower: charge excess
- superposition of emission due to Cherenkov effects in atmosphere

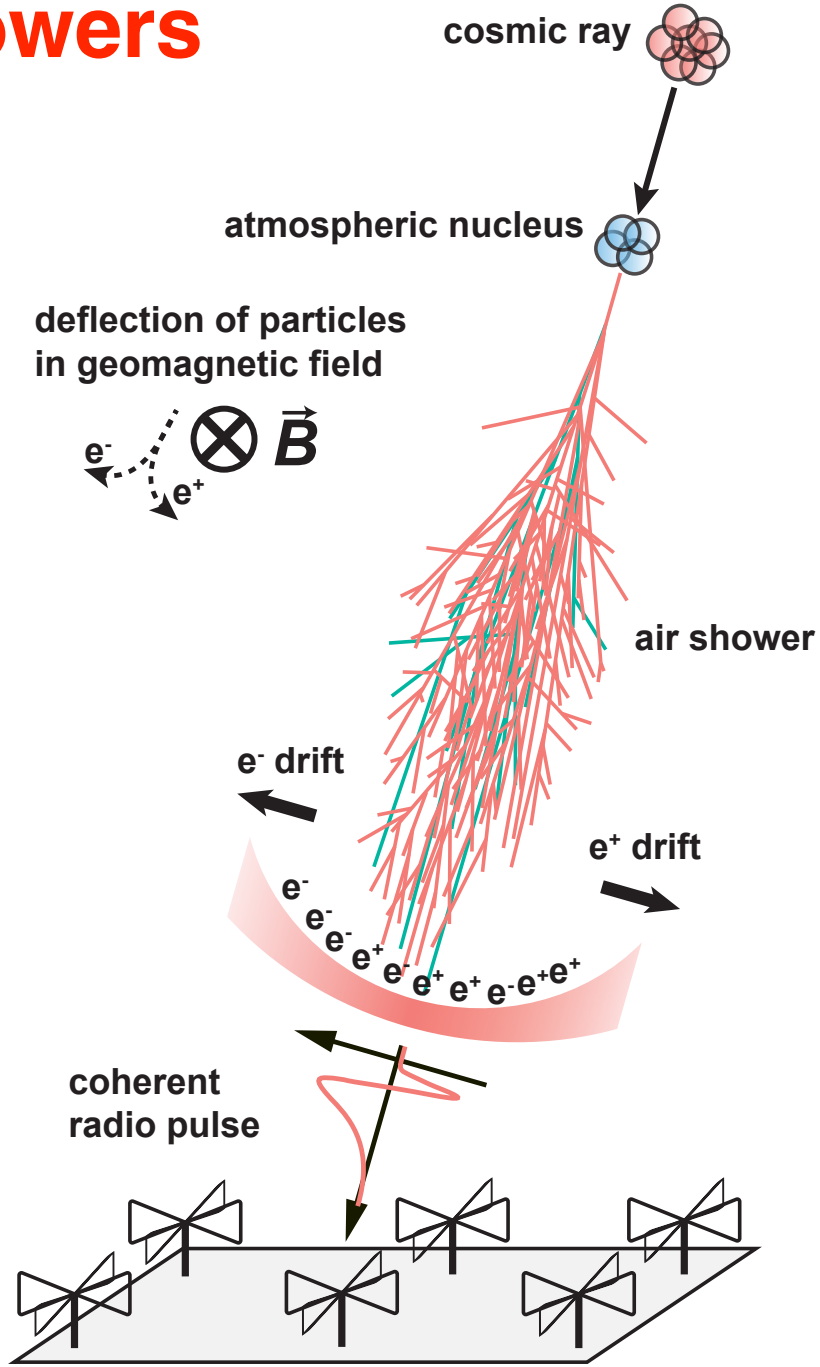
polarization of radio signal

geomagnetic effect



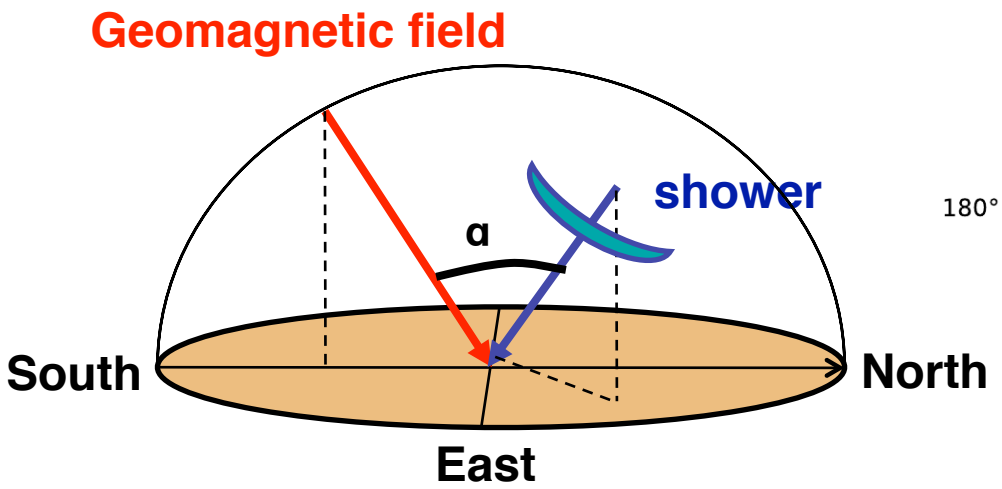
charge excess



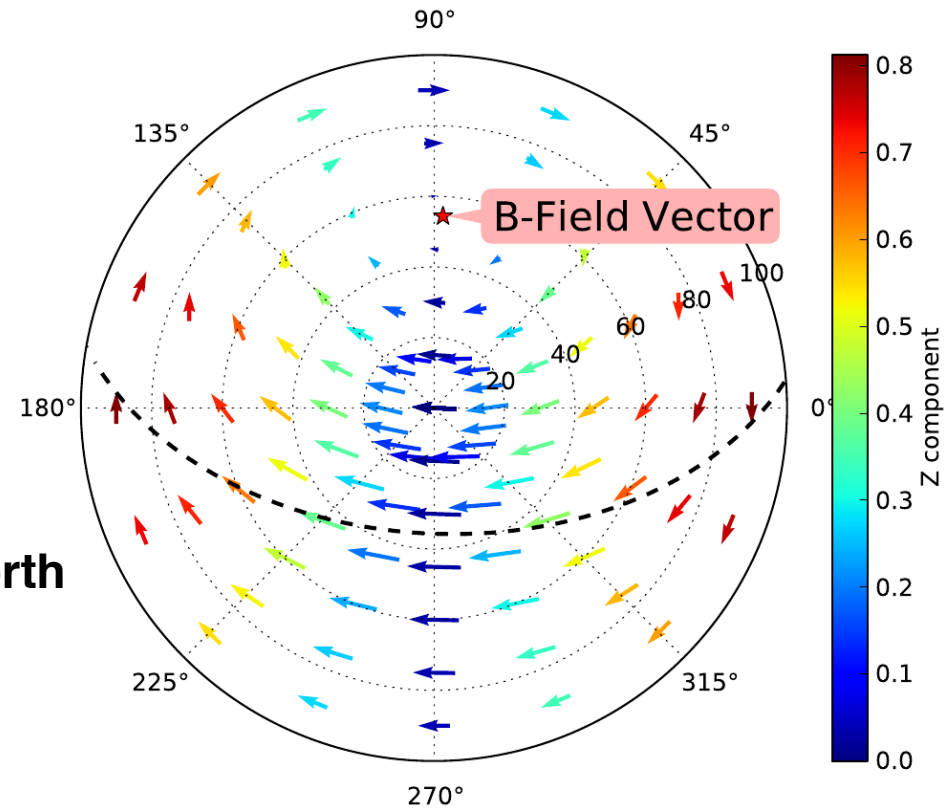


Synchrotron radiation in Geomagnetic Field

- radio emission dominated by geosynchrotron emission
- emission strength depends on angle to Earth's B field



$$\vec{\epsilon} \propto \vec{v} \times \vec{B}$$



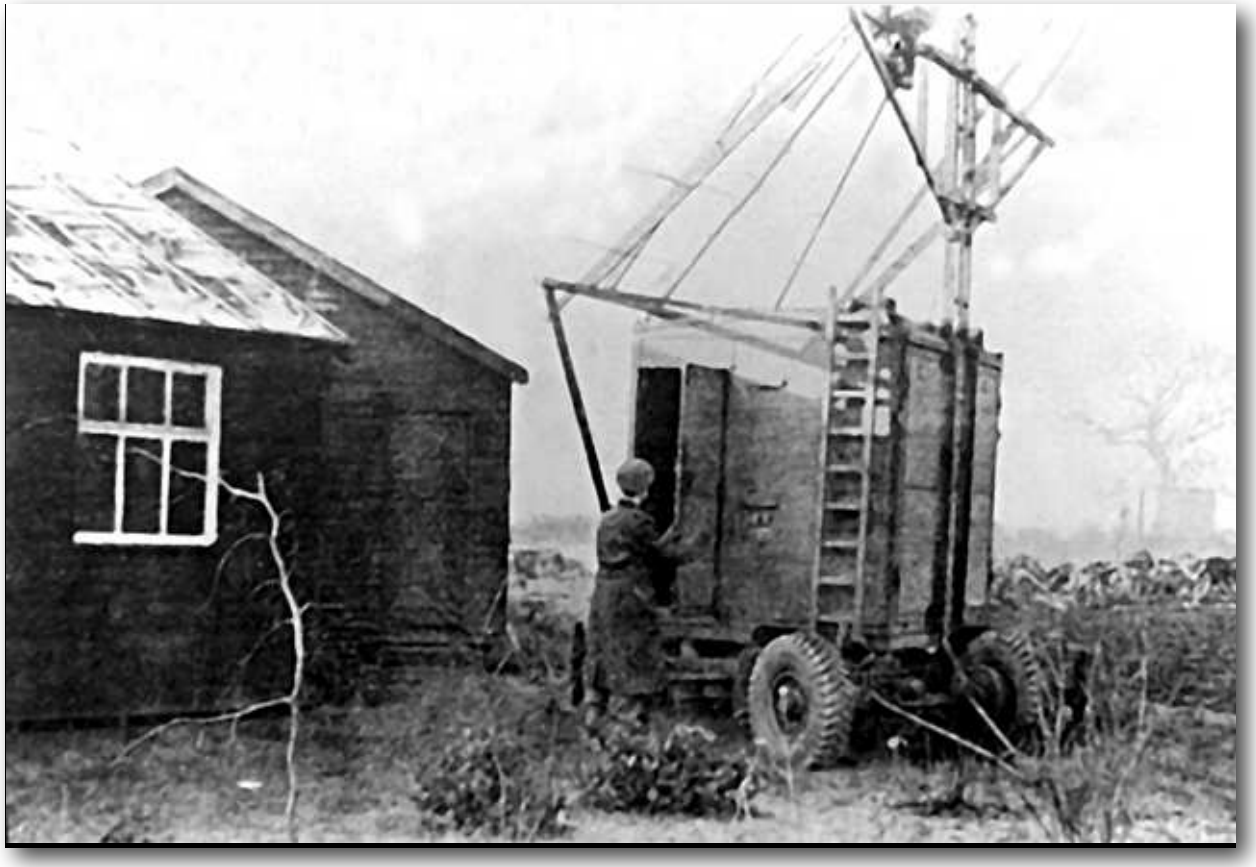
expected polarisation
here simply **v** x **B**

D. Arduin et al., Astropart. Phys. 31 (2009) 192

C. Glaser, ARENA (2012)

History

Jodrell Bank 1946



No air showers detected

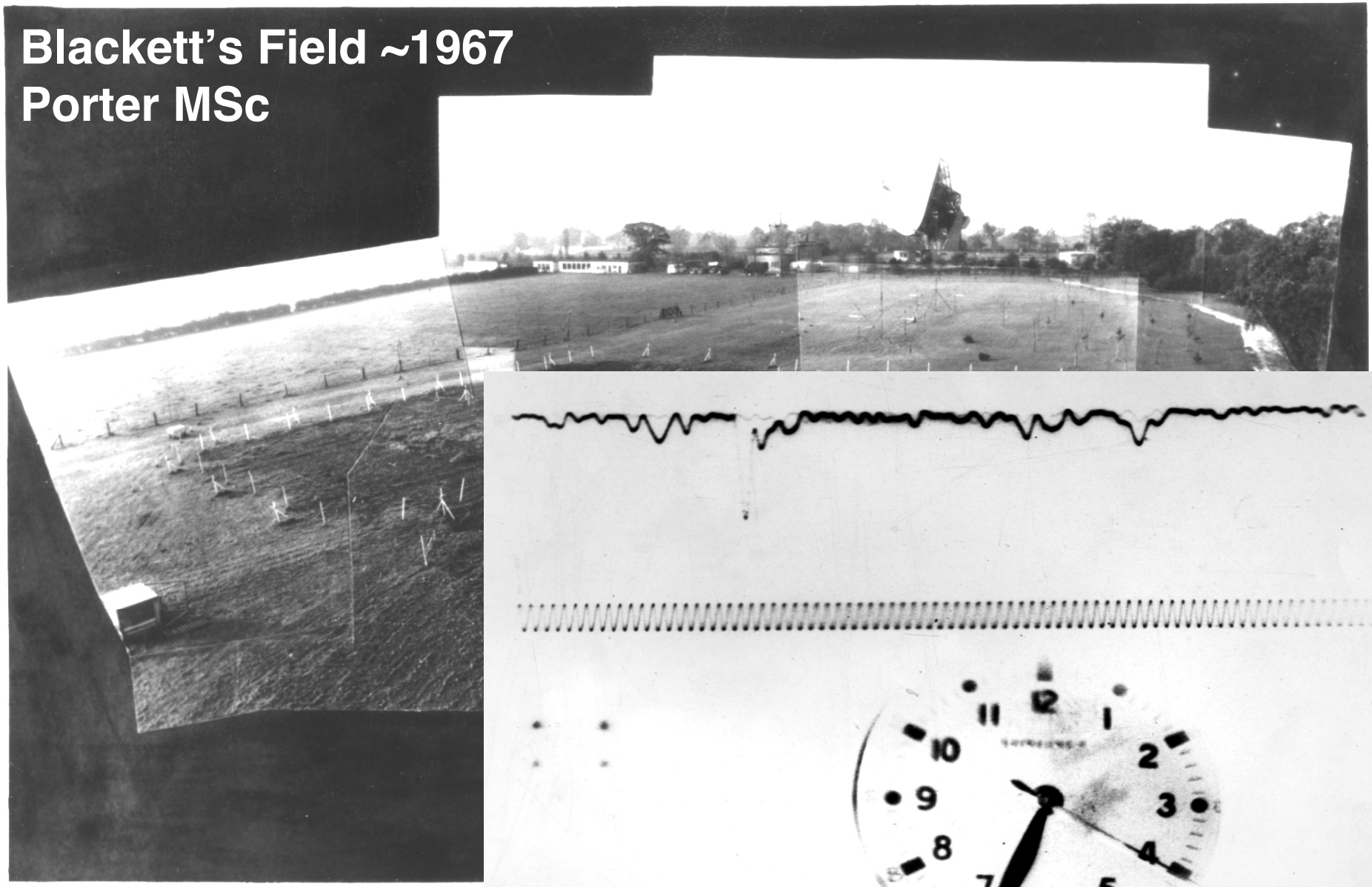
$$O_2 + e \rightarrow O_2^-$$

No luck due to rapid attachment time (ns) of free electrons in the lower atmosphere (damping factor)

Echos from meteor trails
Radio emission from M31

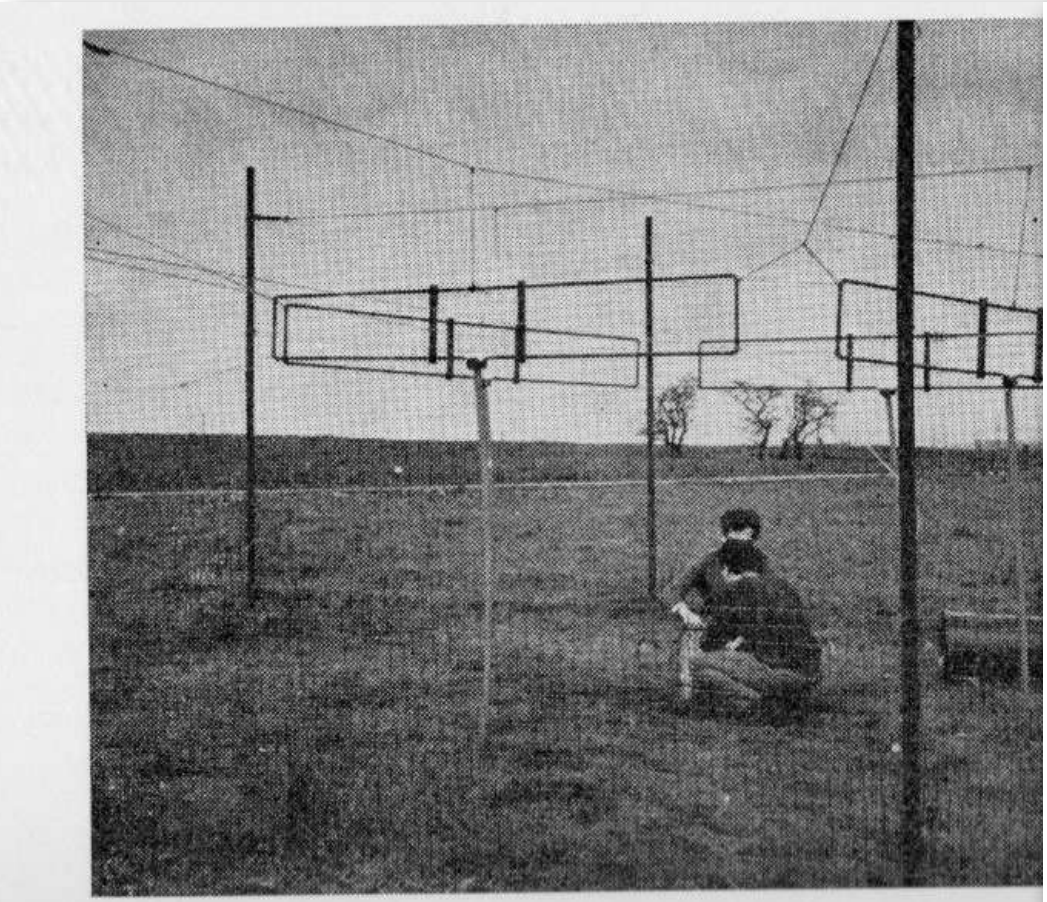
→ **radio astronomy**

First radio detection of air showers 1965

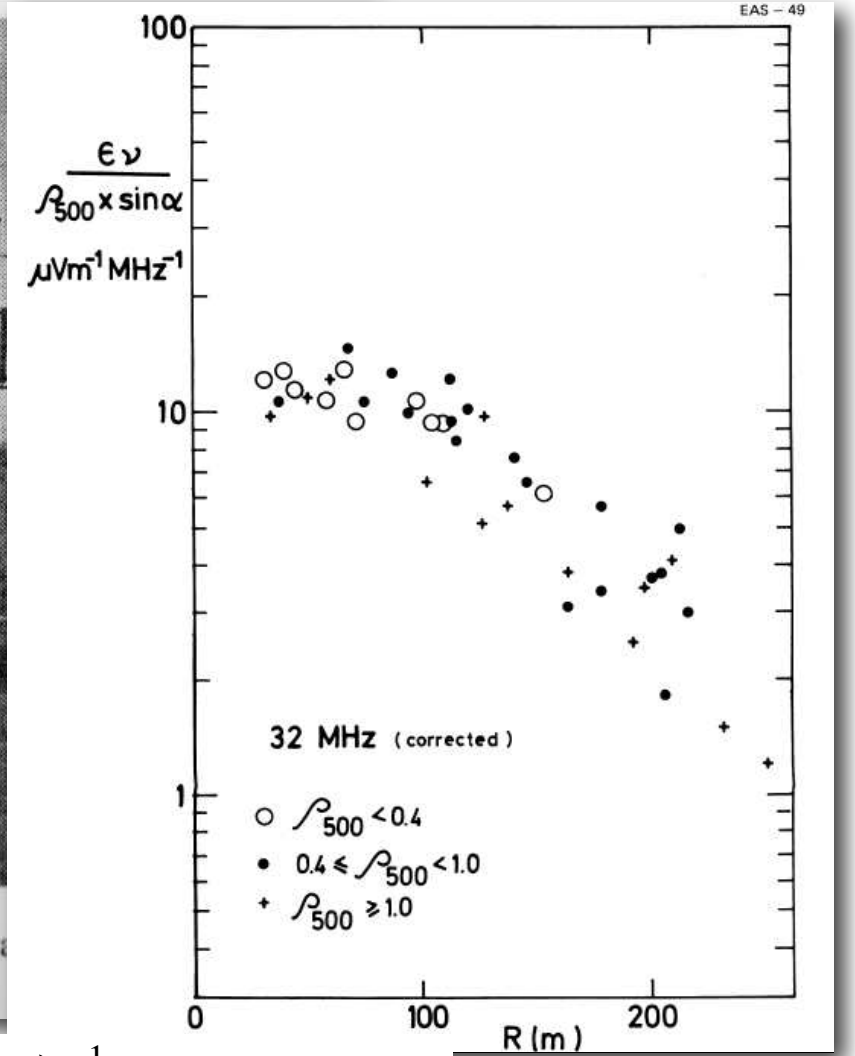


Jelley et al Nature 1965
R. A. Porter MSc Thesis 1967

Haverah Park (Leeds) Allan 1971



Recent receiving antennas (44 MHz) forming part of the Haver
Shower Array.



$$\varepsilon_\nu = 2\left(\frac{E_p}{10^{17}}\right)\left(\frac{\sin\alpha\cos\theta}{\sin 45\cos 30}\right)\exp\left(\frac{-r}{r_0}\right)\left(\frac{\nu}{50}\right)^{-1} \quad \mu\text{V/m/MHz}$$

$r_0 = 110$ m at ν=55 MHz. α=angle to B, θ=Zenith angle

Radio Detectors

to measure properties of cosmic rays

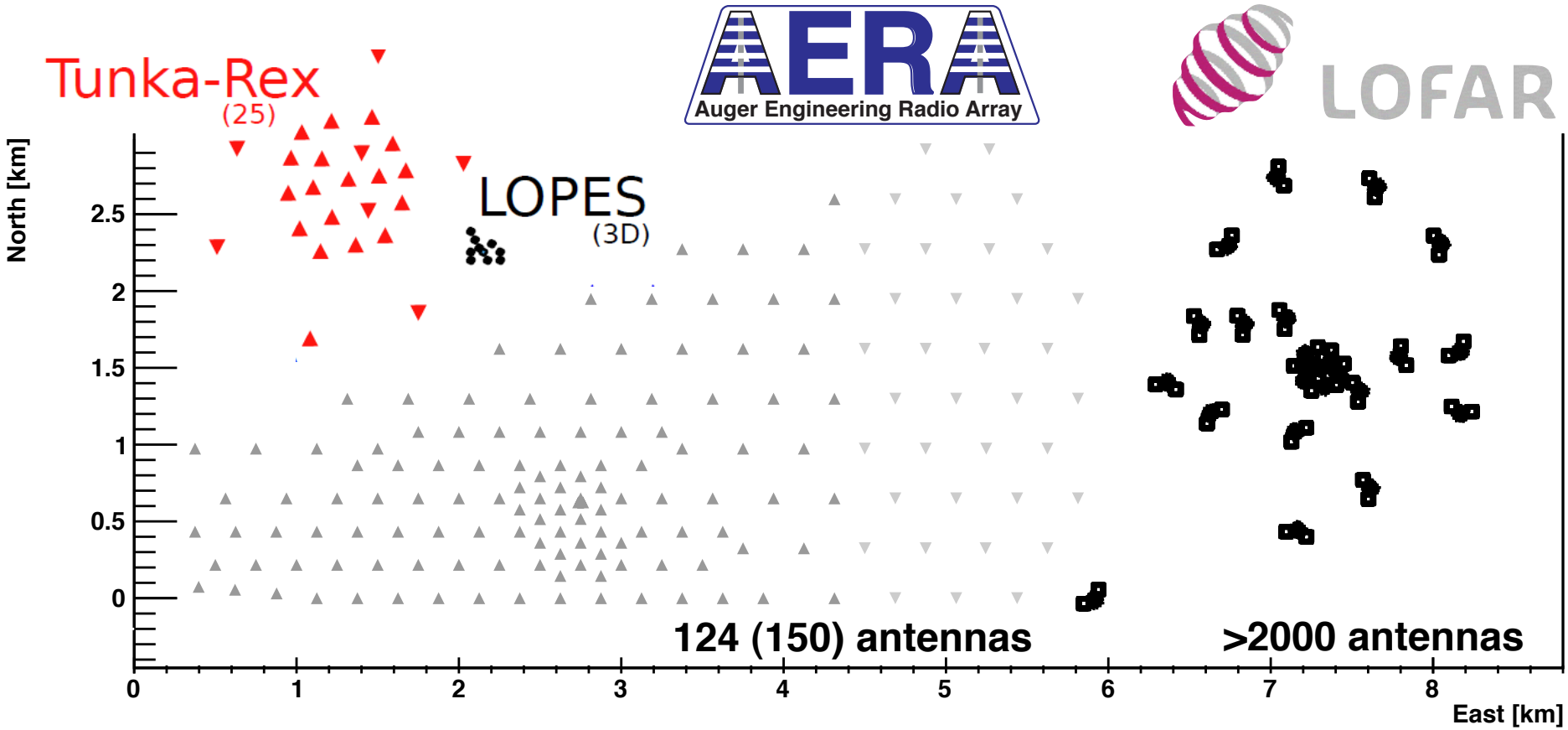
- direction

- energy

- mass/type of particle

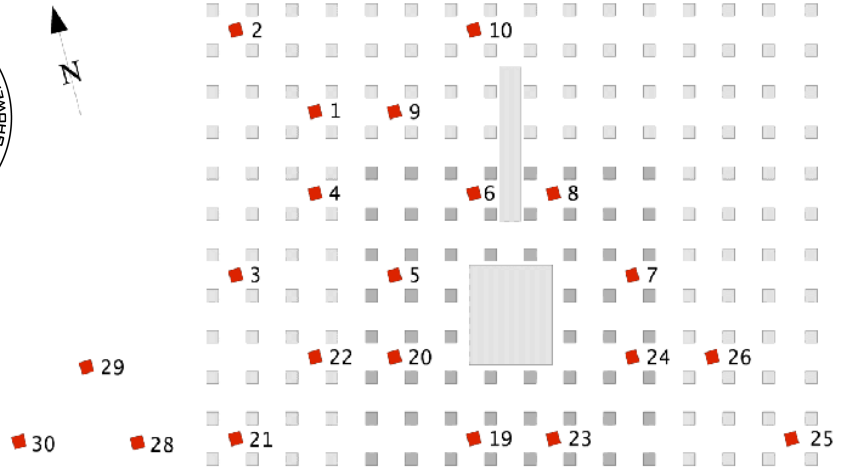
with ~100% duty cycle

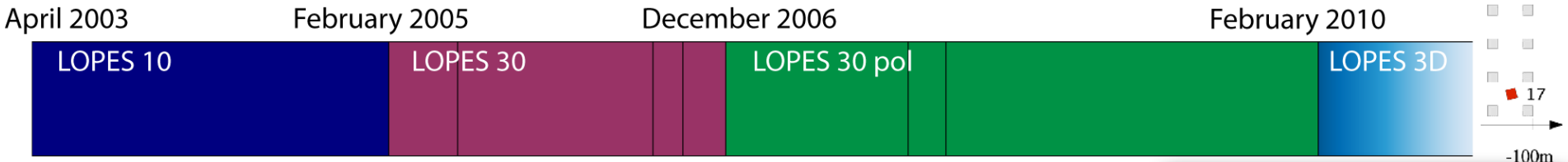
Large-scale radio detectors to measure extensive air showers



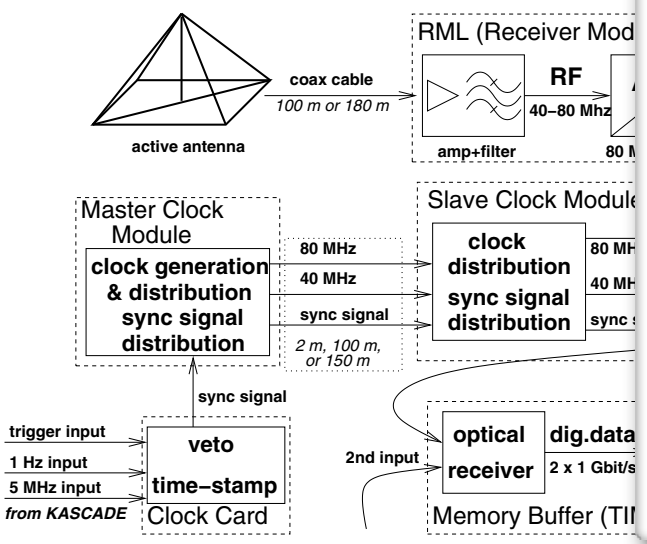
LOPES
Lofar Prototype Station

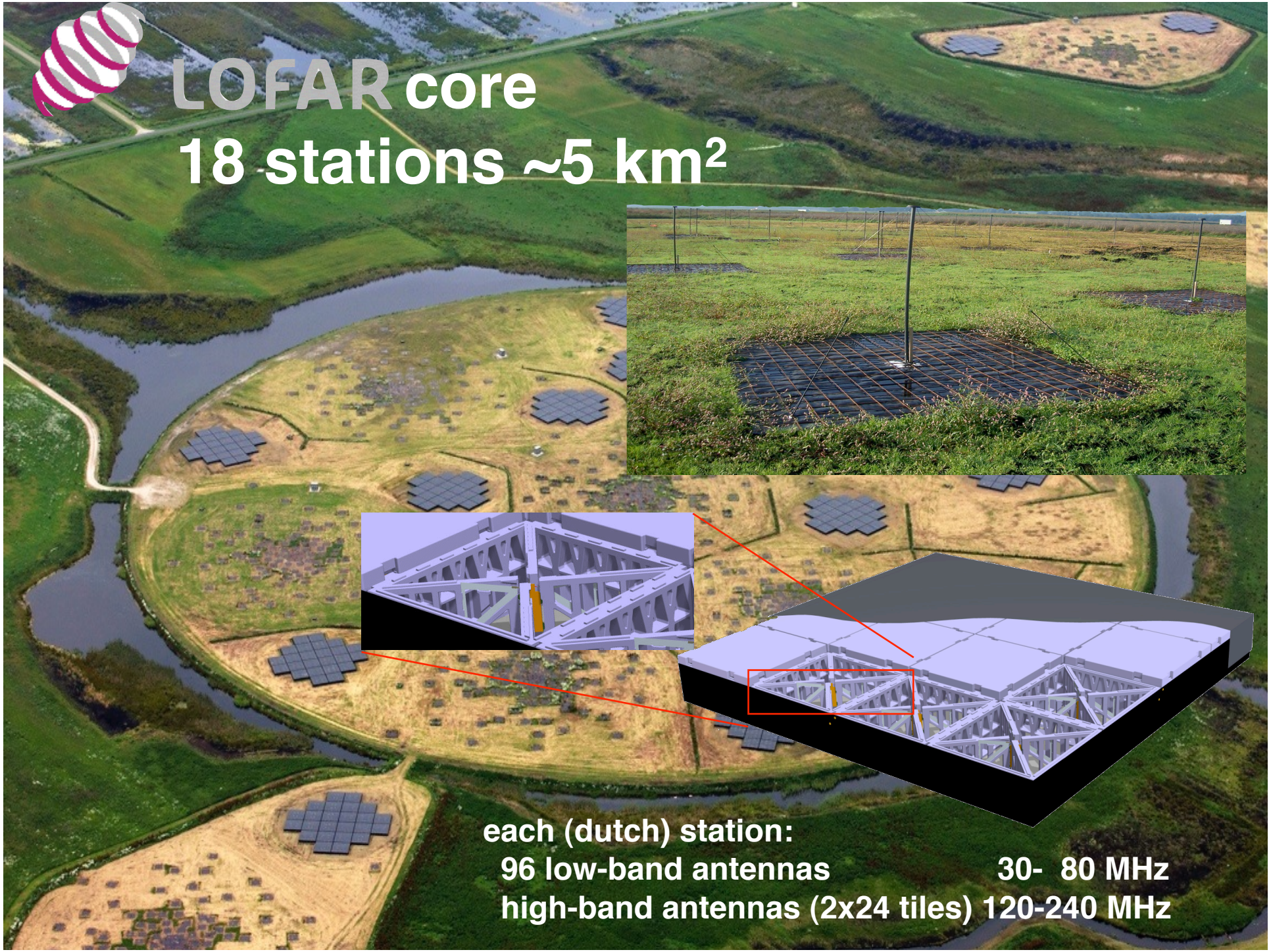
30 antennas operating at KASCADE-Grande





digital radio interferom



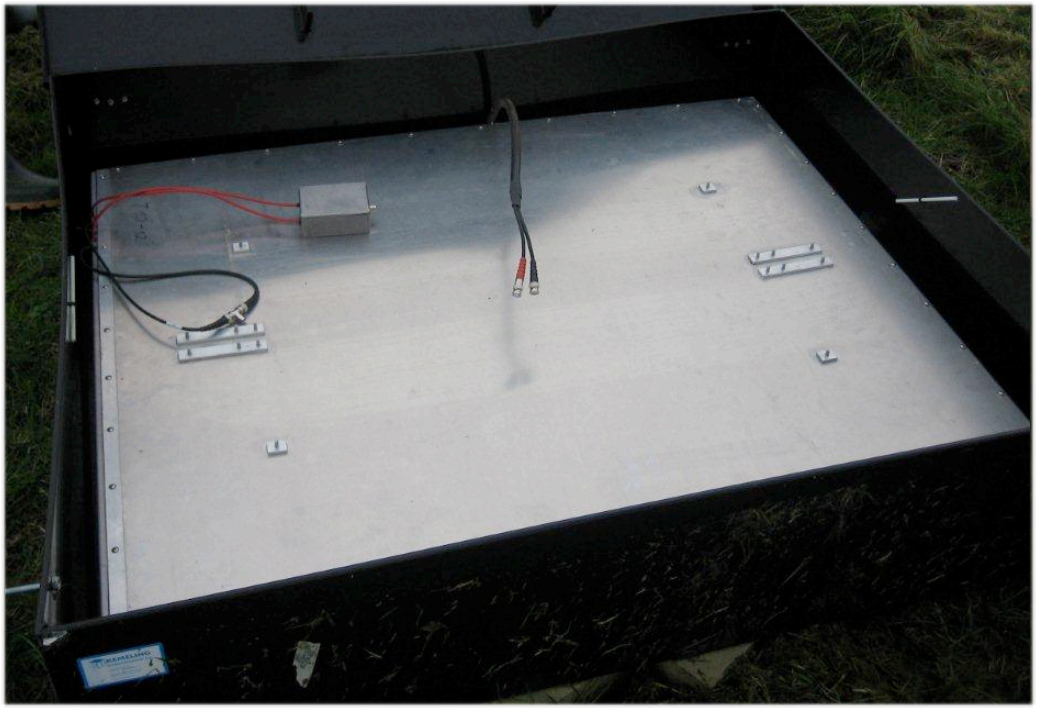

LOFAR core
18 stations ~5 km²
each (dutch) station:
96 low-band antennas 30- 80 MHz
high-band antennas (2x24 tiles) 120-240 MHz

LOFAR Radboud Air Shower Array - LORA

20 scintillator units
(~1 m^2 each)
read out by
wavelength shifter
bar and PMT
in LOFAR core

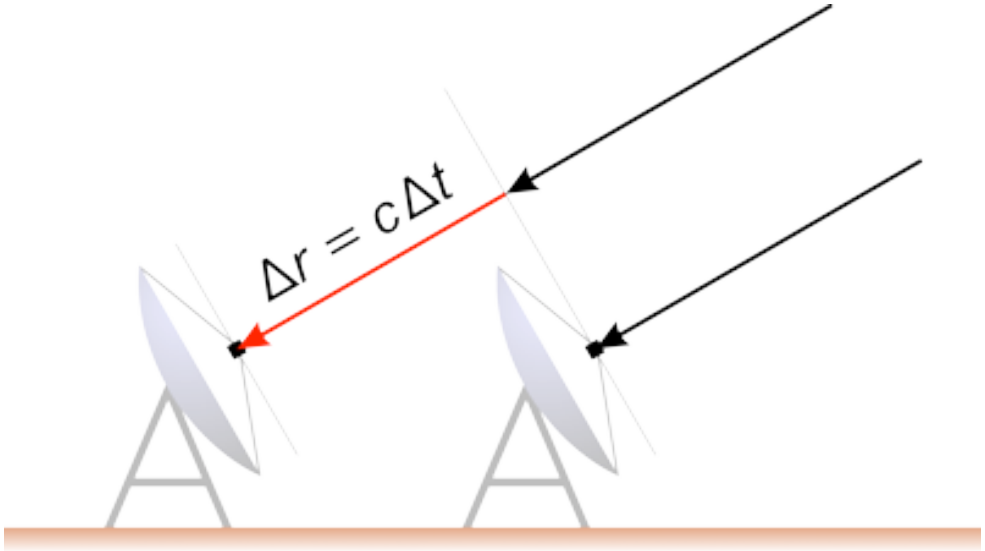
→ provide

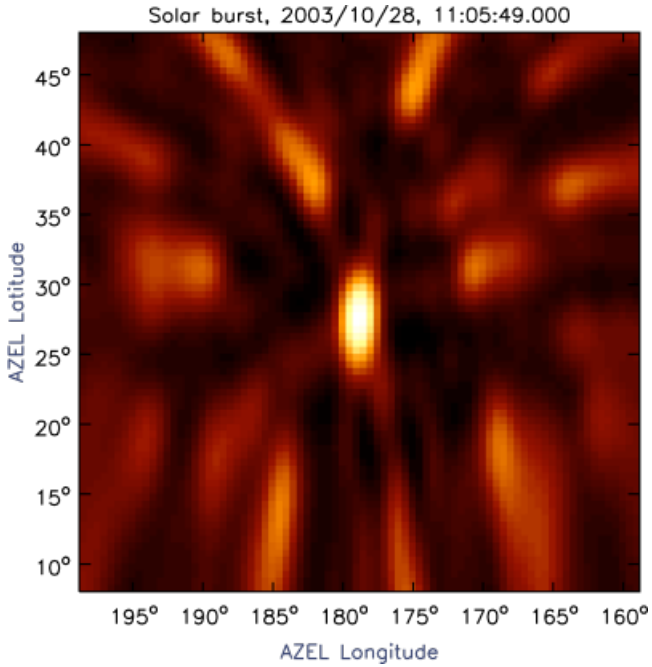
- properties of EAS
- and trigger



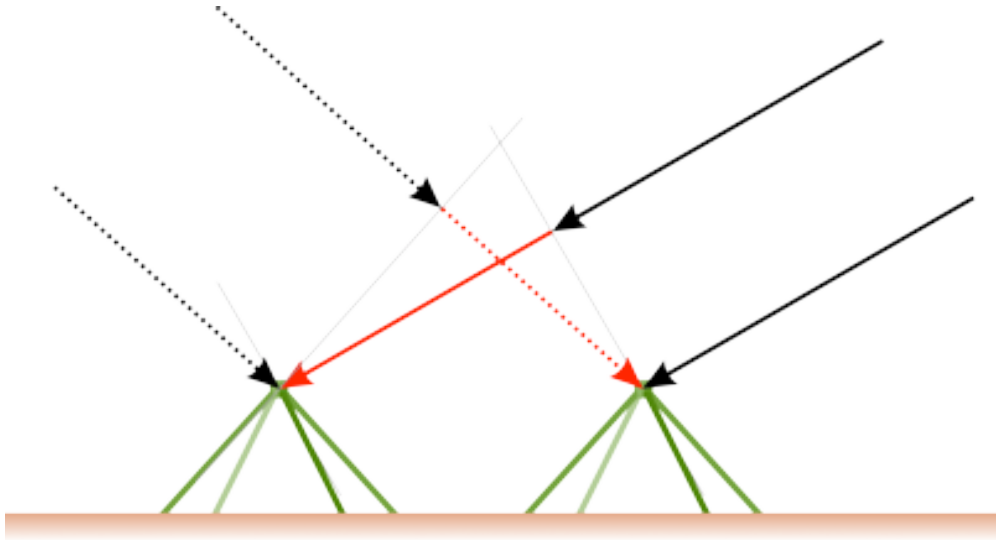
LOFAR

Digital beam forming

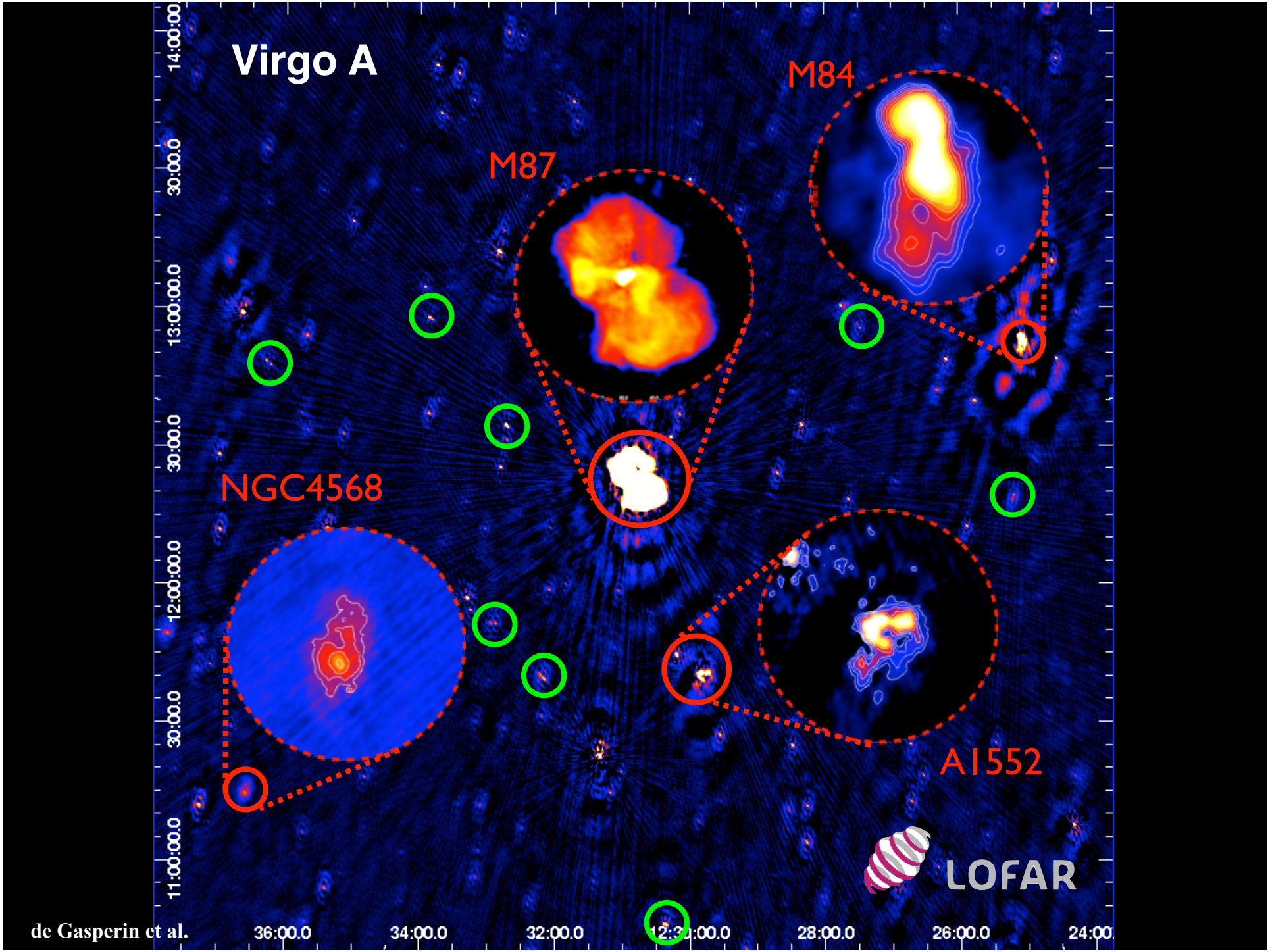




Solar burst observed with LOPES

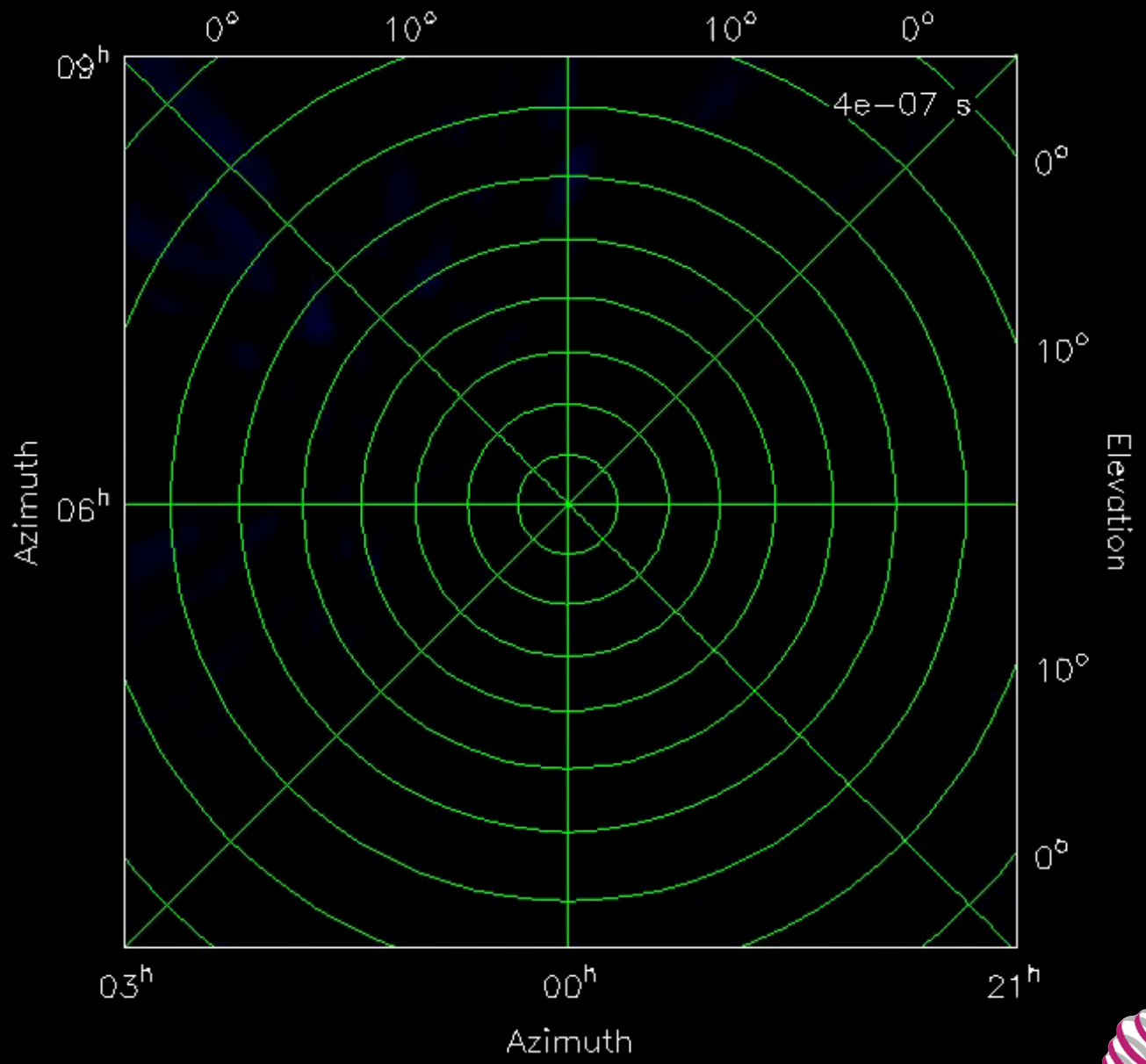


IBM Blue Gene Supercomputer



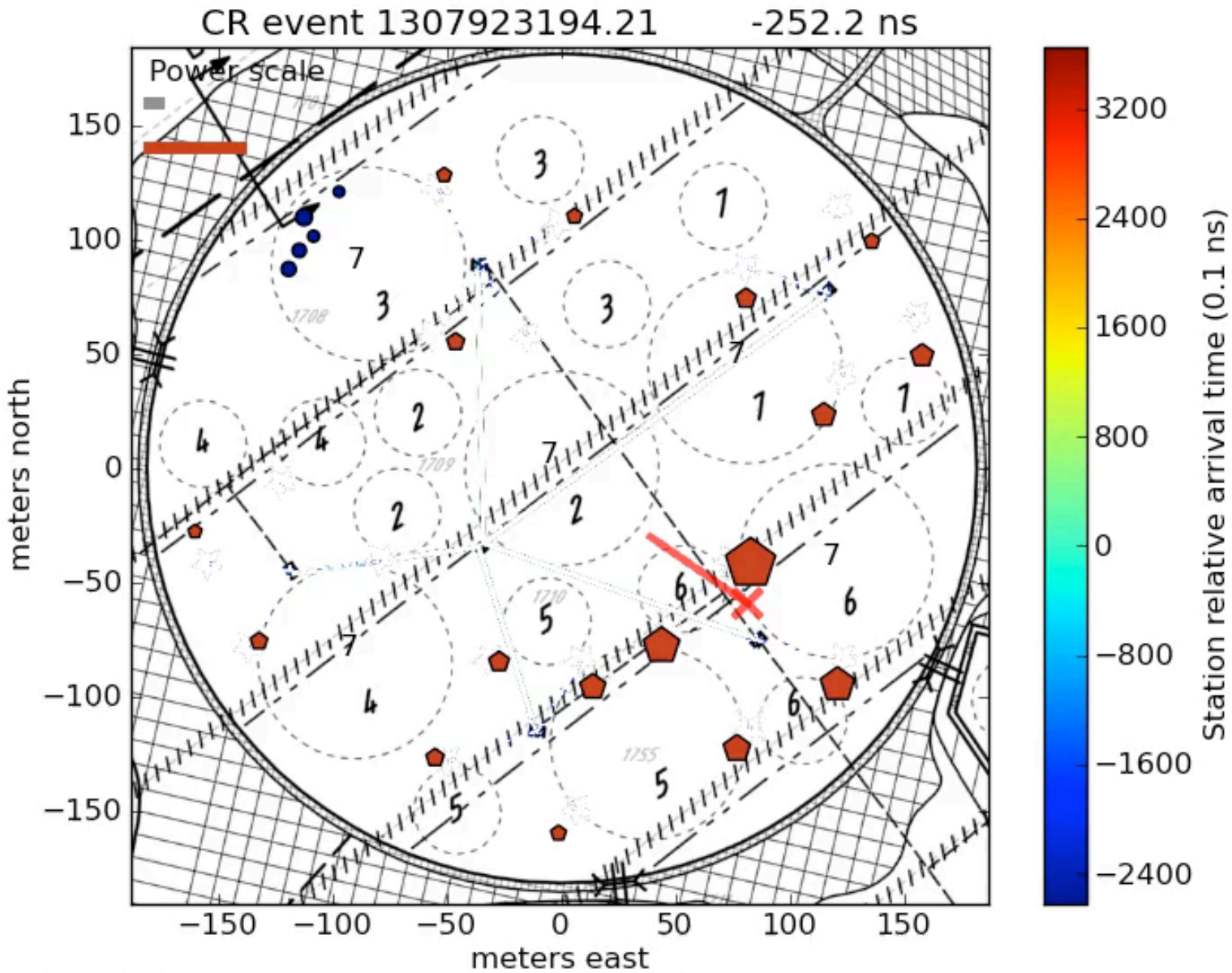
de Gasperin et al.

Radio signals from Air Showers observed by LOFAR



LOFAR

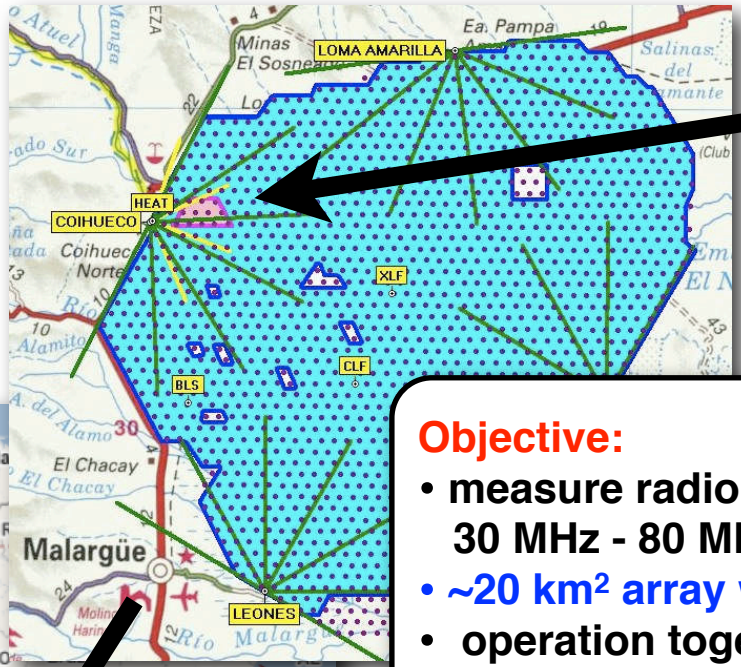
A measured air shower



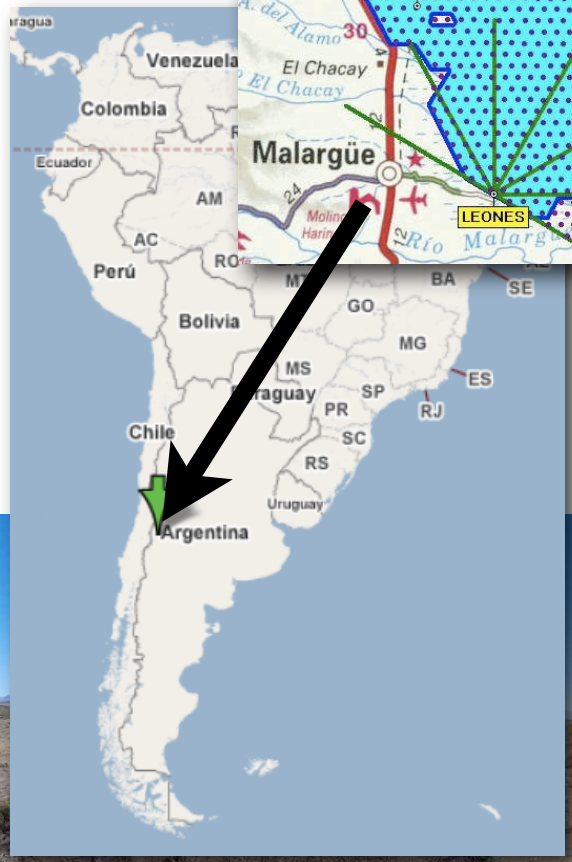
Circles: LOFAR antennas, Pentagons: LORA particle detectors, size denotes signal strength

The Auger Engineering Radio Array

PIERRE AUGER OBSERVATORY



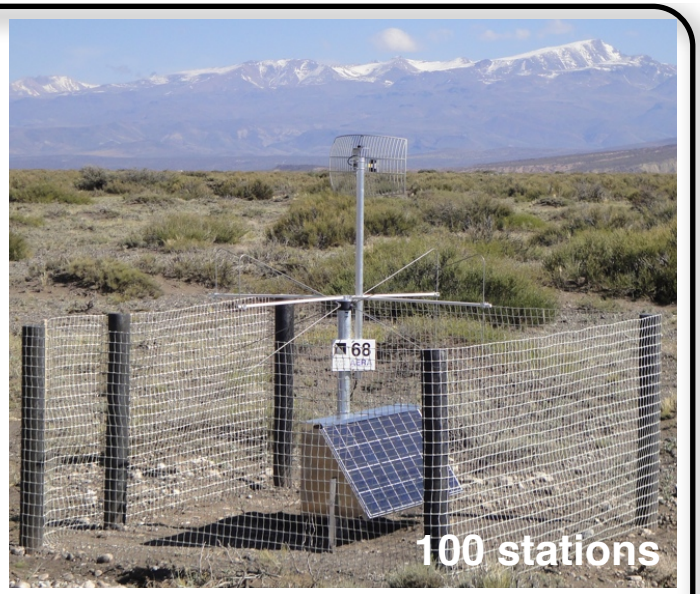
AERA
Auger Engineering Radio Array



Objective:

- measure radio emission from EAS in frequency range 30 MHz - 80 MHz
- ~20 km² array with ~160 antennas
- operation together with infill/HEAT/AMIGA
- three antenna spacings to cover efficiently $17.2 < \lg E/eV < 19.0$
- measure composition of cosmic rays in energy region of transition from galactic to extragalactic cosmic rays

since August 2010



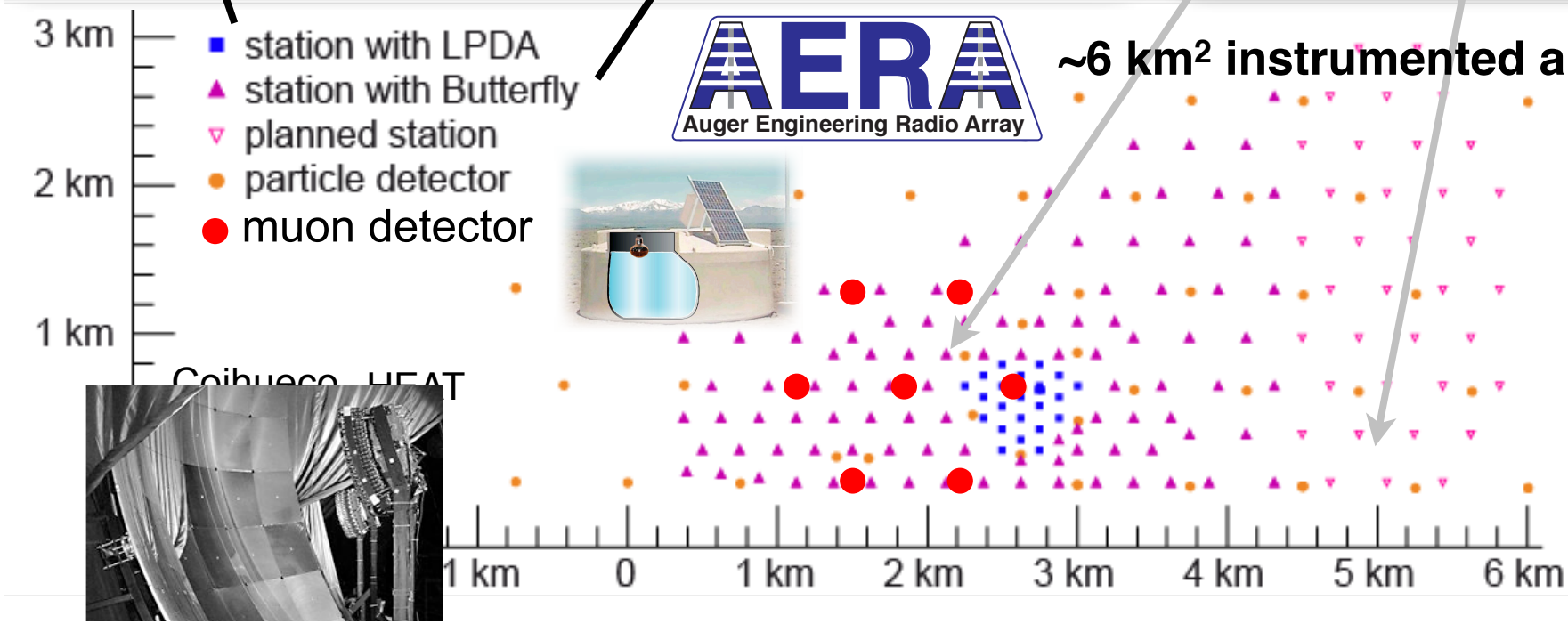
since May 2013

124 stations „working horse“

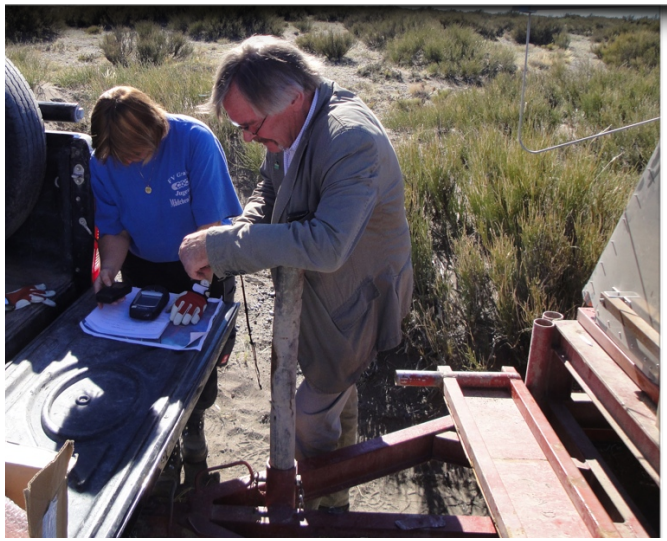
R&D for vertical polarization

AERA
Auger Engineering Radio Array

~6 km² instrumented area

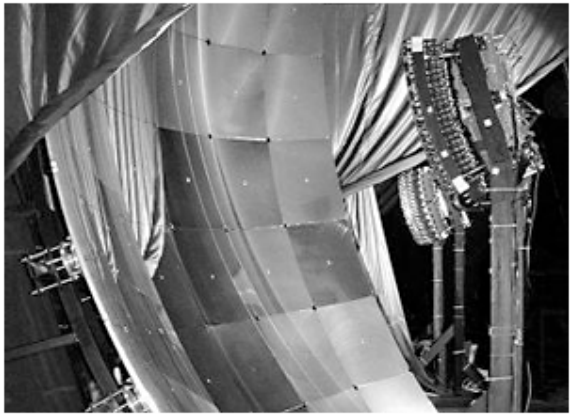


installation April/May 2013



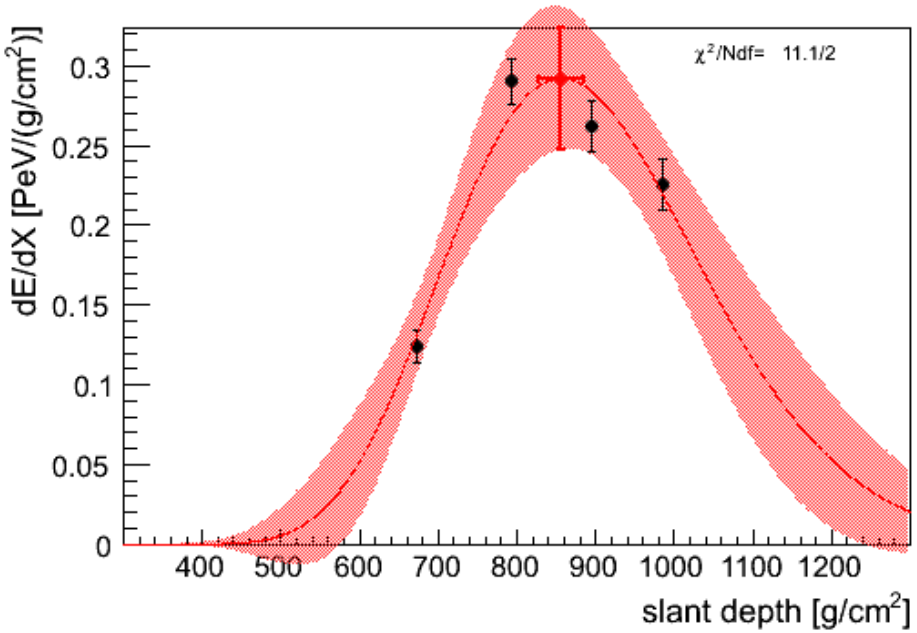
An air shower measured simultaneously with ...

the Fluorescence Telescopes

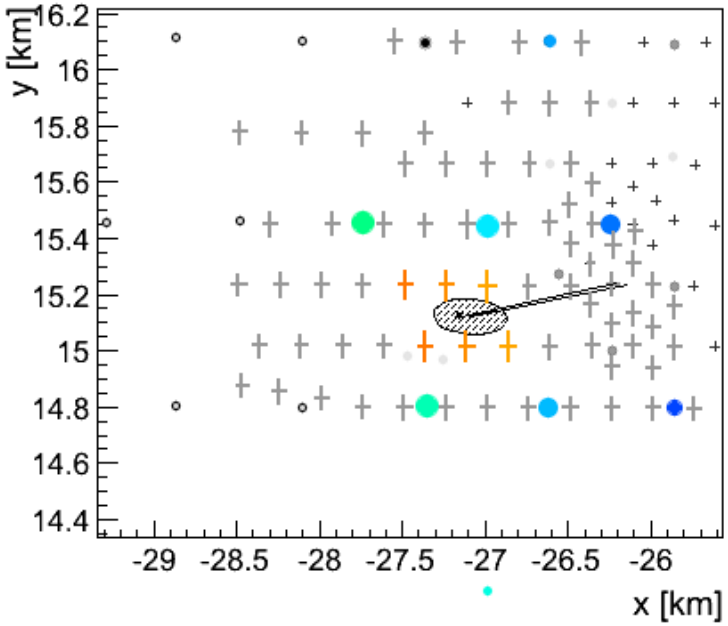


the Surface Detectors

longitudinal shower profile



footprint

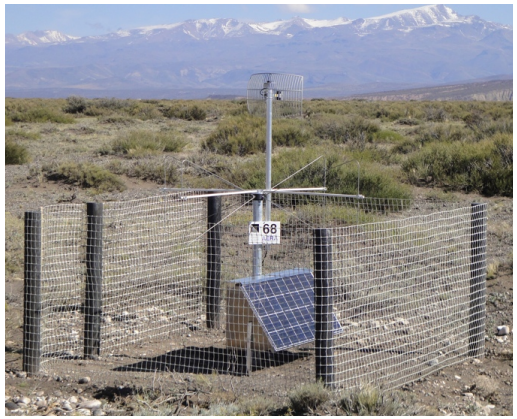


E ~ 2*10^{17} eV X_{max} ~ 860 g/cm^2 zenith angle ~ 75° azimuth angle ~ 8°

PIERRE AUGER OBSERVATORY

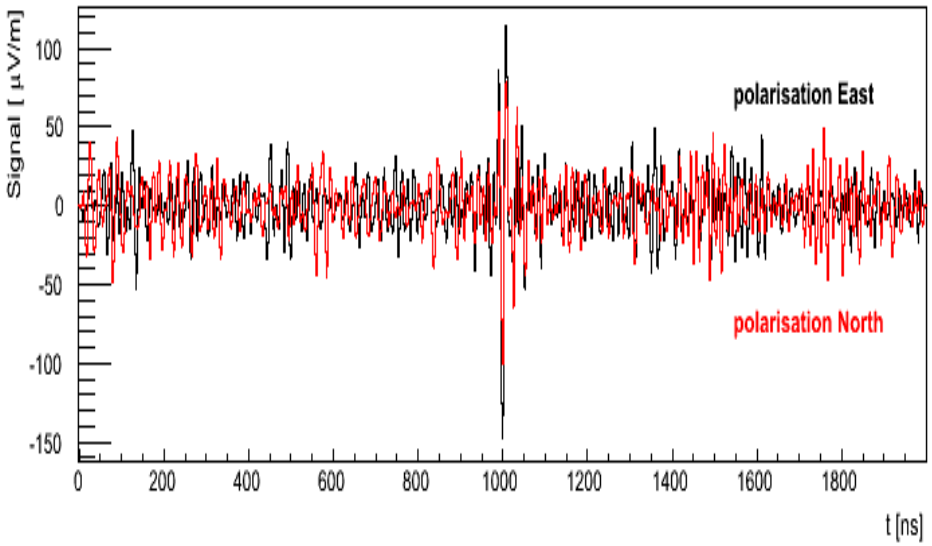
An air shower measured simultaneously with ...

the Radio Detectors

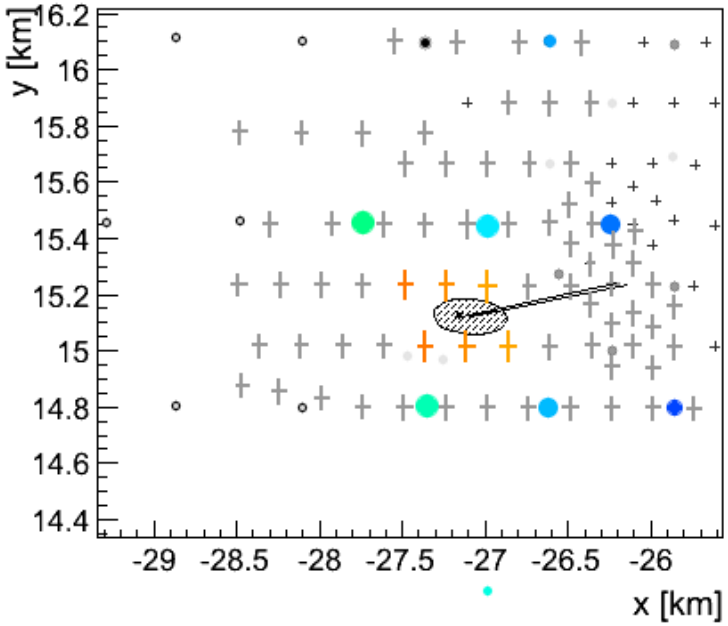


the Surface Detectors

radio pulse



footprint



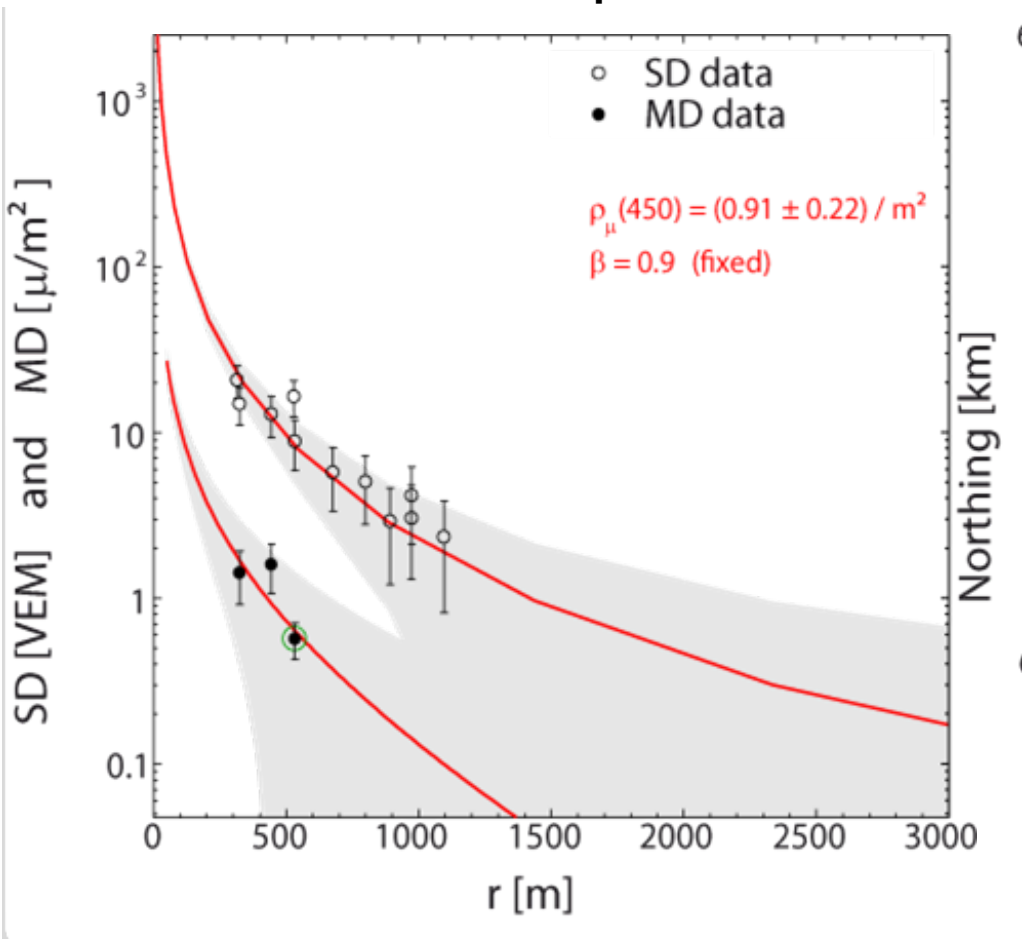
E ~ 2*10^{17} eV X_{max} ~ 860 g/cm^2 zenith angle ~ 75° azimuth angle ~ 8°

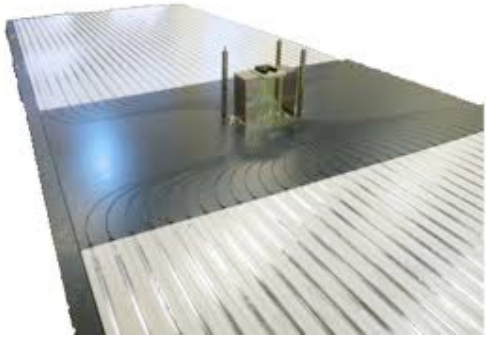
PIERRE AUGER OBSERVATORY

An air shower measured simultaneously with ...

the Muon Detectors | **the Surface Detectors**

lateral shower profile

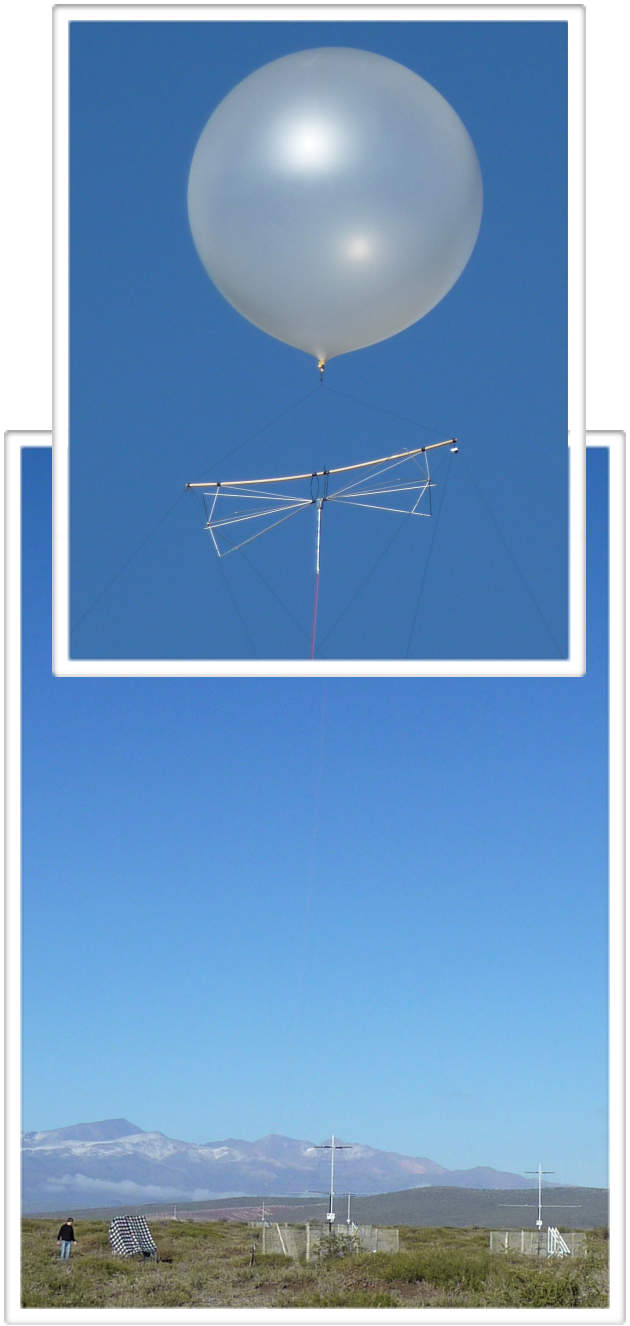




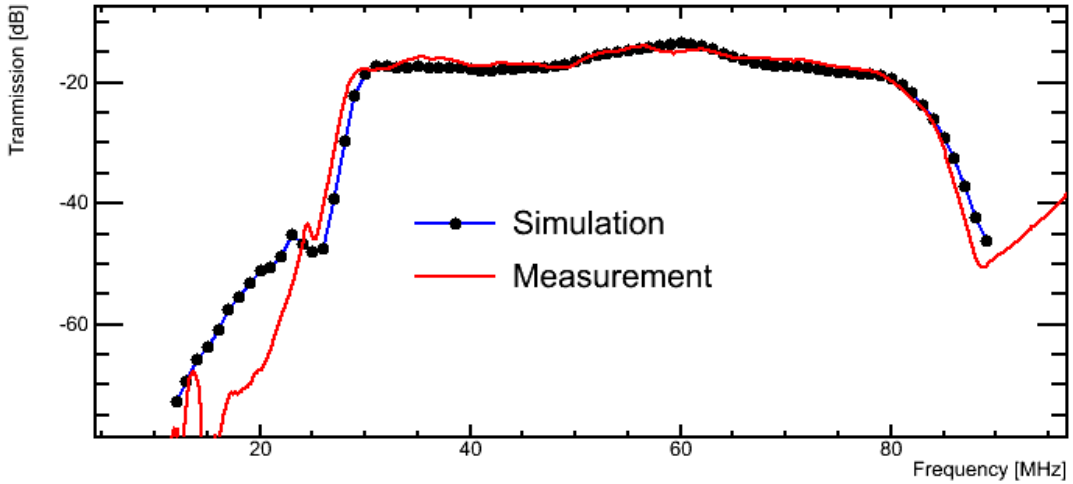
E ~ 2*10^{17} eV **X_{max} ~ 860 g/cm^2** **zenith angle ~ 75°** **azimuth angle ~ 8°**

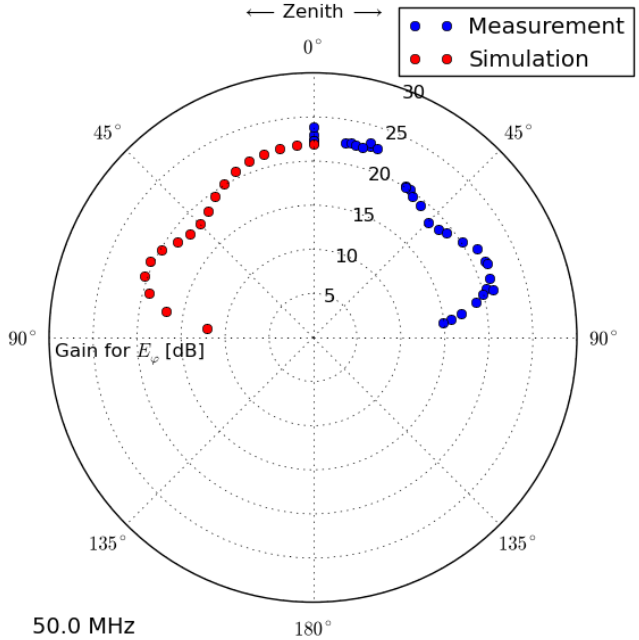
PIERRE AUGER OBSERVATORY

In-situ calibration



frequency dependent antenna gain





horizontal gain

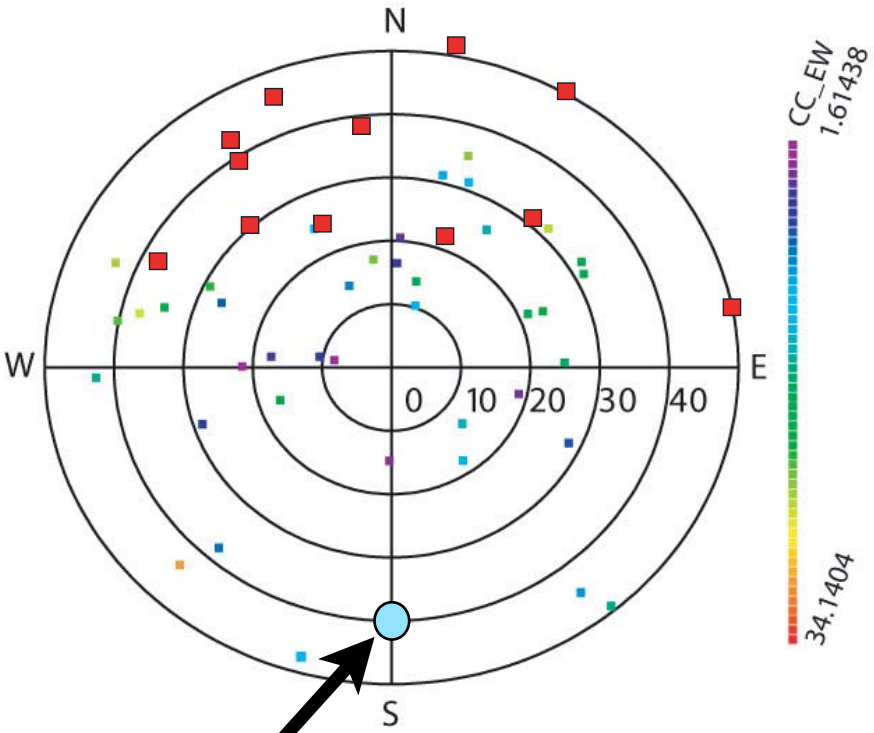
Auger Engineering Radio Array

Polarization

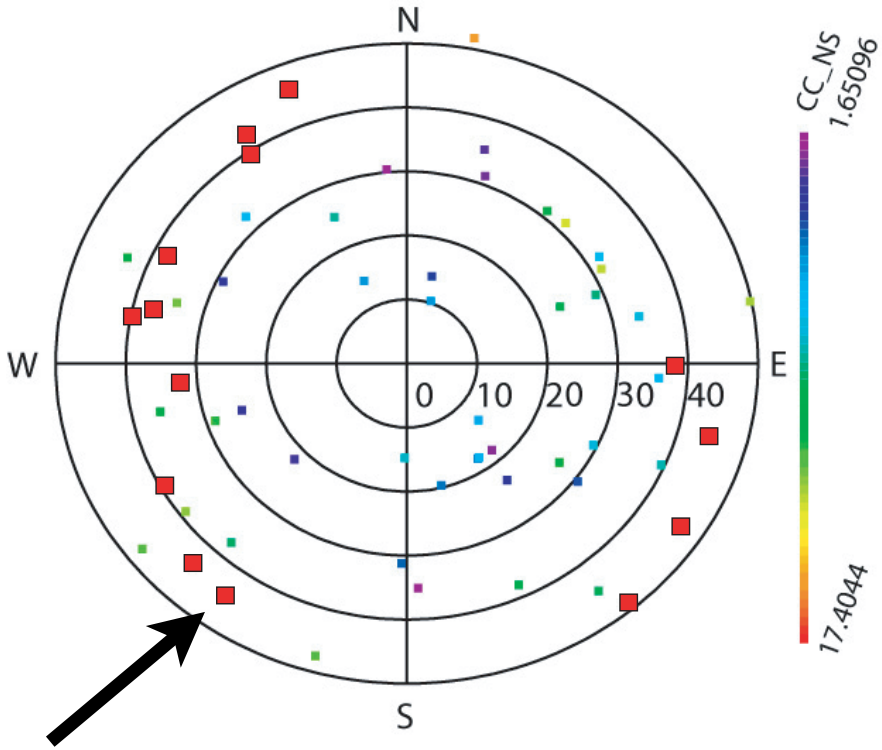
Geosynchrotron component

arrival direction of cosmic rays (sky map)

E-W polarization



N-S polarization



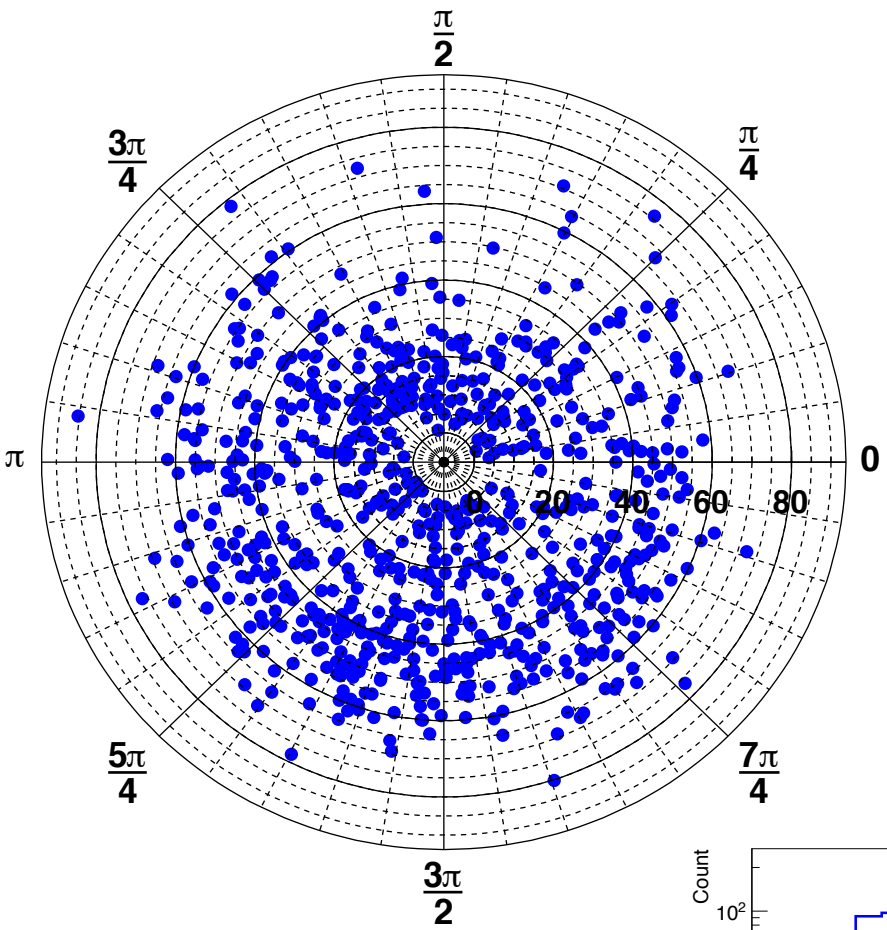
strongest events

magnetic field
inclination: 64° 36‘
declination: 1° 22‘

v x B effect
synchrotron radiation dominates signal

P.G. Isar et al., Nucl. Instr. & Meth. A 604(2009) S81

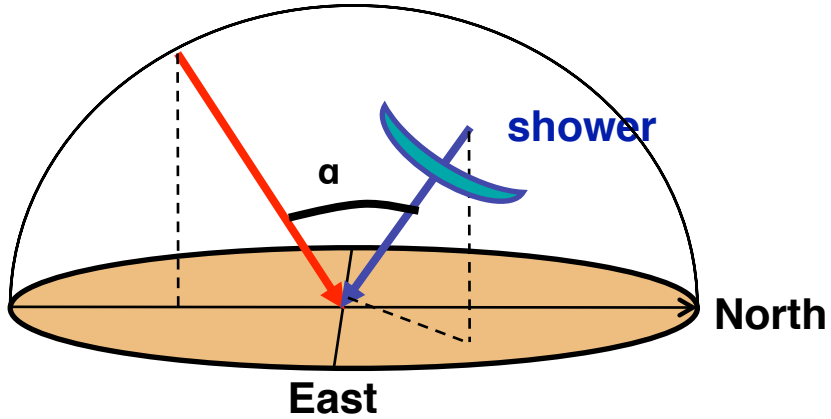
Arrival direction



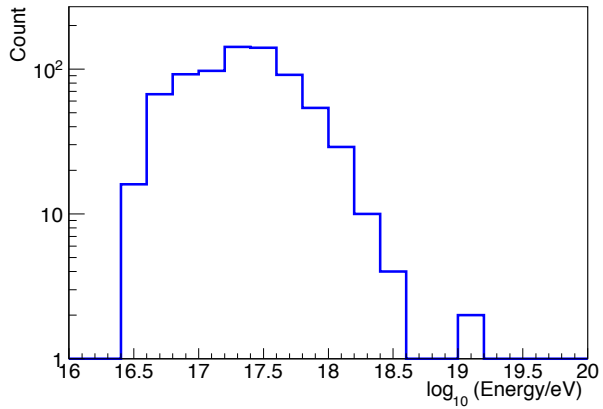
of showers with strong radio signal

north-south asymmetry
v x B effect

Geomagnetic field



$$\vec{\epsilon} \propto \vec{v} \times \vec{B}$$



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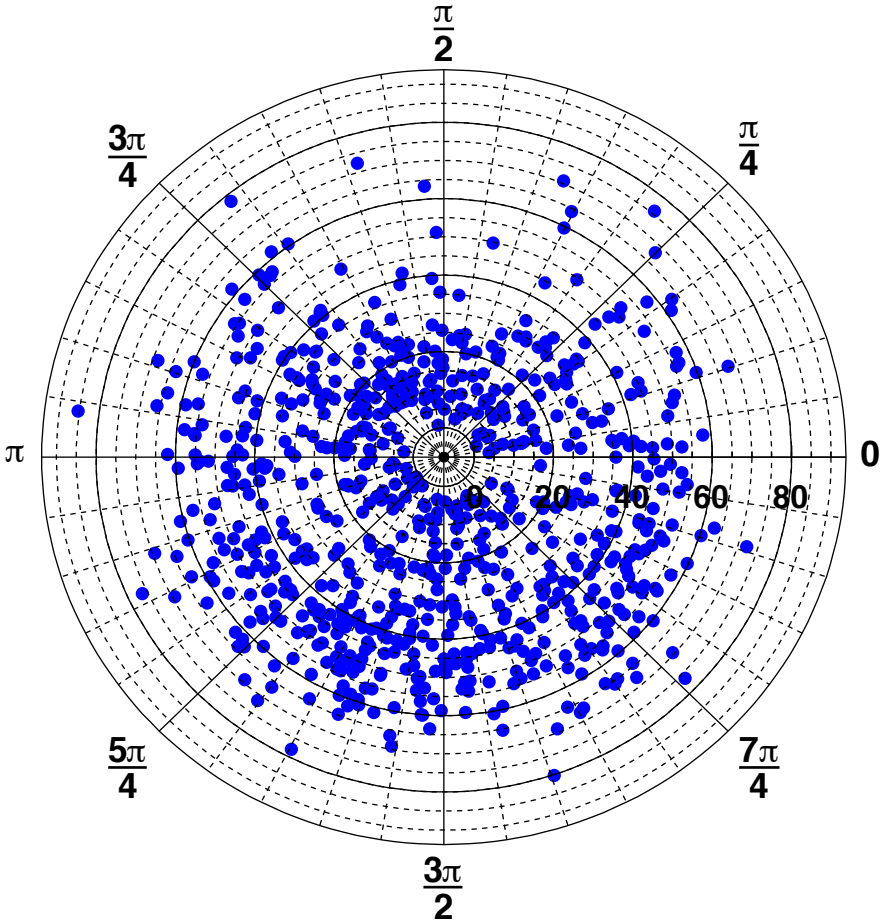
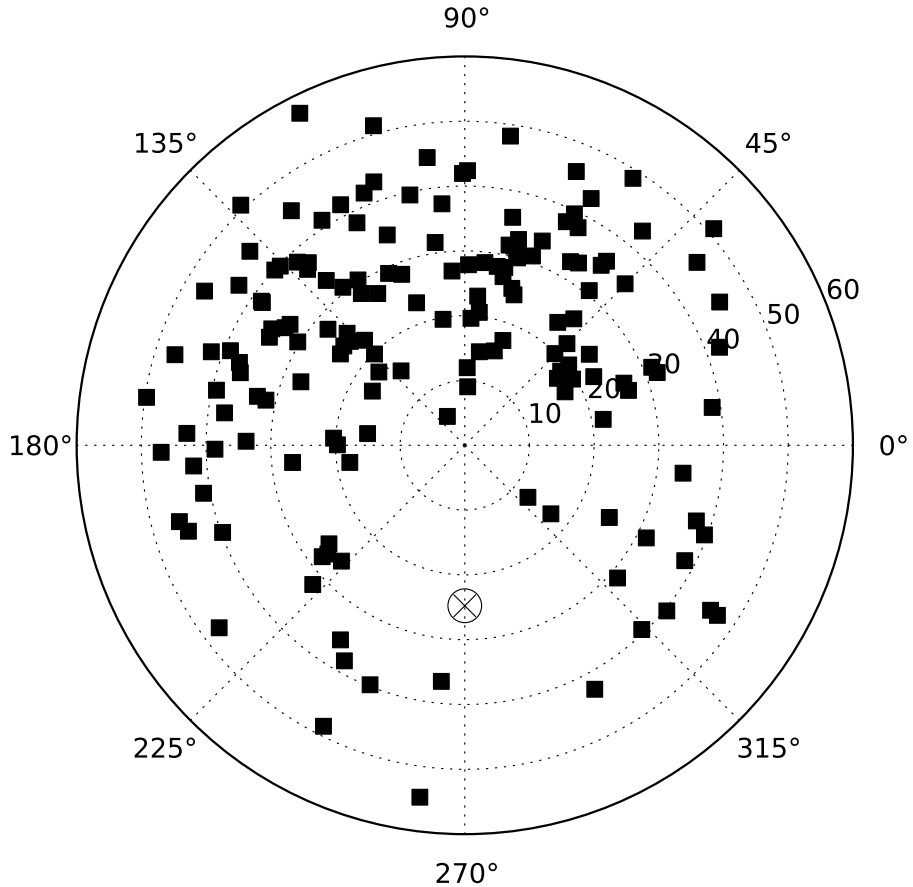
Arrival direction





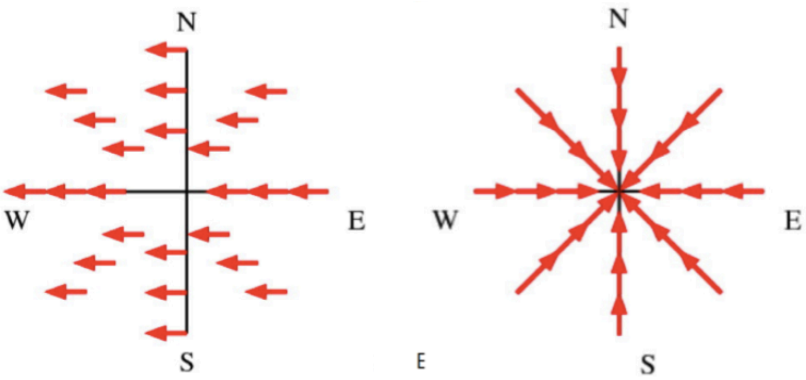
AERA
Auger Engineering Radio Array

LOFAR

Polarization of the radio signal

measure direction of electric field vector at different positions

geomagnetic **Askaryan**



$$a \equiv \sin(\alpha)\,\frac{|E^{\mathrm{A}}|}{|E^{\mathrm{G}}|}\,.$$

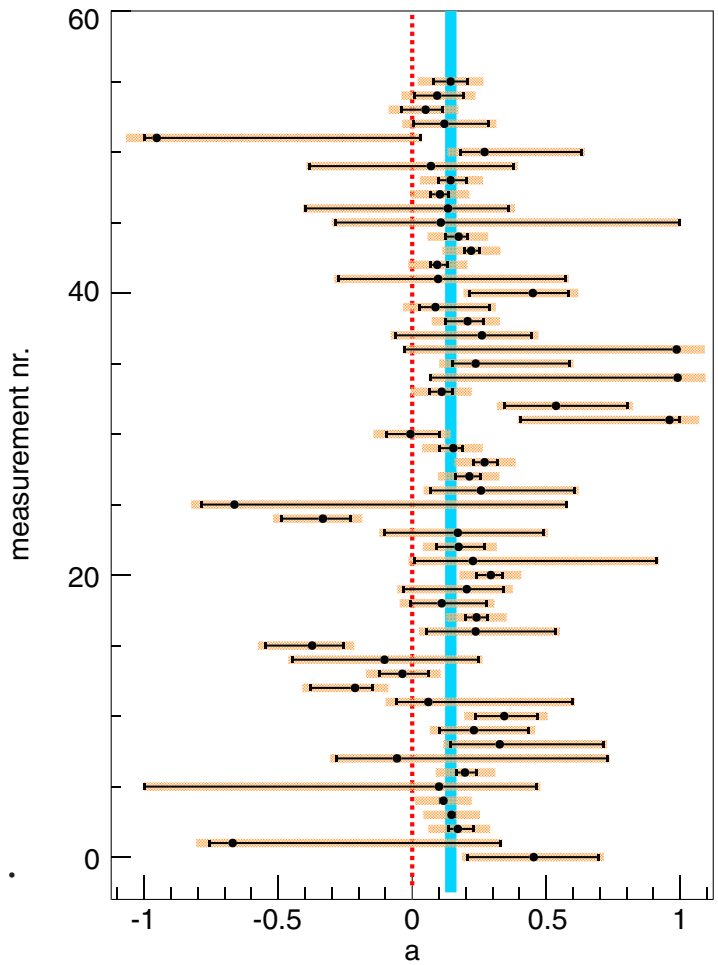


FIG. 9 (color online). Distribution of most probable values of a [see Eq. (10)] and their uncertainties for the AERA24 data set (see Appendix B for details). The 68% confidence belt around the mean value of a is shown as the solid blue line; the value $a = 0$ is indicated with the dotted red line; see text for further details.

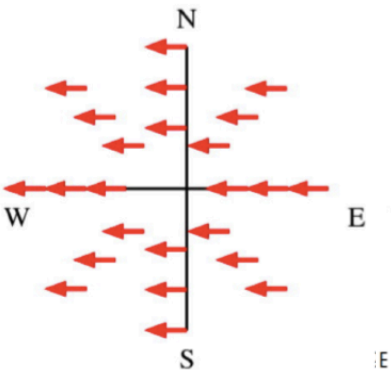
emission dominated by geomagnetic emission
14 +/- 2 % charge excess processes

A. Aab et al, Phys. Rev. D 89 (2014) 052002

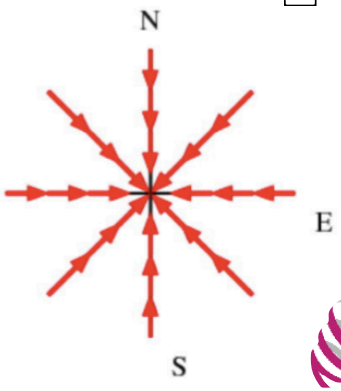
Polarization footprint

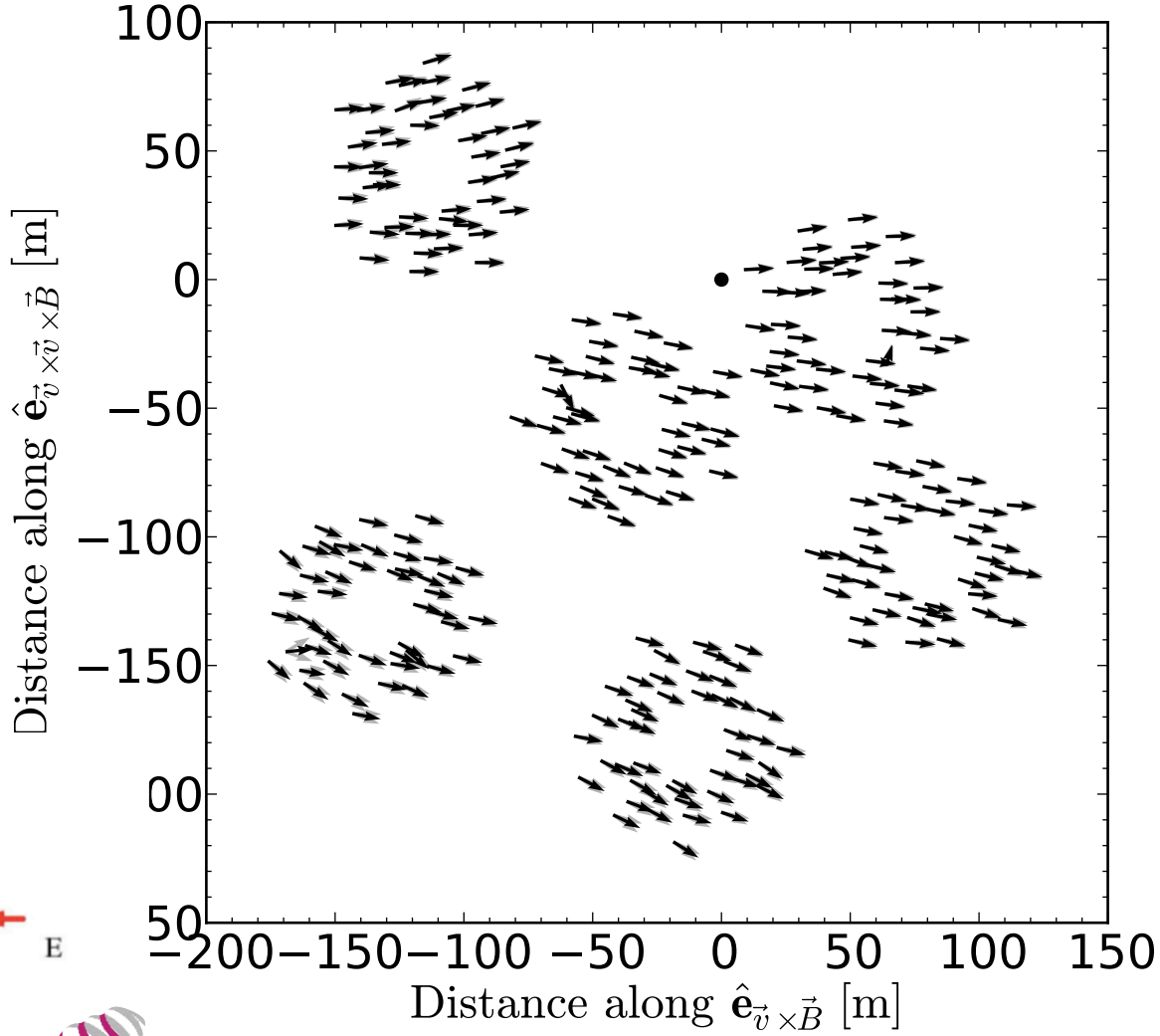
of an individual air shower

geomagnetic



Askaryan

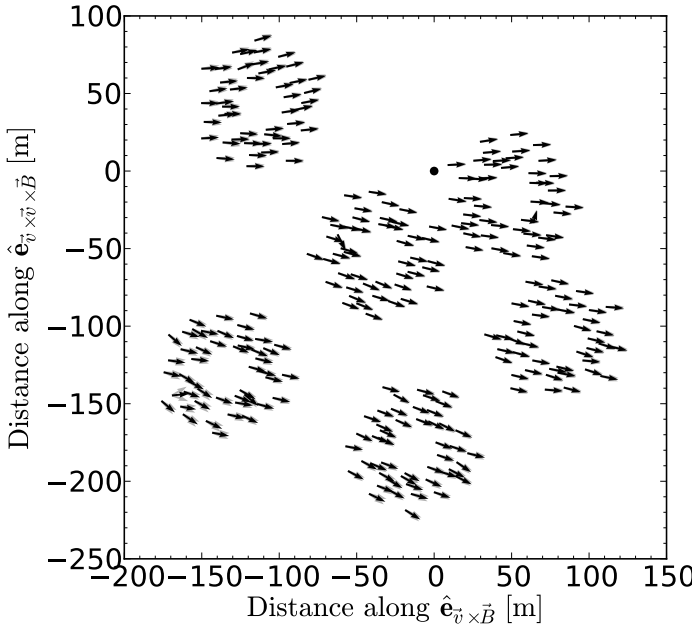


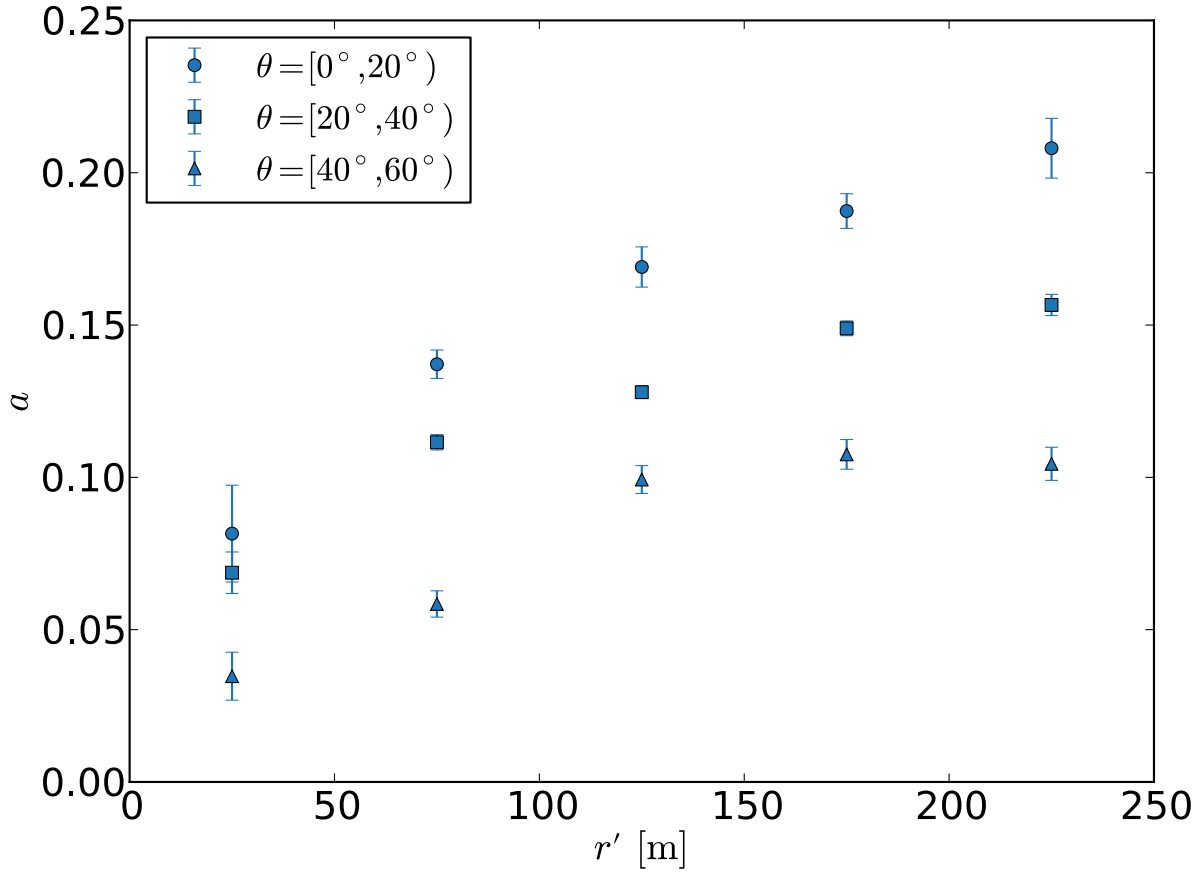


LOFAR

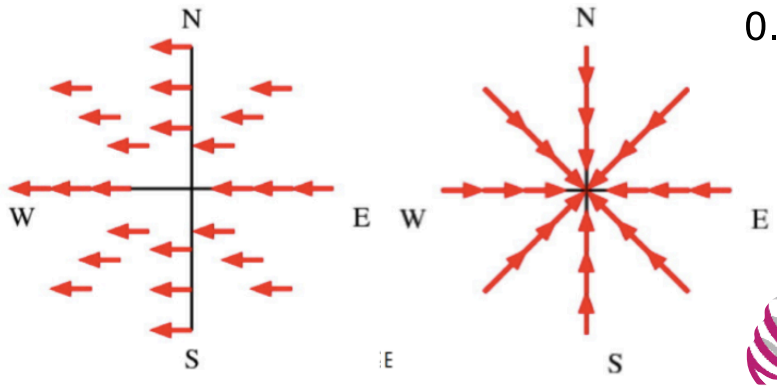
JCAP in press, arXiv:1406.1355

Charge excess fraction





geomagnetic **Askaryan**

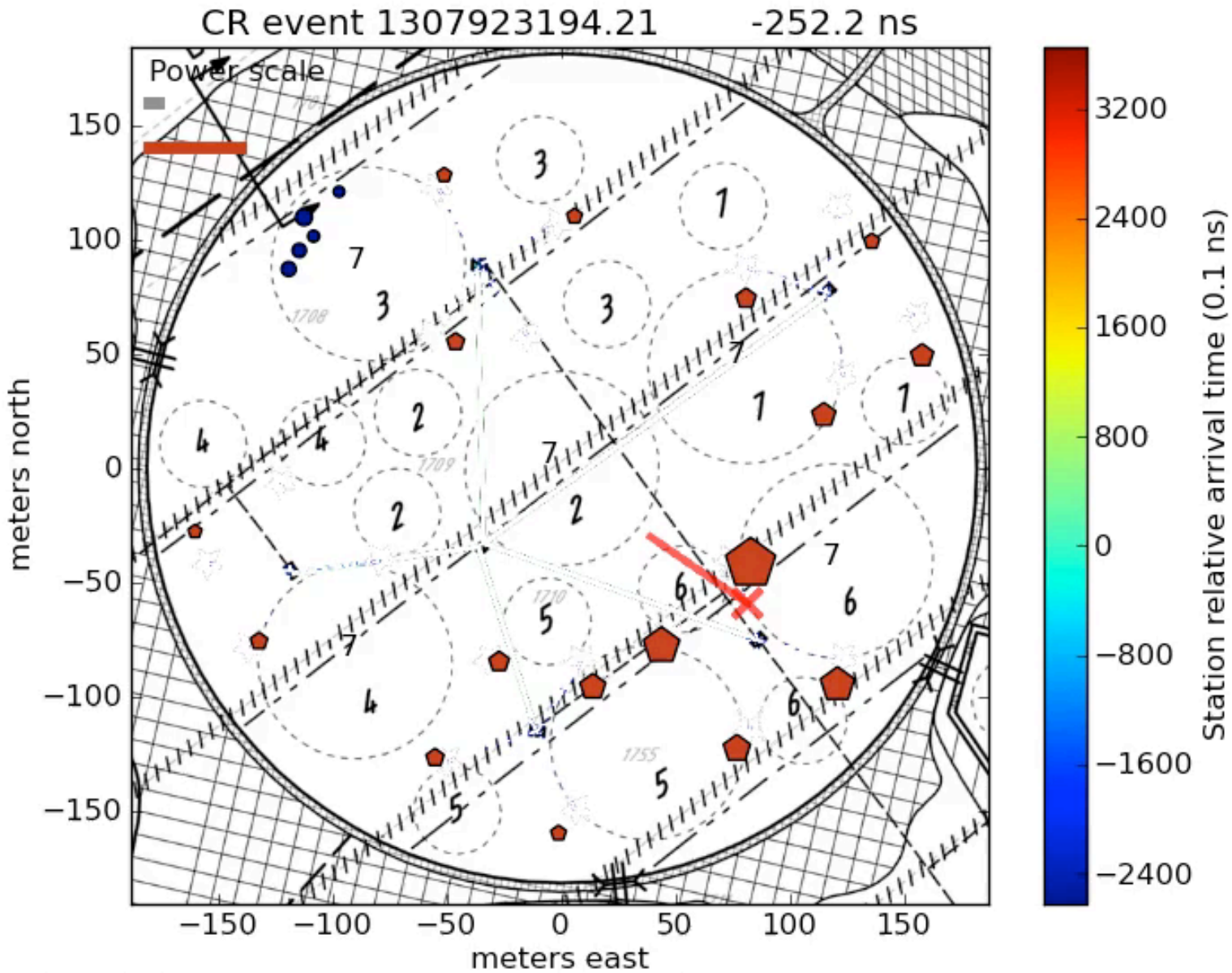


LOFAR

JCAP in press, arXiv:1406.1355

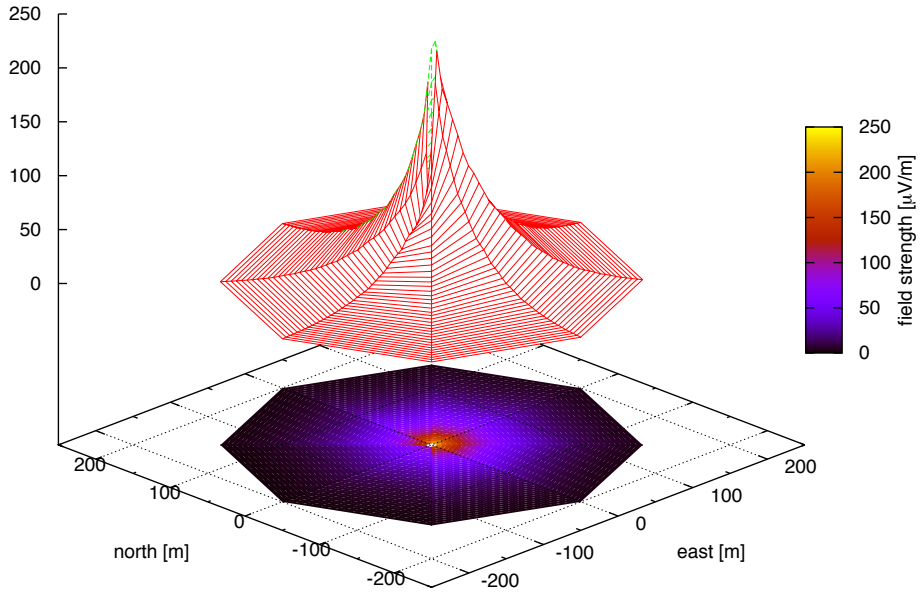
Lateral Distribution

A measured air shower

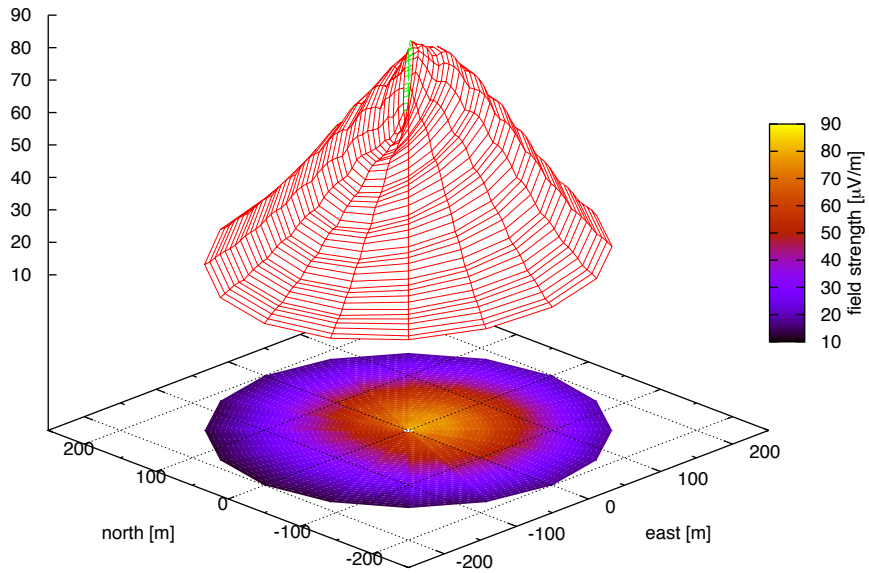


Circles: LOFAR antennas, Pentagons: LORA particle detectors, size denotes signal strength

Predicted radio intensity pattern



Proton

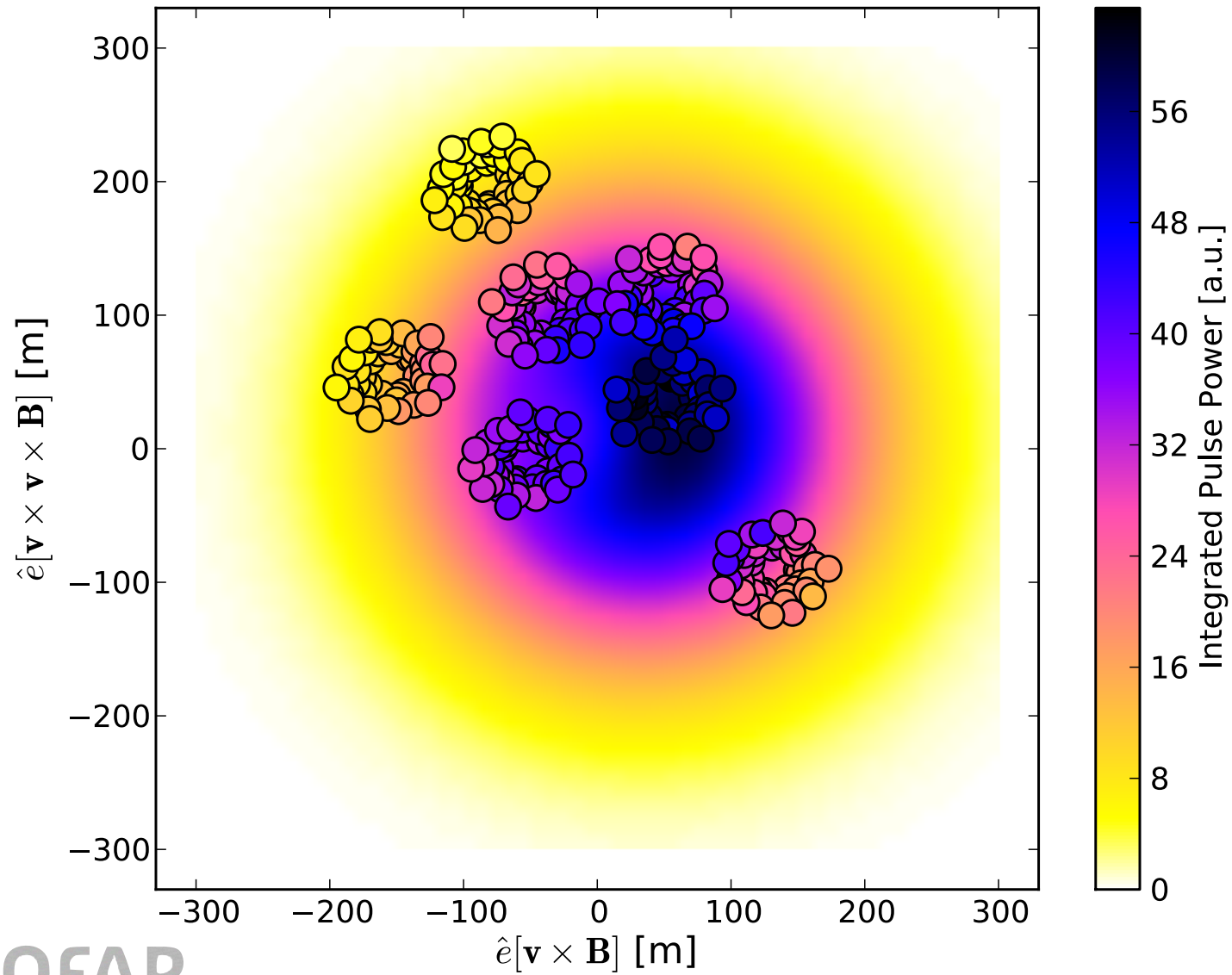


Iron nucleus

Huege et al. 2013

Lateral distribution of radio signals

as measured by LOFAR

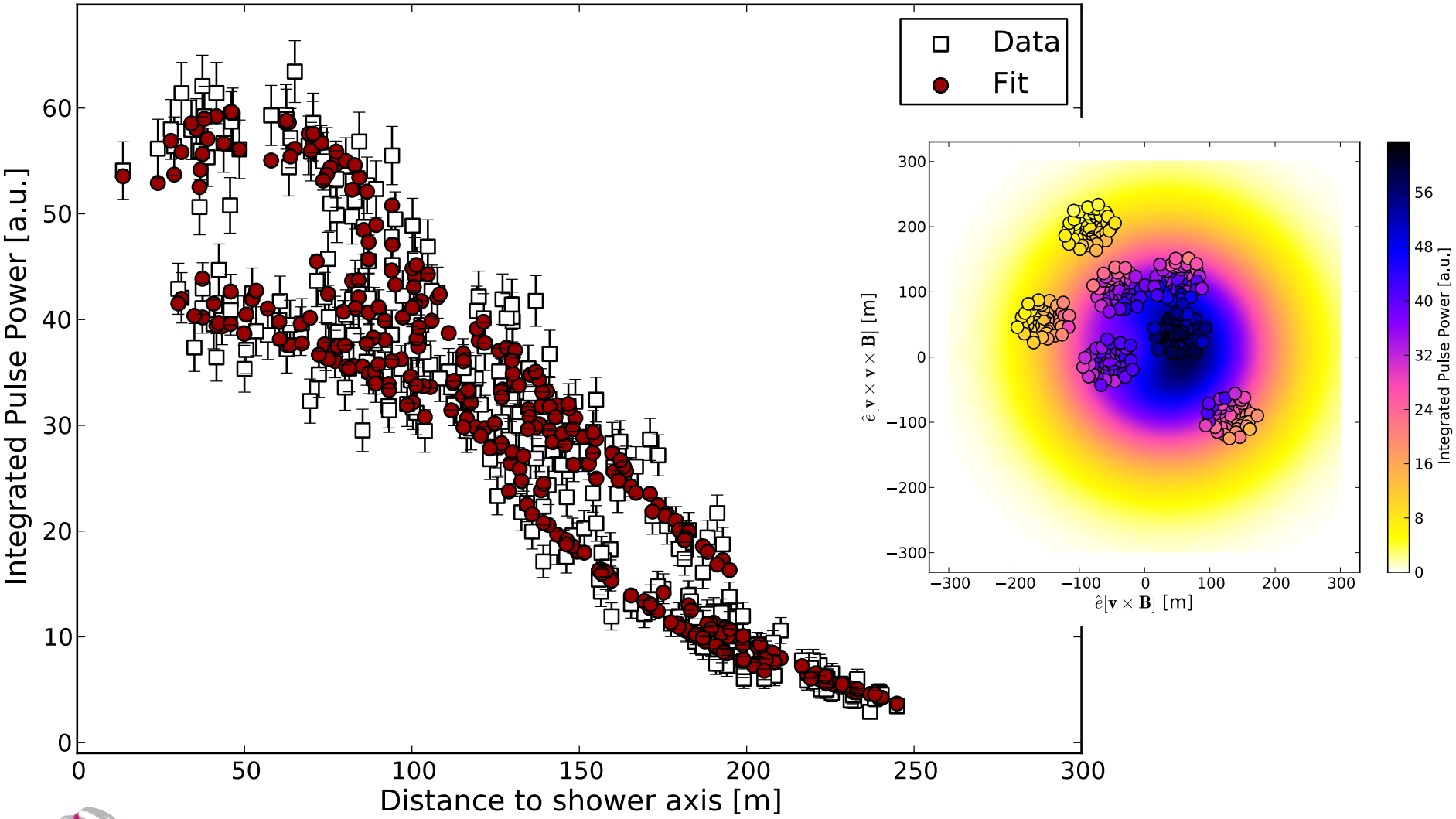


LOFAR

A. Nelles et al., Astropart. Phys. 60 (2015) 13

Lateral distribution of radio signals

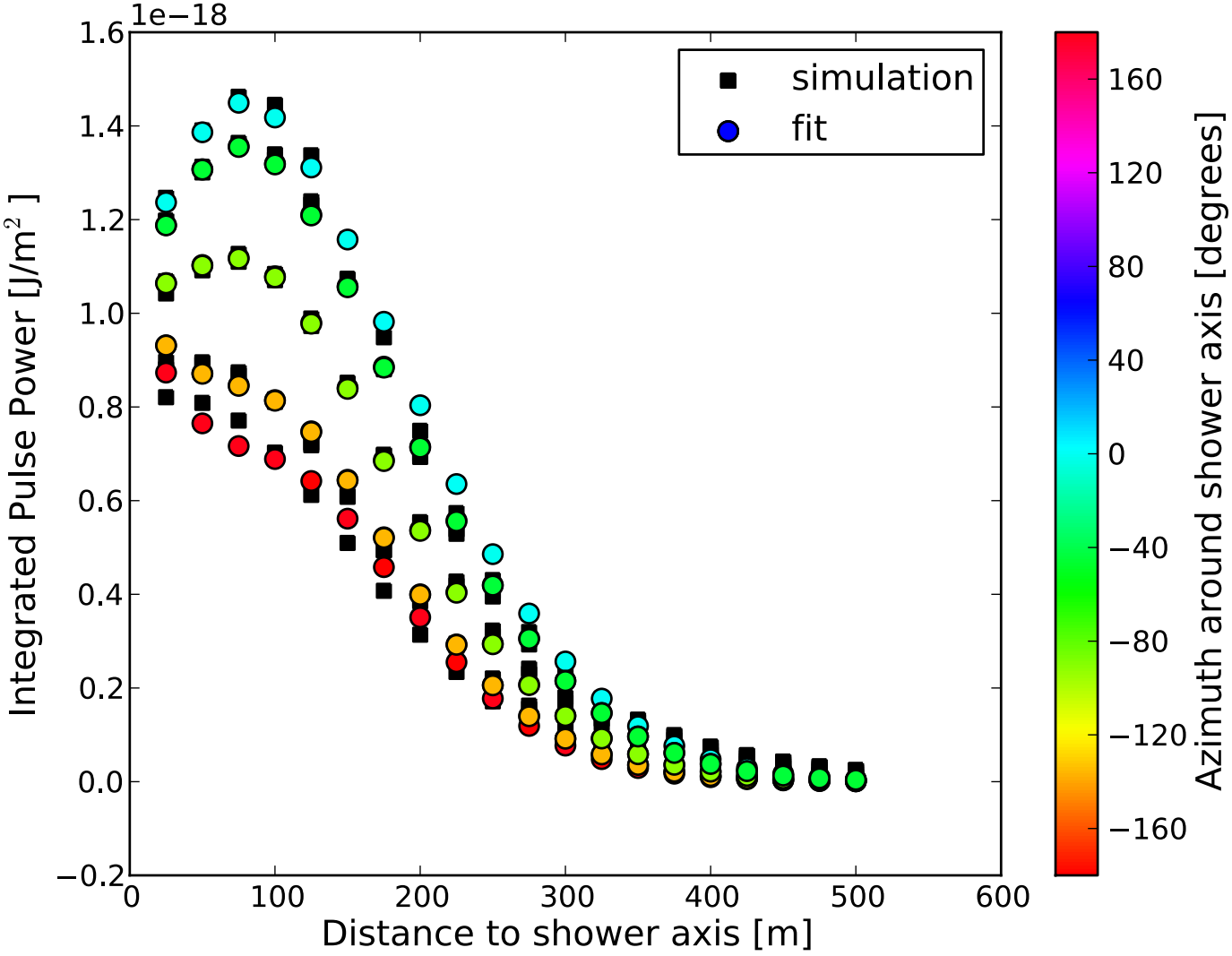
as measured by LOFAR



LOFAR

A. Nelles et al., Astropart. Phys. 60 (2015) 13

Lateral distribution of radio signals

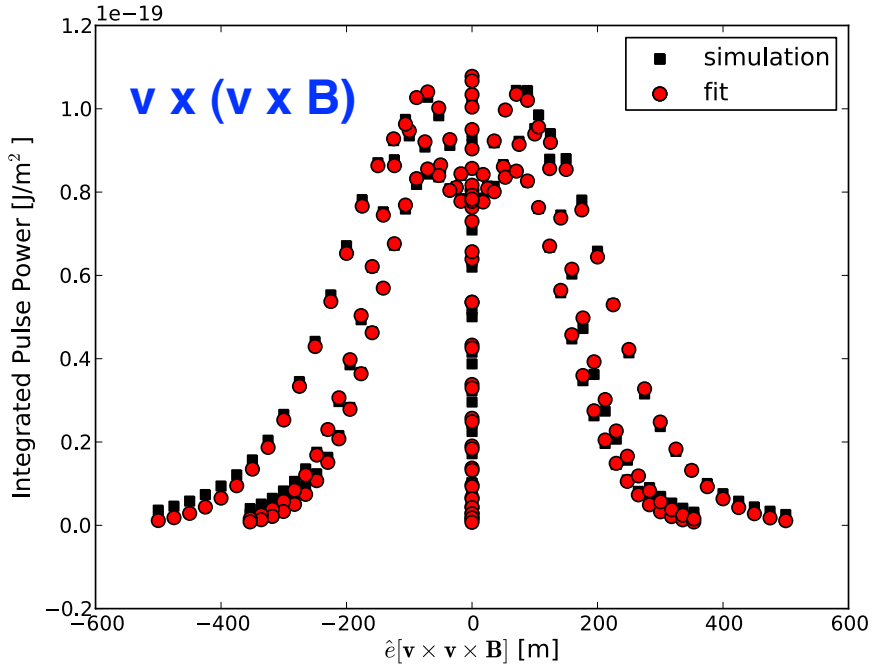


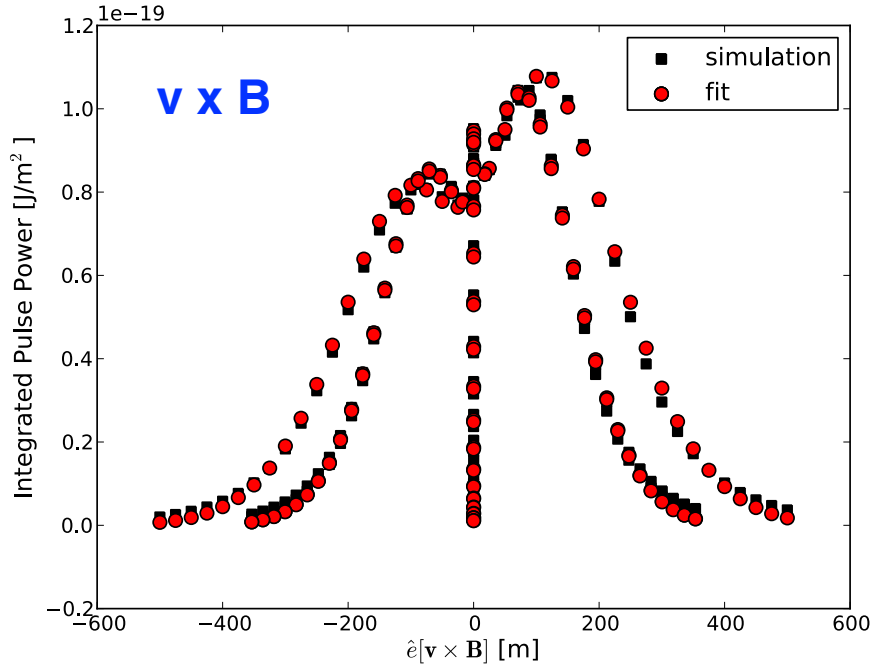
Lateral distribution of radio signals

not rotational symmetric

fit two Gaussian functions

$$P(x',y') = A_+ \cdot \exp\left(\frac{-[(x'-X_+)^2+(y'-Y_+)^2]}{\sigma_+^2}\right) - A_- \cdot \exp\left(\frac{-[(x'-X_-)^2+(y'-Y_-)^2]}{\sigma_-^2}\right) + O$$

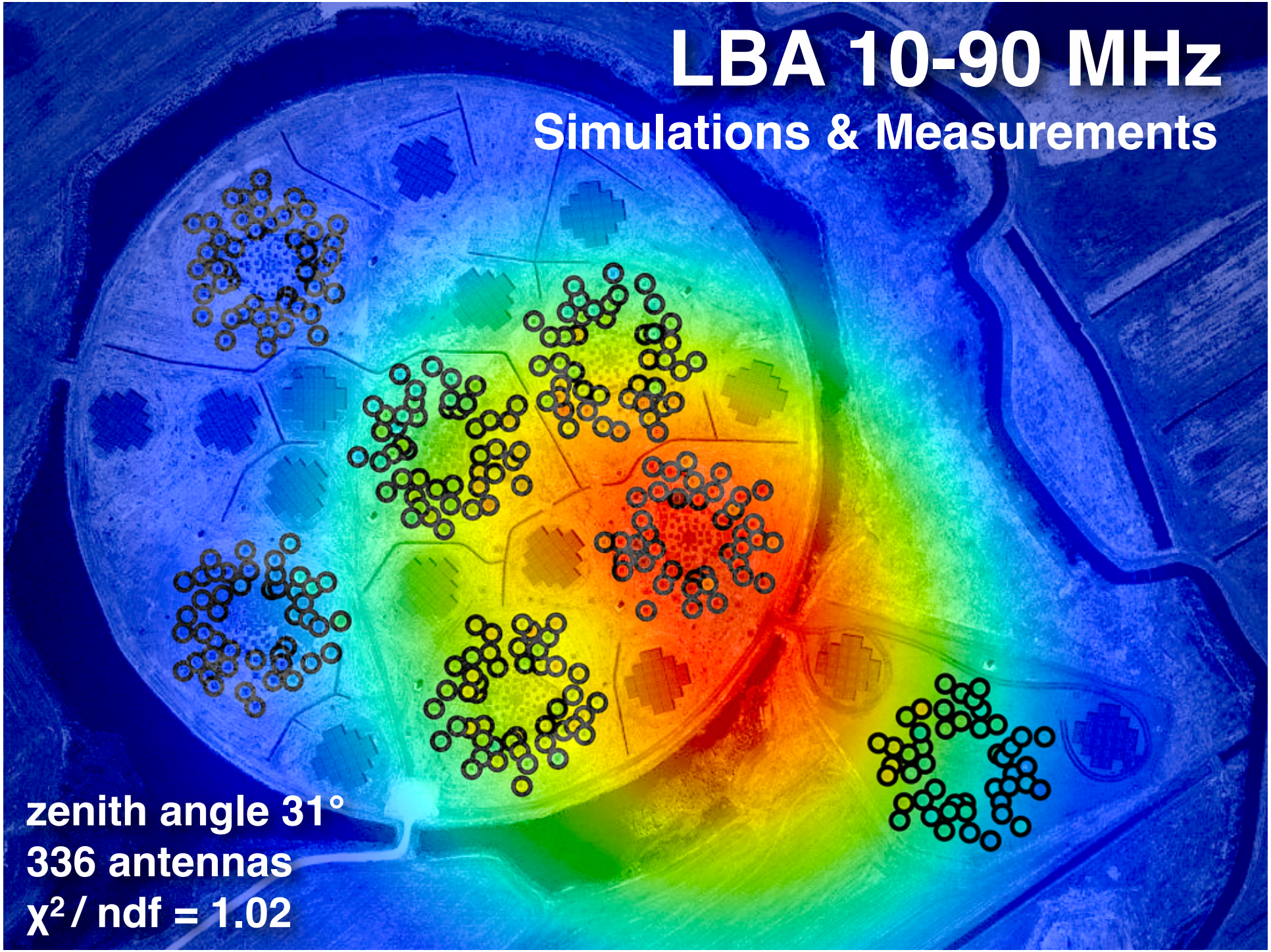




A. Nelles et al., Astropart. Phys. 60 (2015) 13

LBA 10-90 MHz

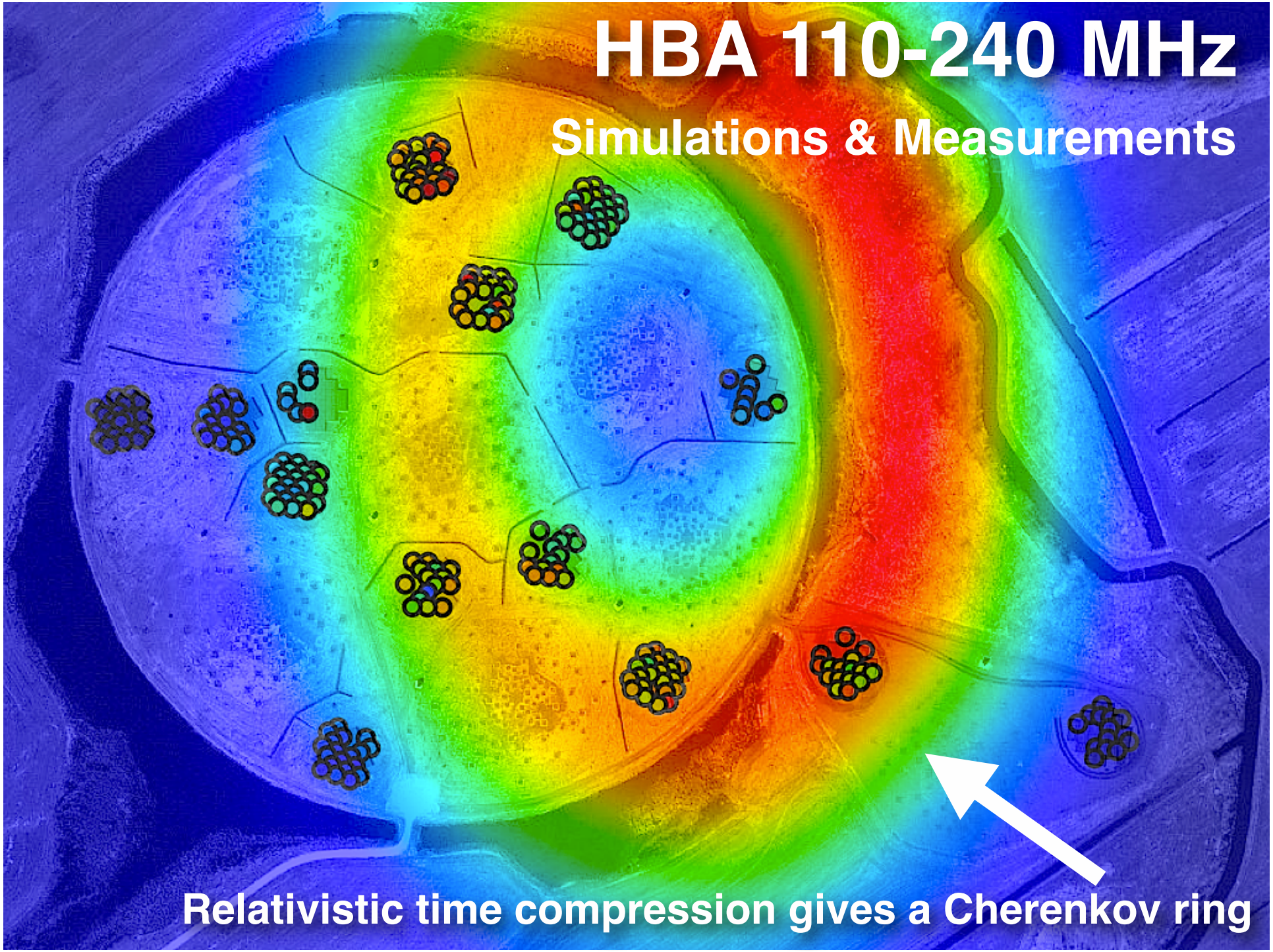
Simulations & Measurements



zenith angle 31°
336 antennas
χ^2 / ndf = 1.02

HBA 110-240 MHz

Simulations & Measurements

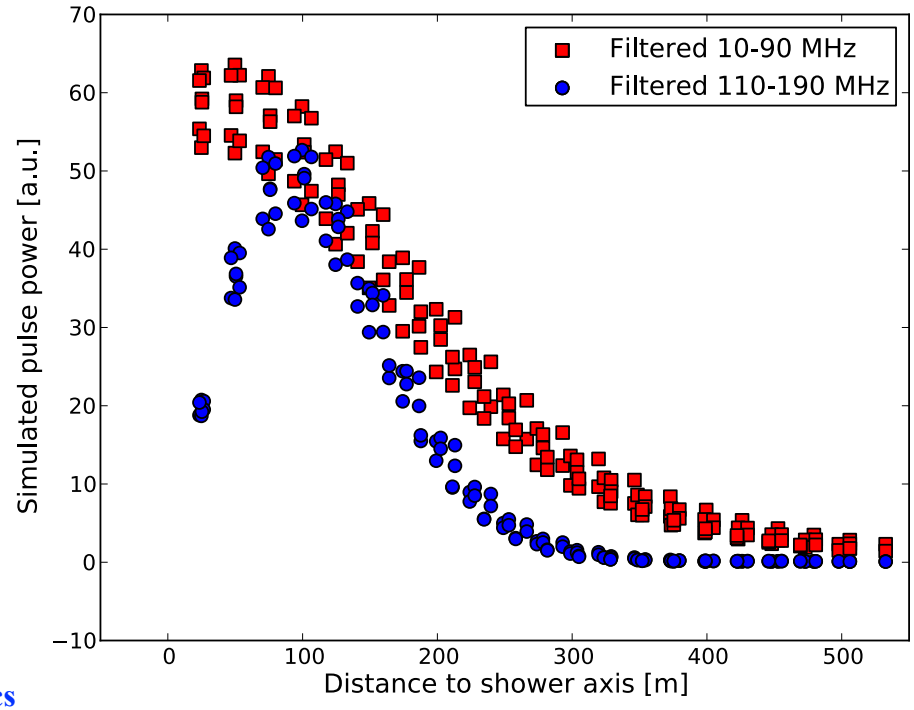


Relativistic time compression gives a Cherenkov ring

Radio emission at 120 - 240 MHz

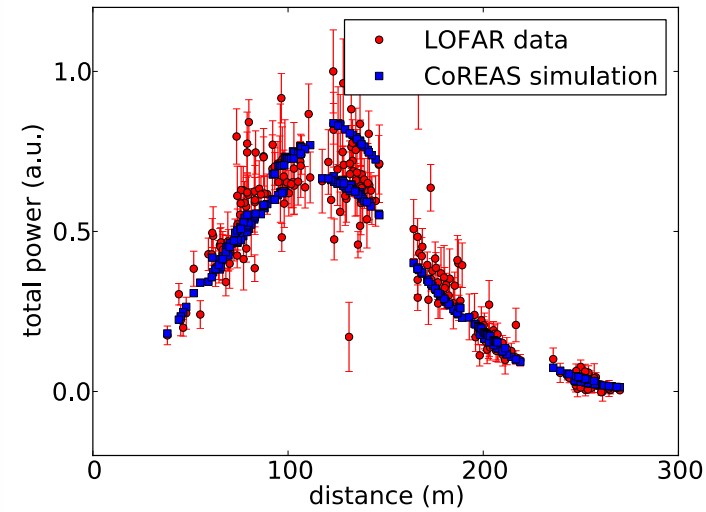
- LOFAR is the only dedicated experiment with high-band antennas
  - tuned to astronomical observations
  - include analogue beamforming
  - complicated calibration routine

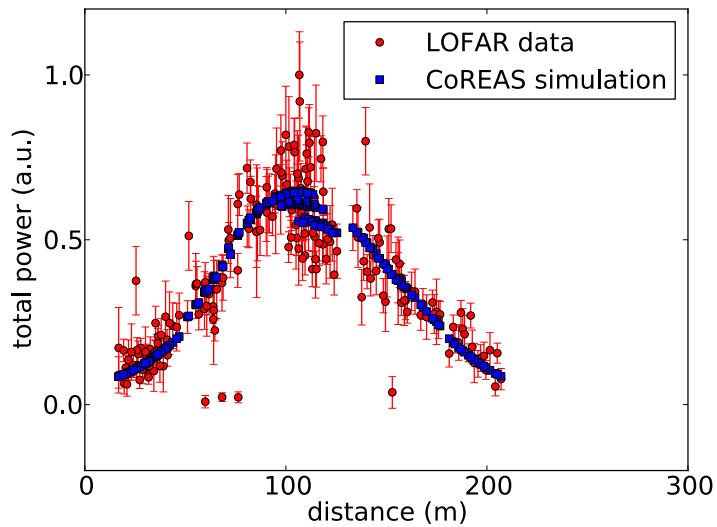
- Signals expected to be
  - more affected by Cherenkov enhancement
  - concentrated on a ring of emission



A. Nelles et al (LOFAR Collaboration), subm. to Astroparticle Physics

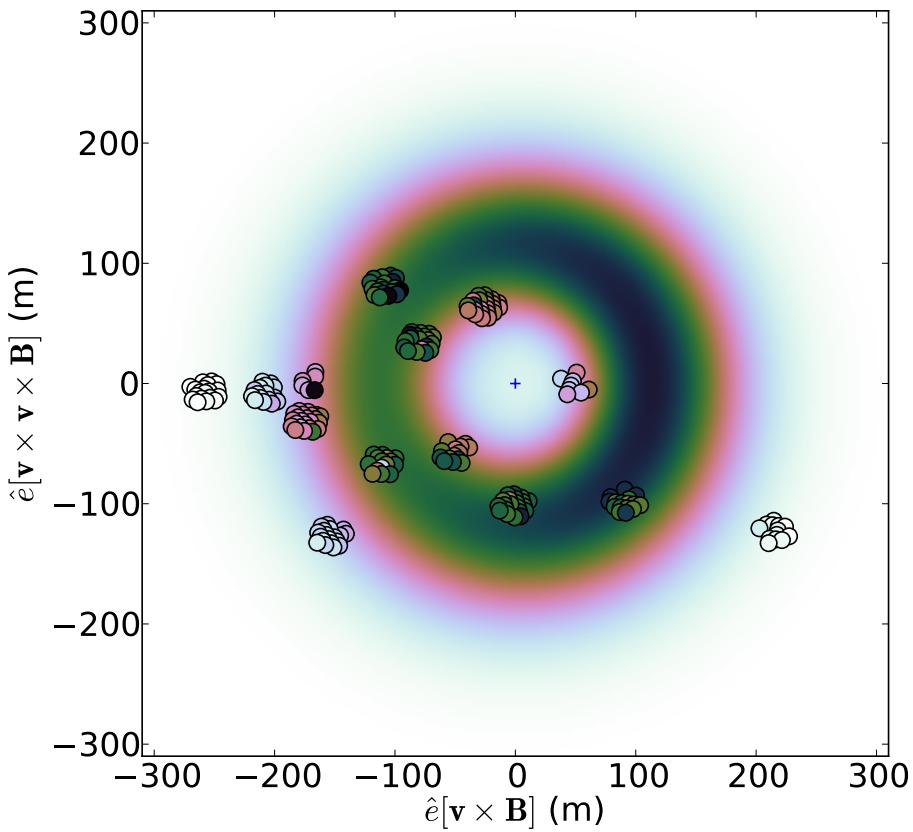
Measuring Cherenkov Rings





A. Nelles et al (LOFAR Collaboration), subm. to Astroparticle Physics

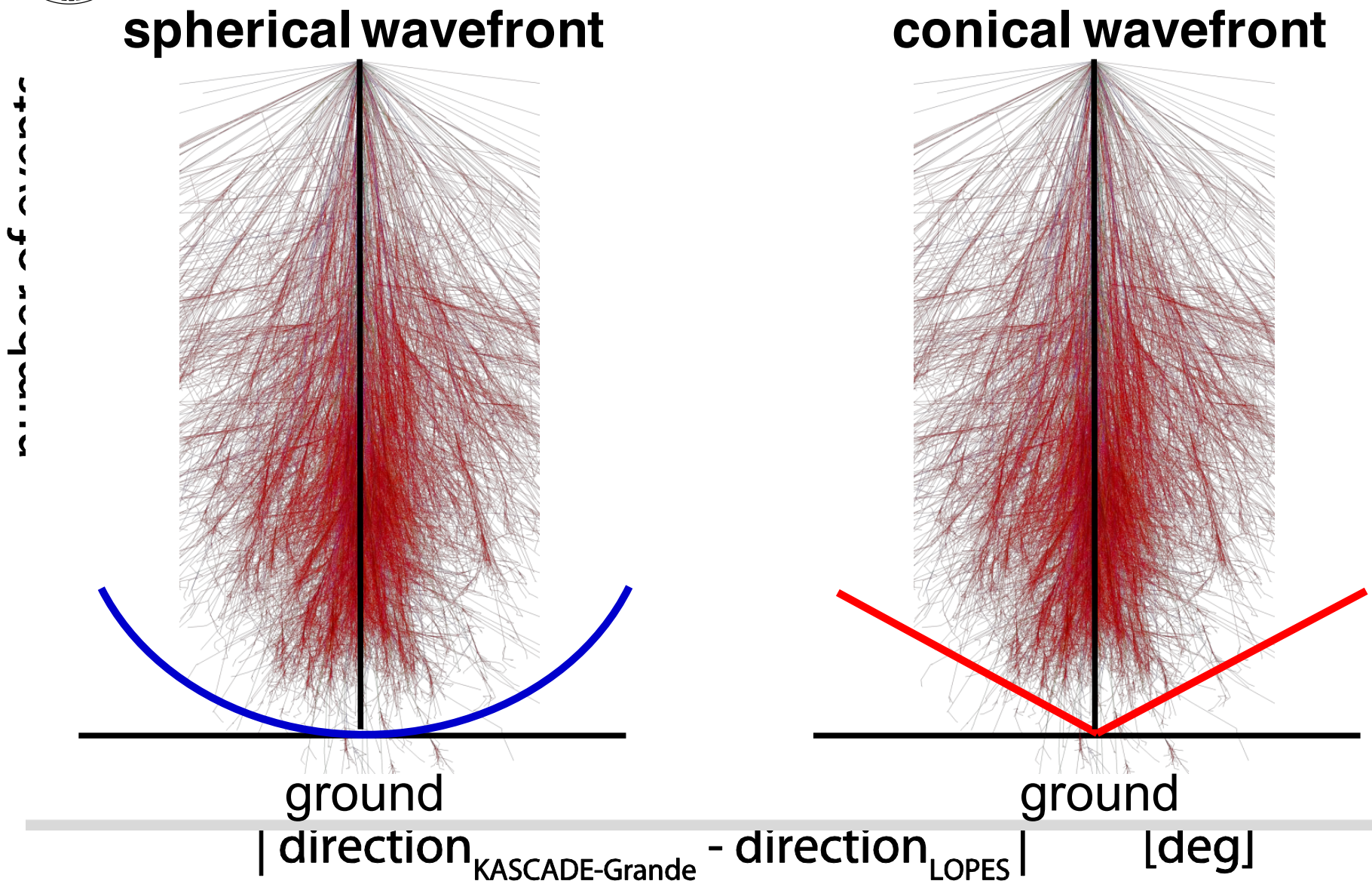
110 - 190 MHz



- **higher frequency-range: dominance of relativistic time-compression**
- **first experiment to observe these in single events**

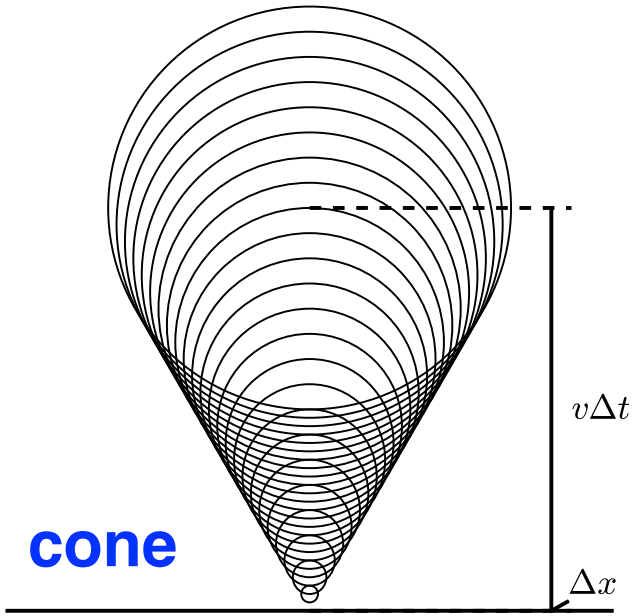
Direction

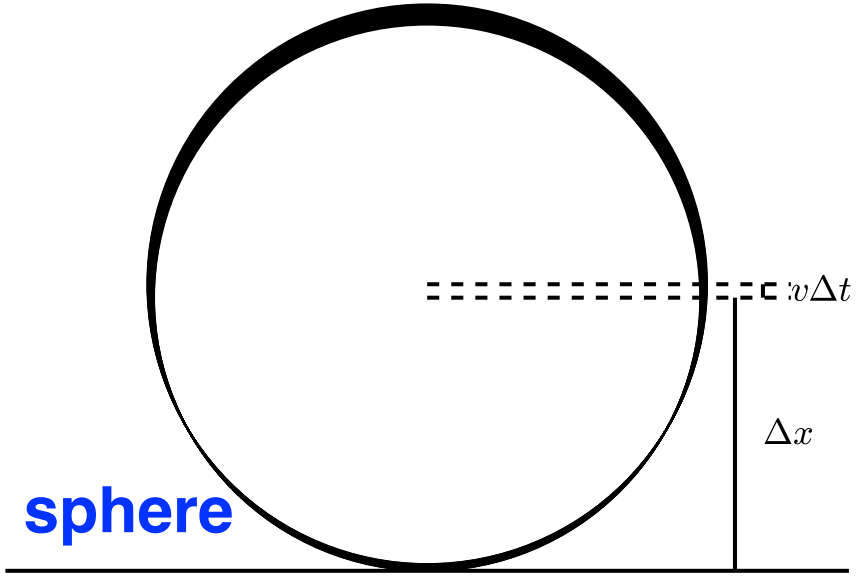
LOPES: direction of shower

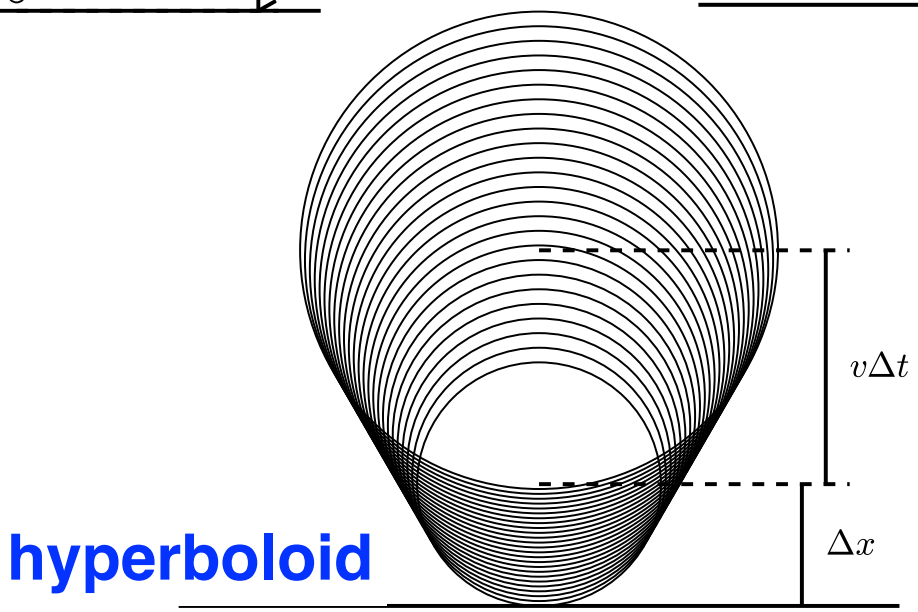


F. Schröder, ARENA (2012)

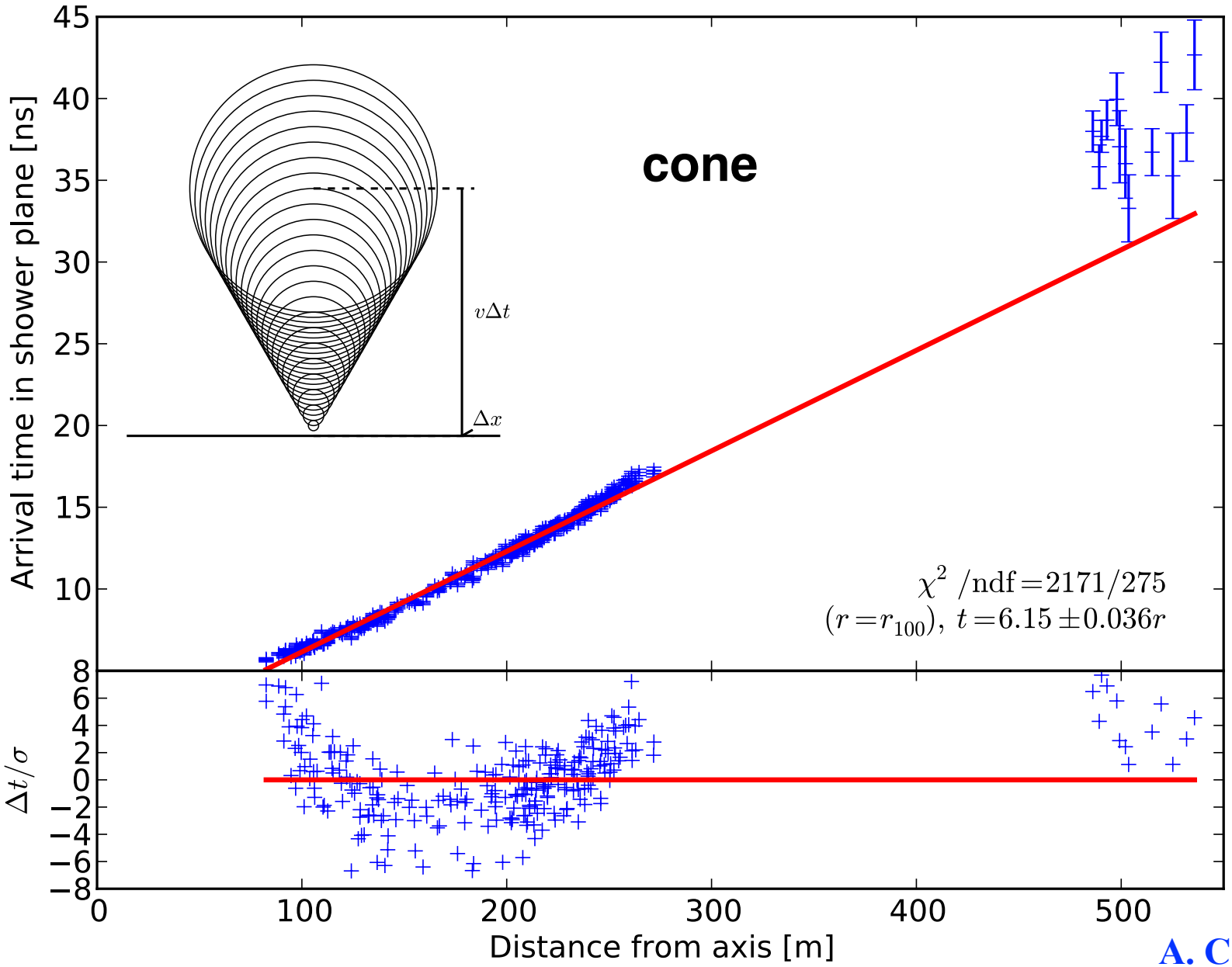
Shape of the Shower Front





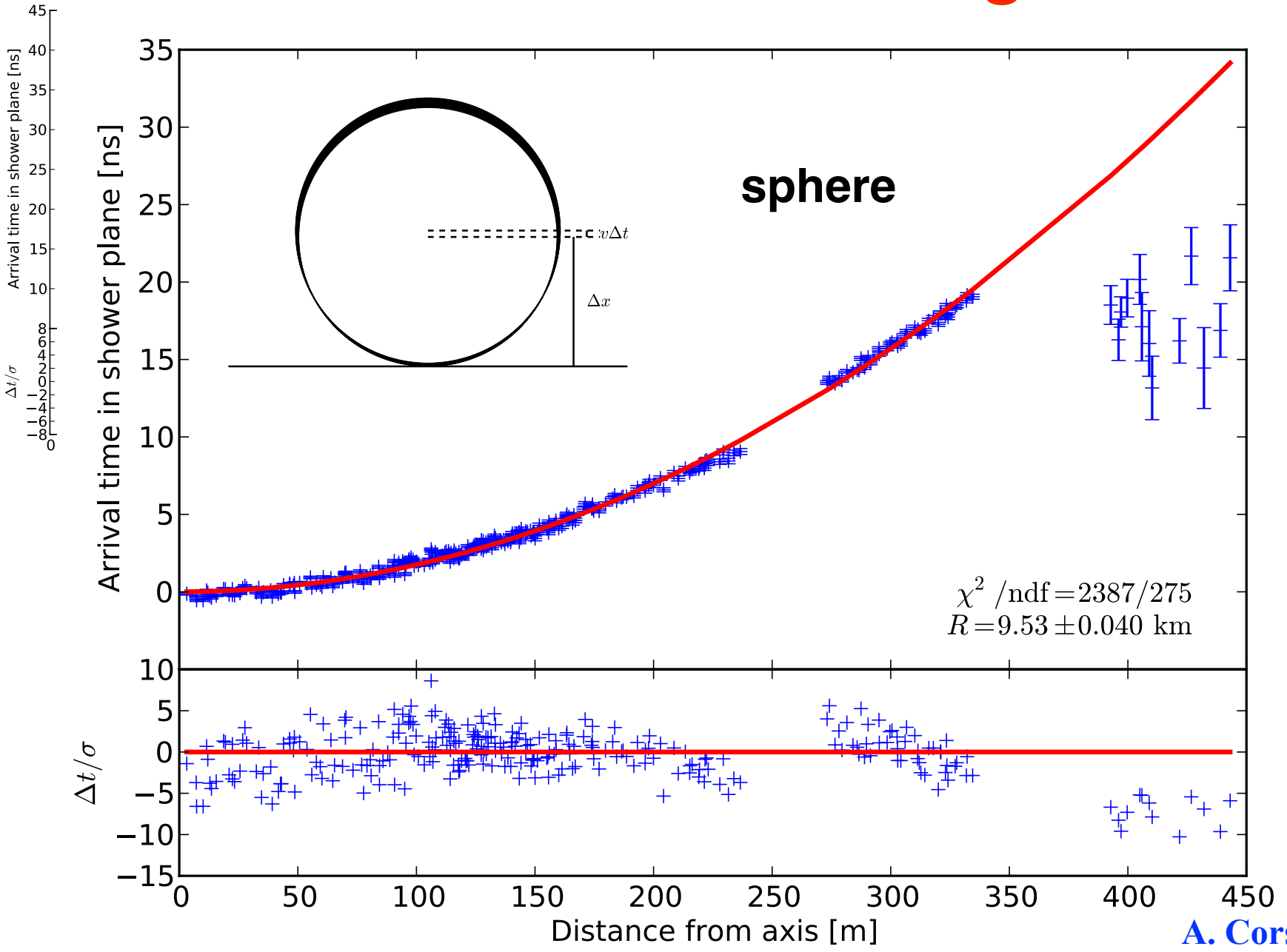


Arrival time of radio signals



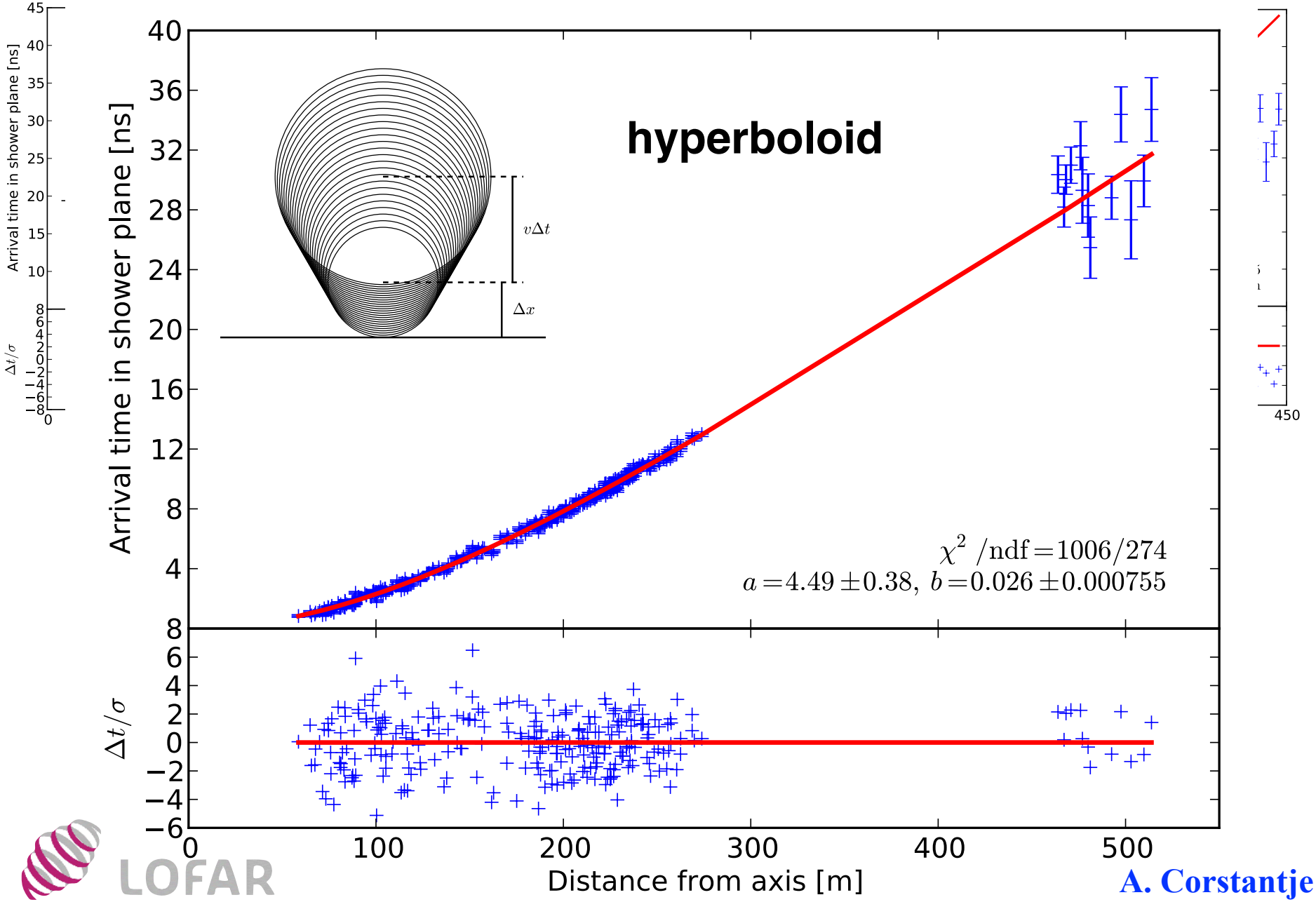
A. Corstantje

Arrival time of radio signals



A. Corstantje

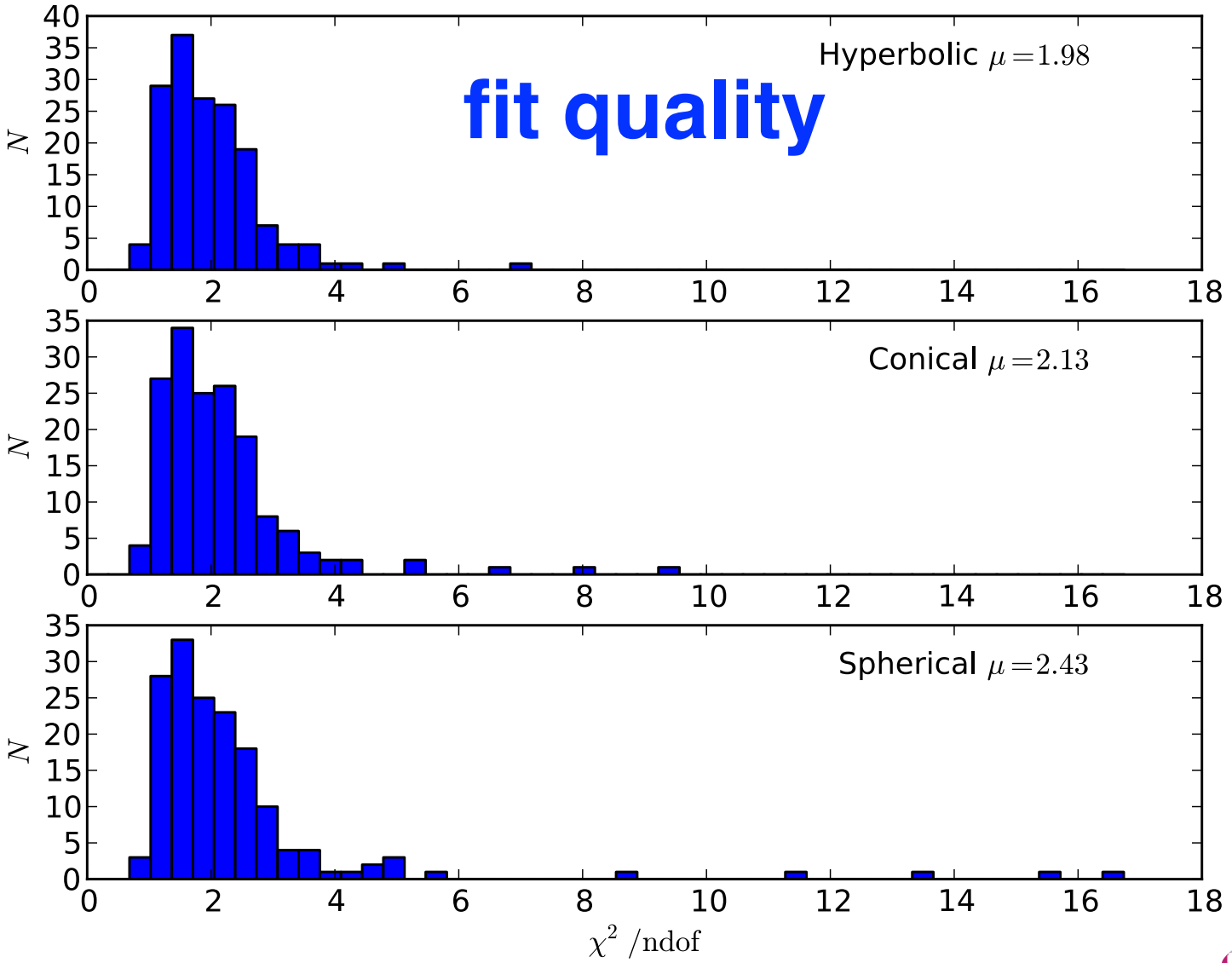
Arrival time of radio signals

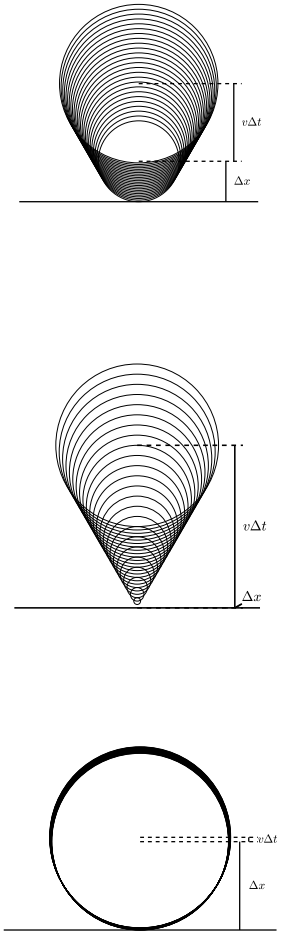


LOFAR

A. Corstantje

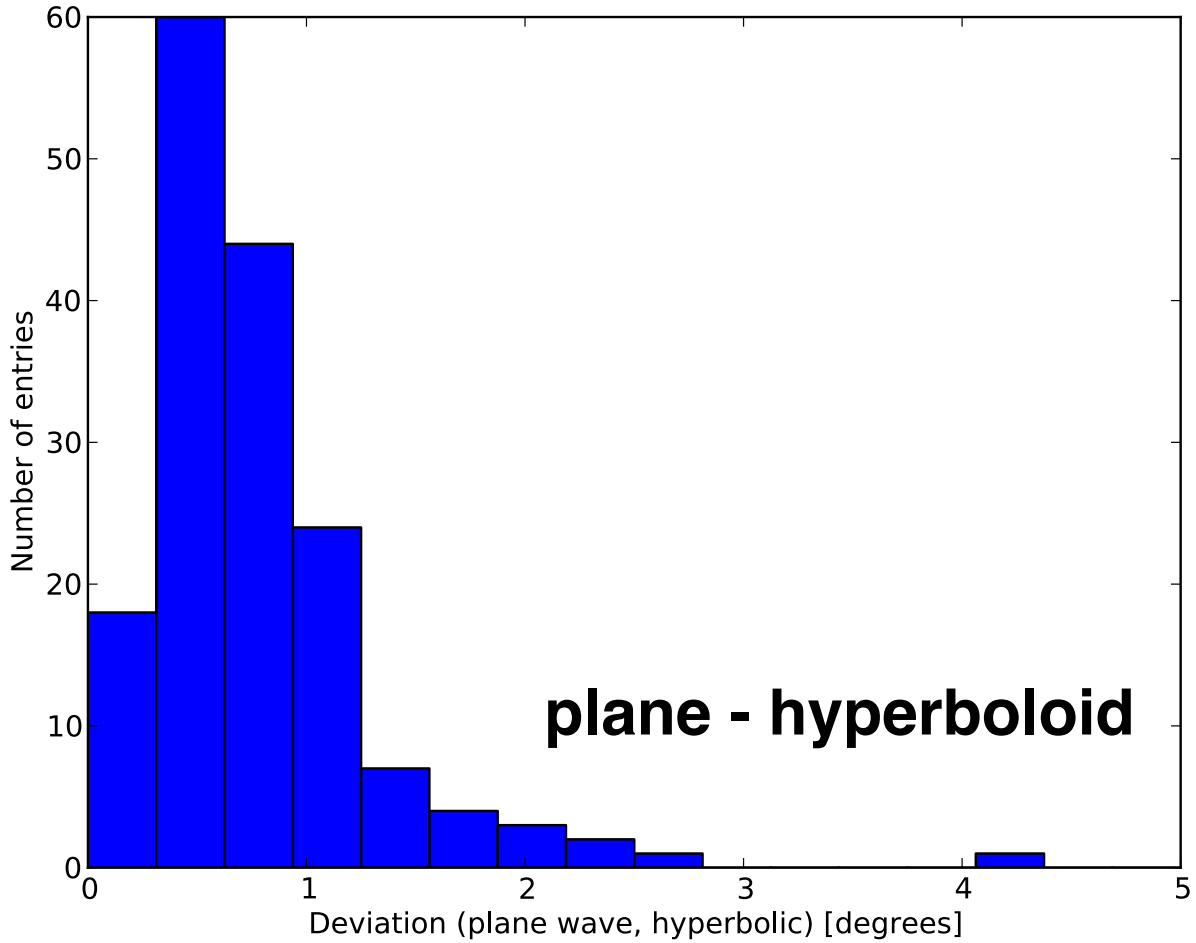
Shape of Shower Front

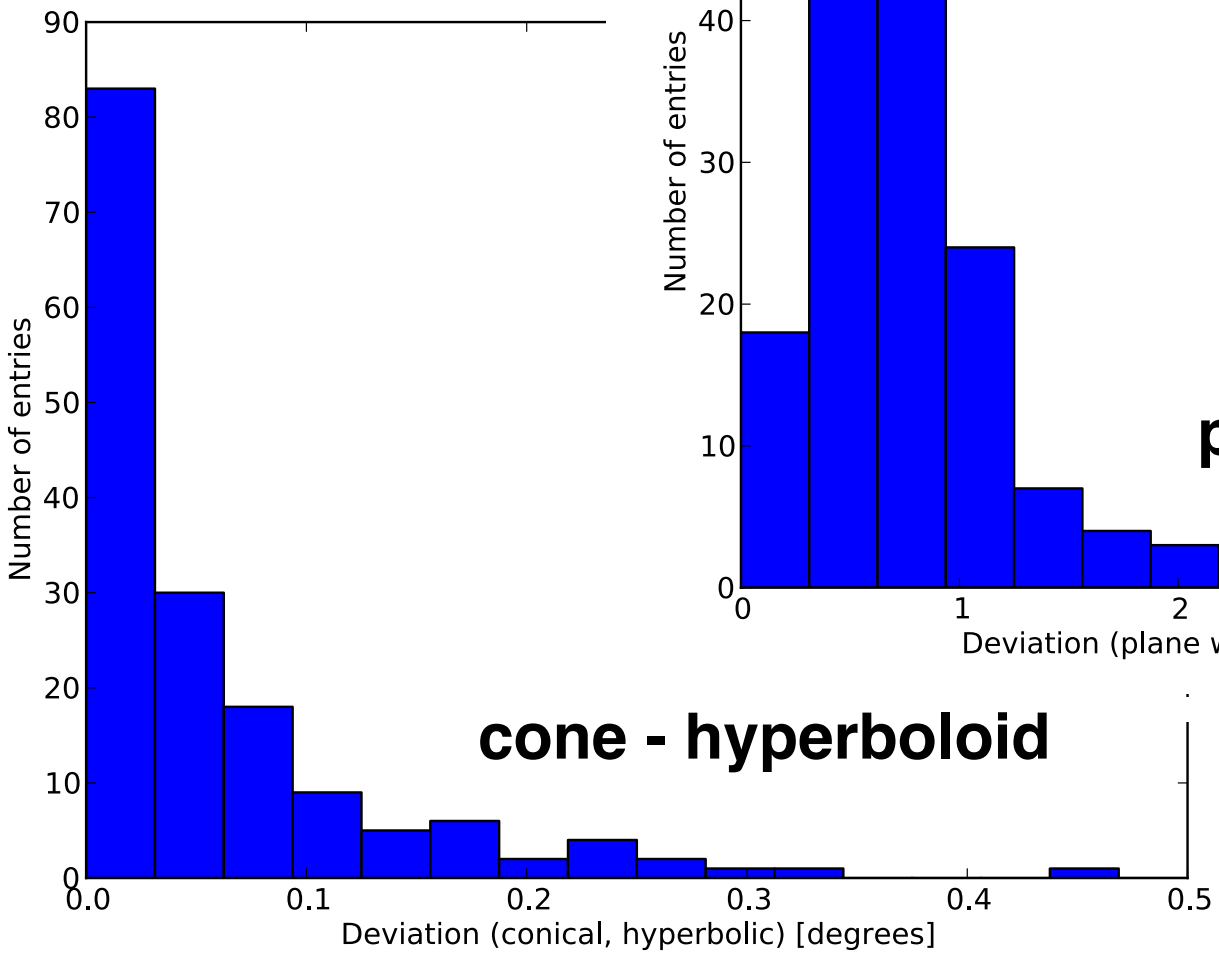




Accuracy of Shower Direction

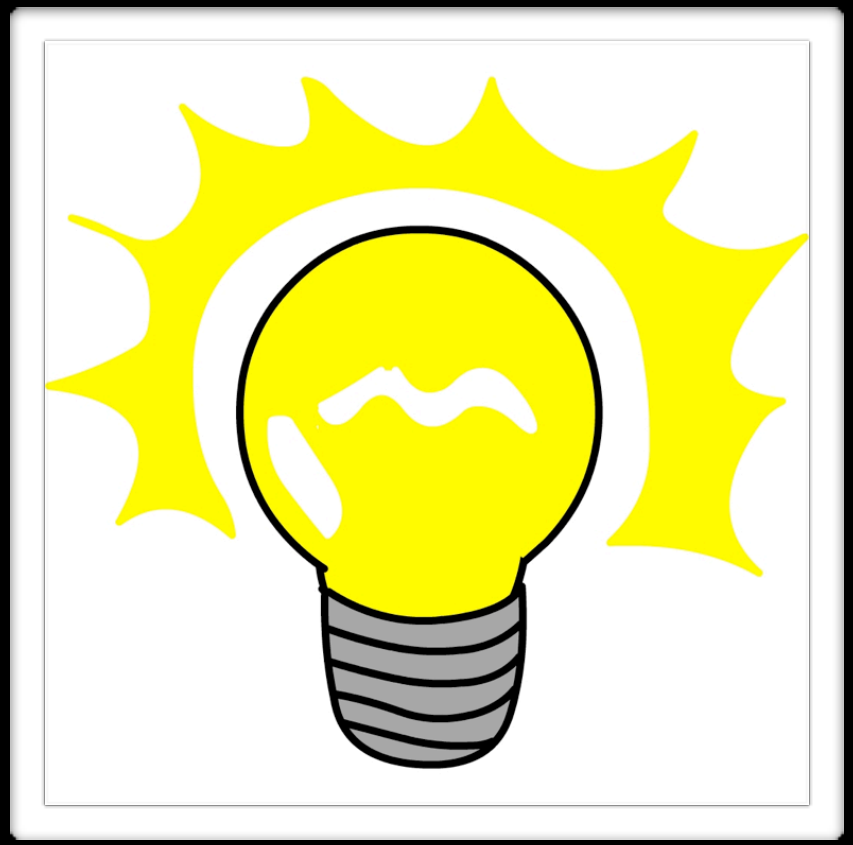
angular difference between..



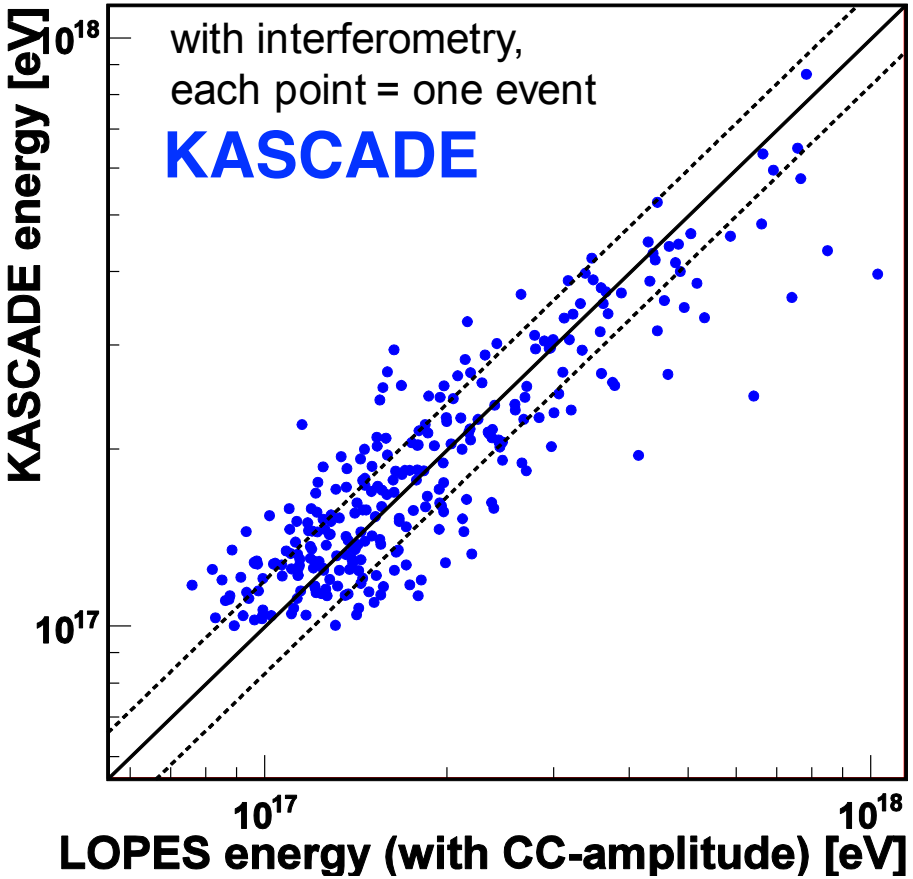


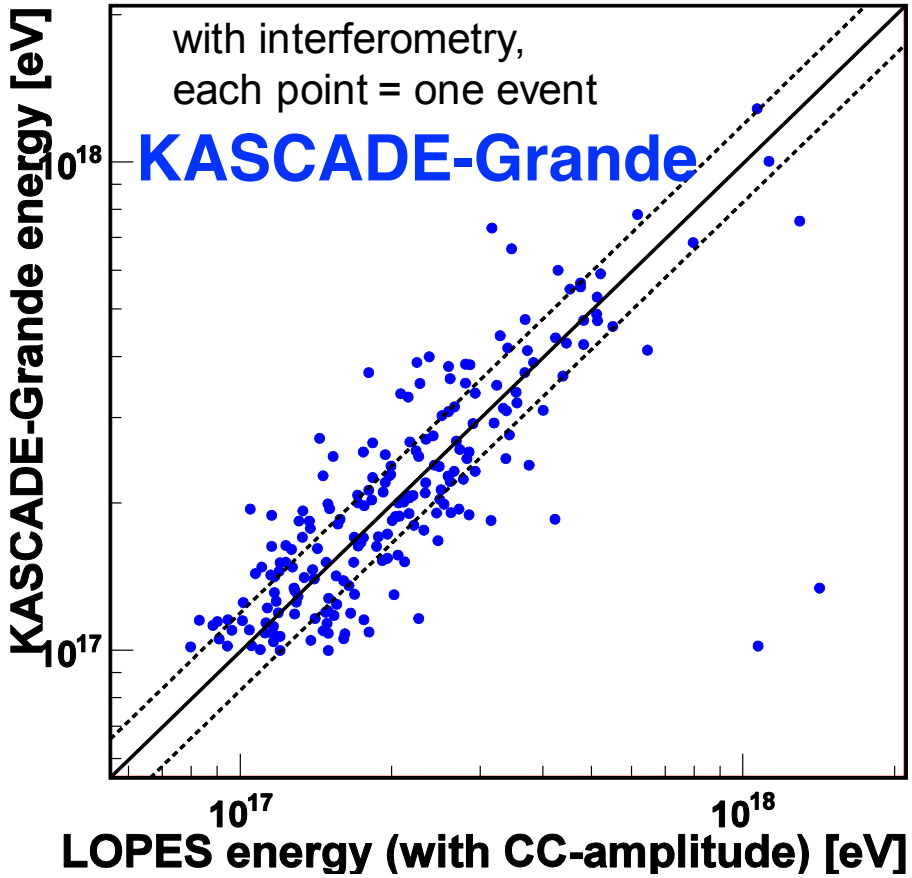
LOFAR

Energy



LOPES: energy correlation with





$$E = a \cdot \frac{\varepsilon_{CC-beam(east-west)}}{\left|\vec{v} \times \vec{B}\right|_{EW} \cdot \exp(-d/180\mathrm{m})}$$

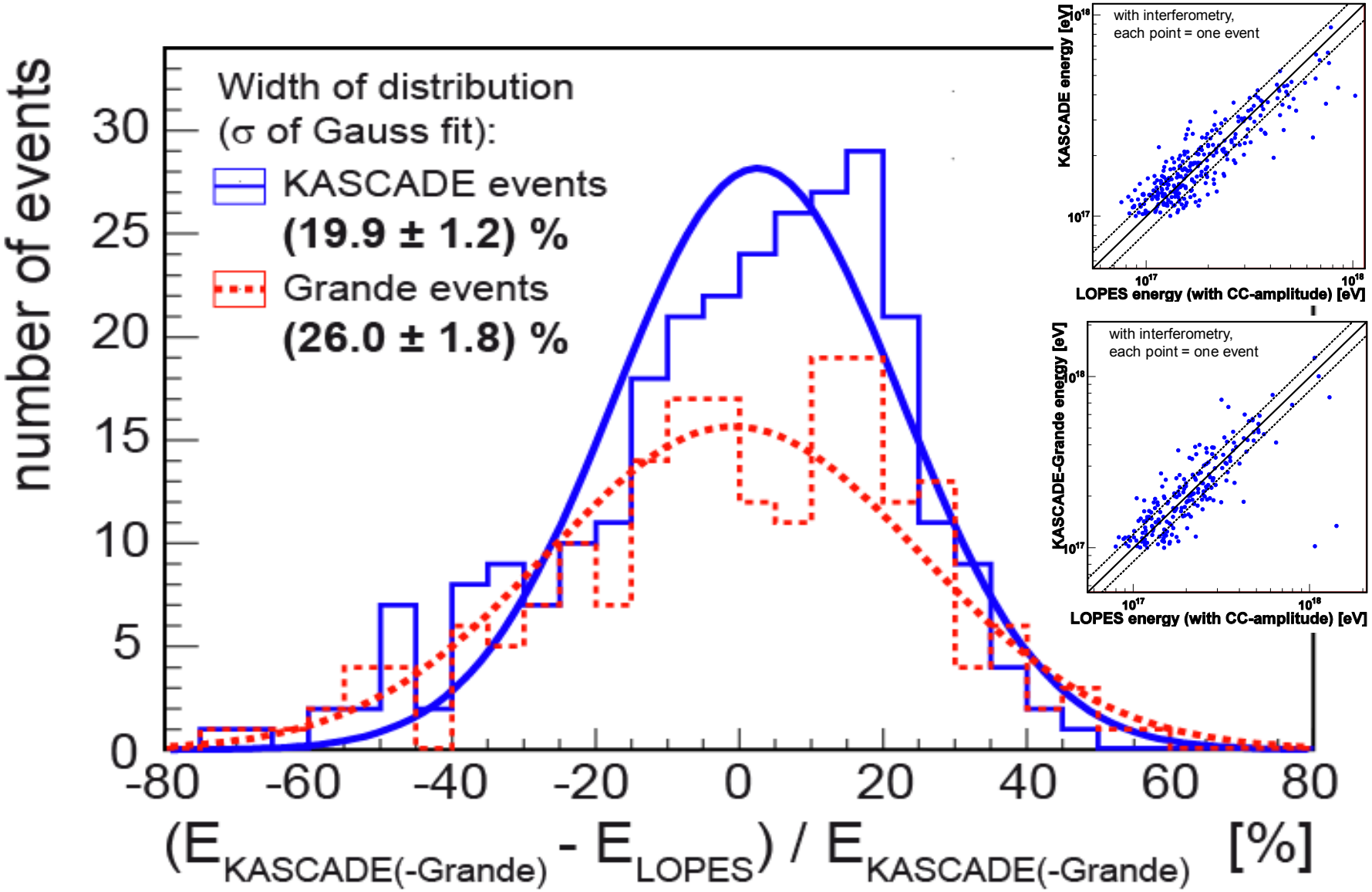
$$E = b \cdot \frac{\varepsilon_{CC-beam(east-west)}}{\left|\vec{v} \times \vec{B}\right|_{EW} \cdot \exp(-d/180\mathrm{m})}$$

$$b/a \approx 77\ \%$$

F. Schröder, ARENA (2012)

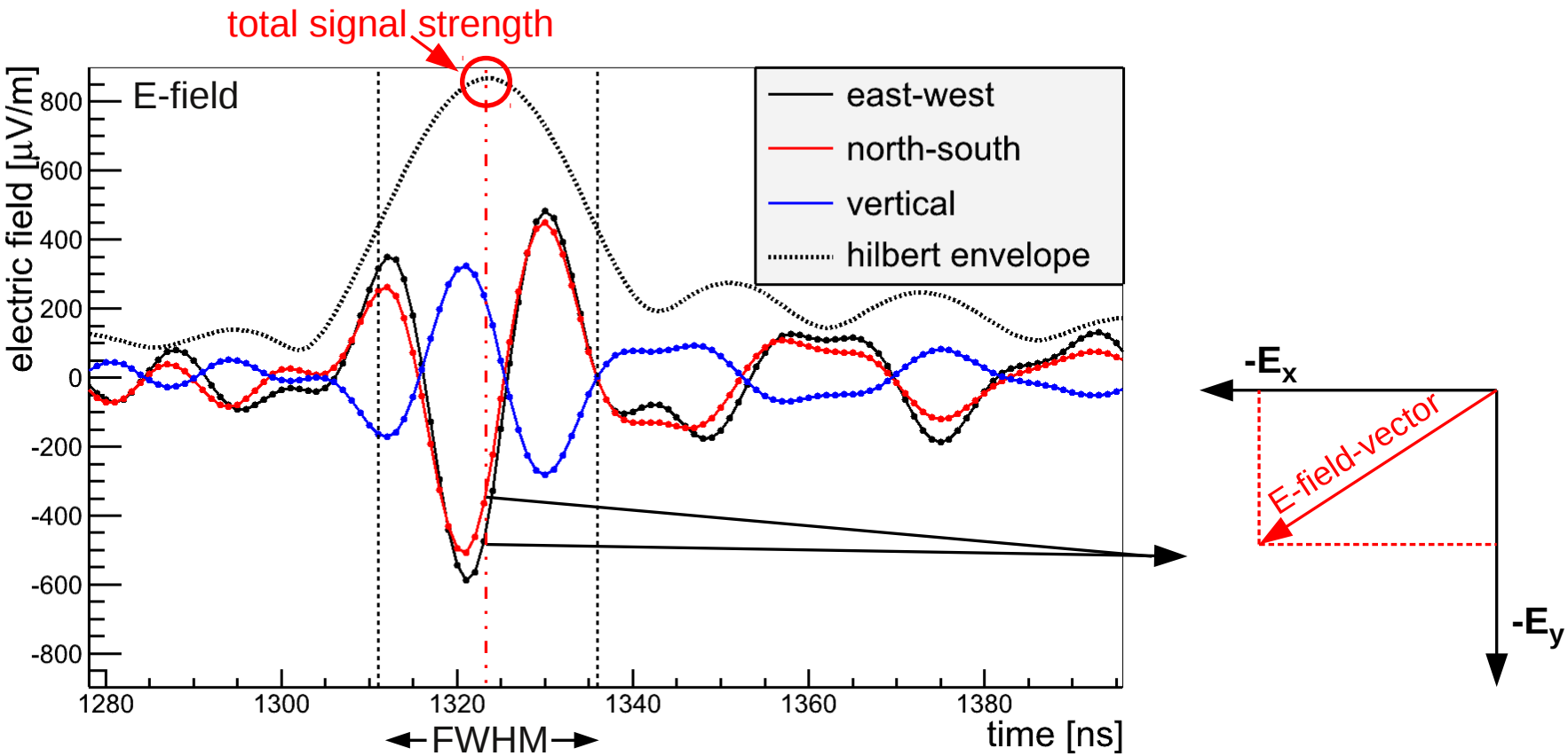
LOPES: energy correlation

with KASCADE and KASCADE-Grande



F. Schröder, ARENA (2012)

AERA: direction of E field vector

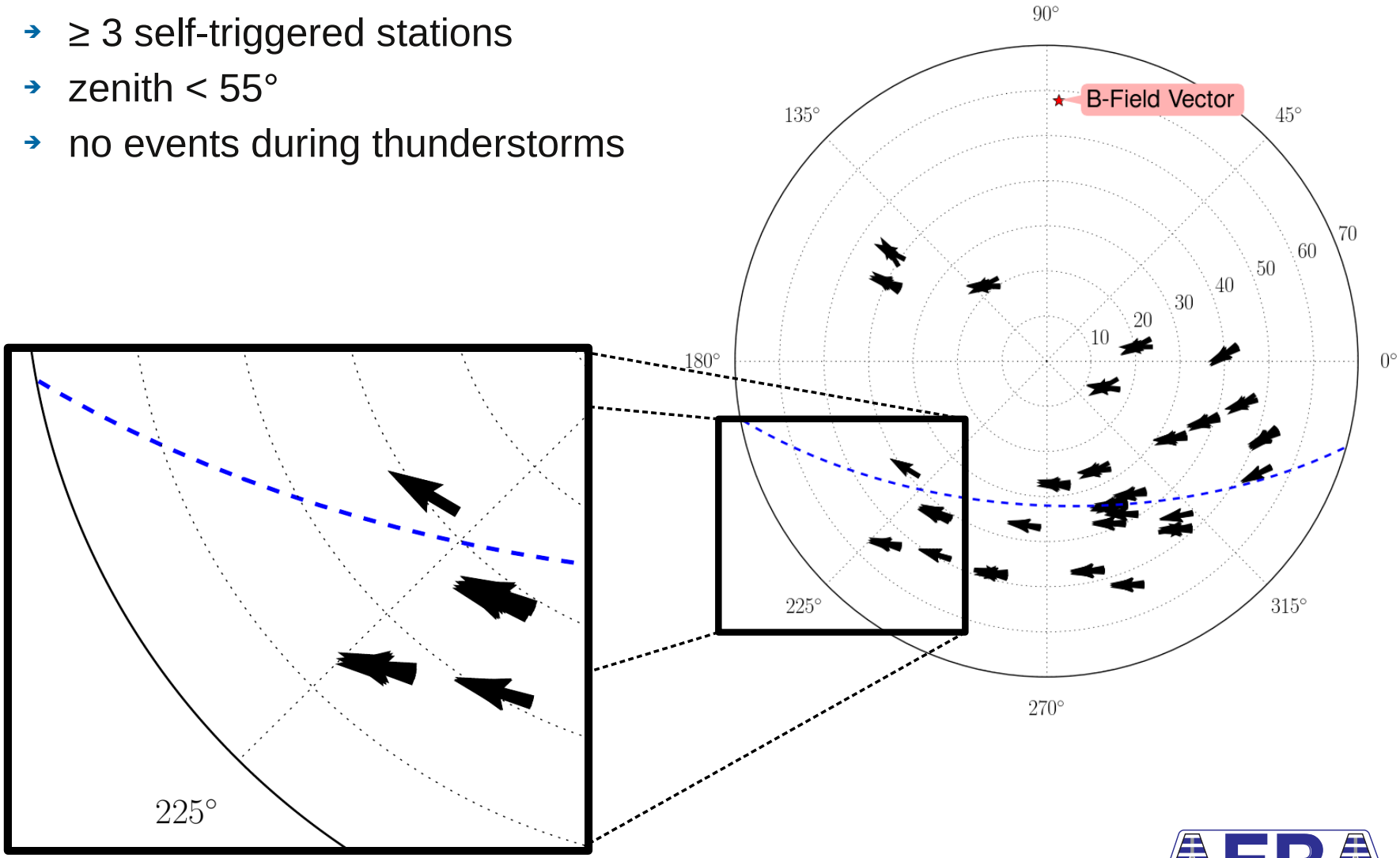


C. Glaser, ARENA (2012)

AERA
Auger Engineering Radio Array

AERA: direction of E field vector

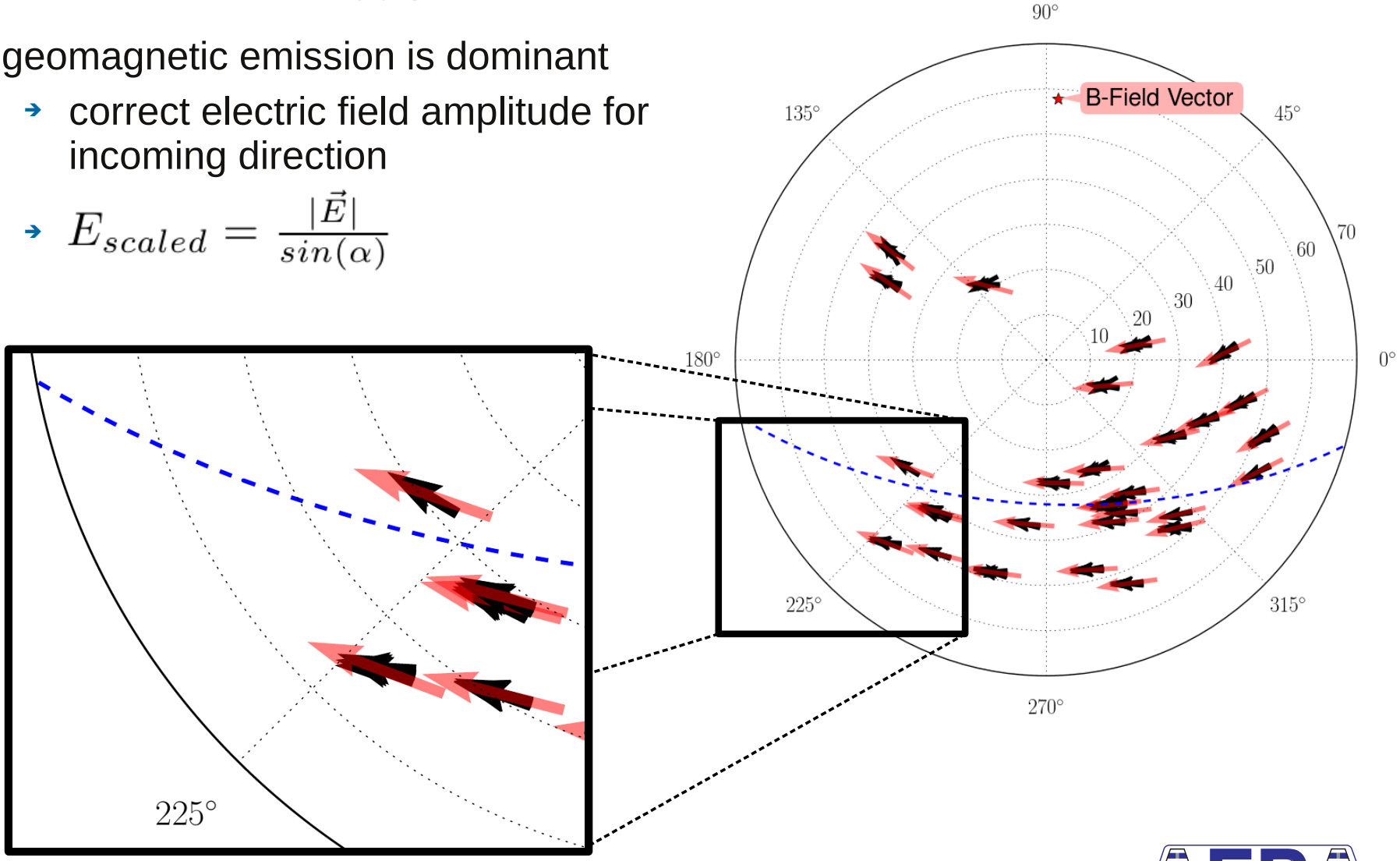
- event selection:
  - ≥ 3 self-triggered stations
  - zenith < 55°
  - no events during thunderstorms



C. Glaser, ARENA (2012)

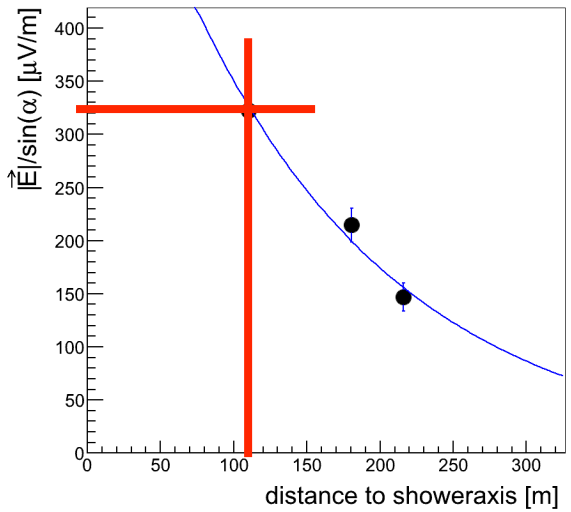
AERA: measured vs. expected values

- electric field is strongly polarised
- geomagnetic emission is dominant
  - correct electric field amplitude for incoming direction
  - $E_{scaled} = \frac{|\vec{E}|}{sin(\alpha)}$



C. Glaser, ARENA (2012)

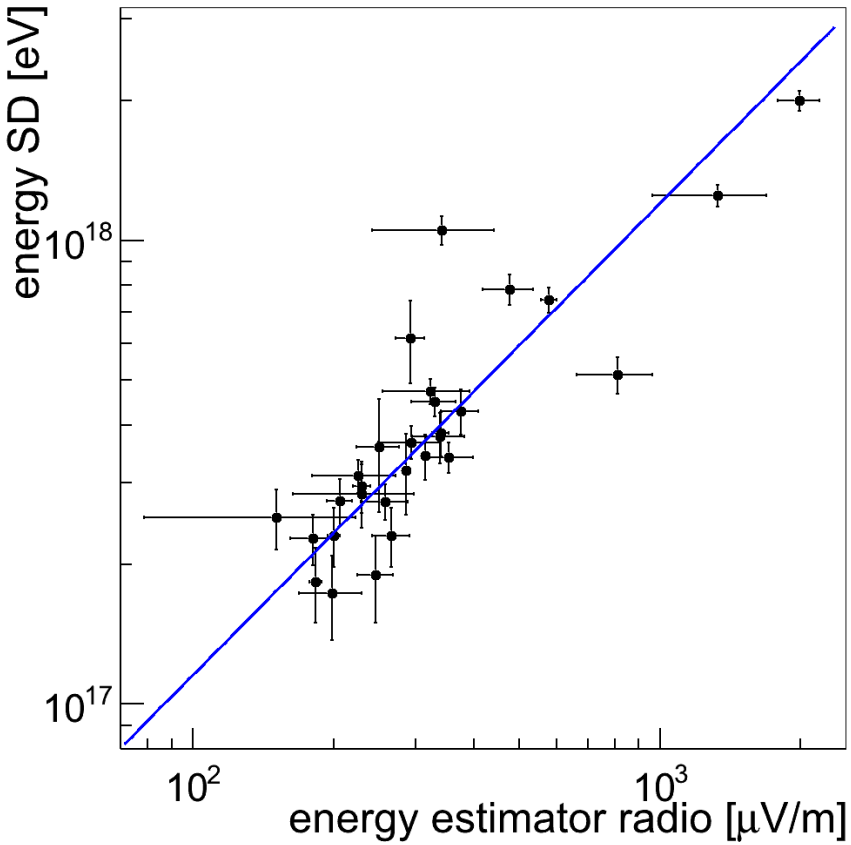
AERA: energy correlation

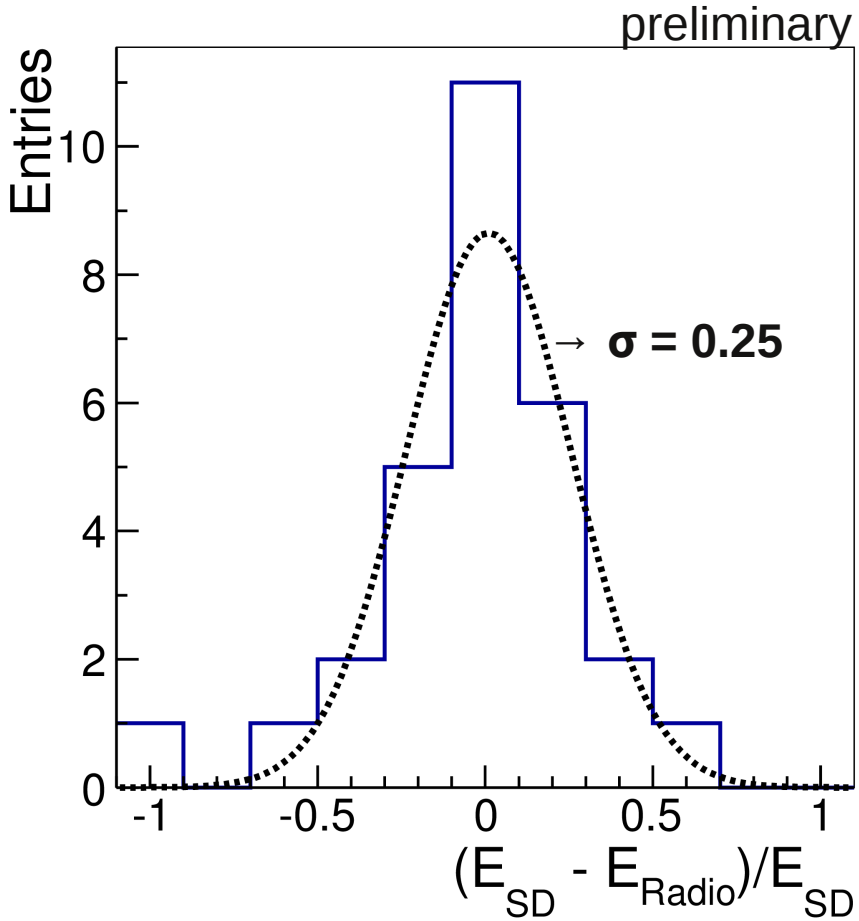


$$E_{scaled} = \frac{|\vec{E}|}{sin(\alpha)}$$

$$E_{scaled} = A \cdot exp(D/R_0)$$

energy resolution 25%
(incl. surface detector resolution)

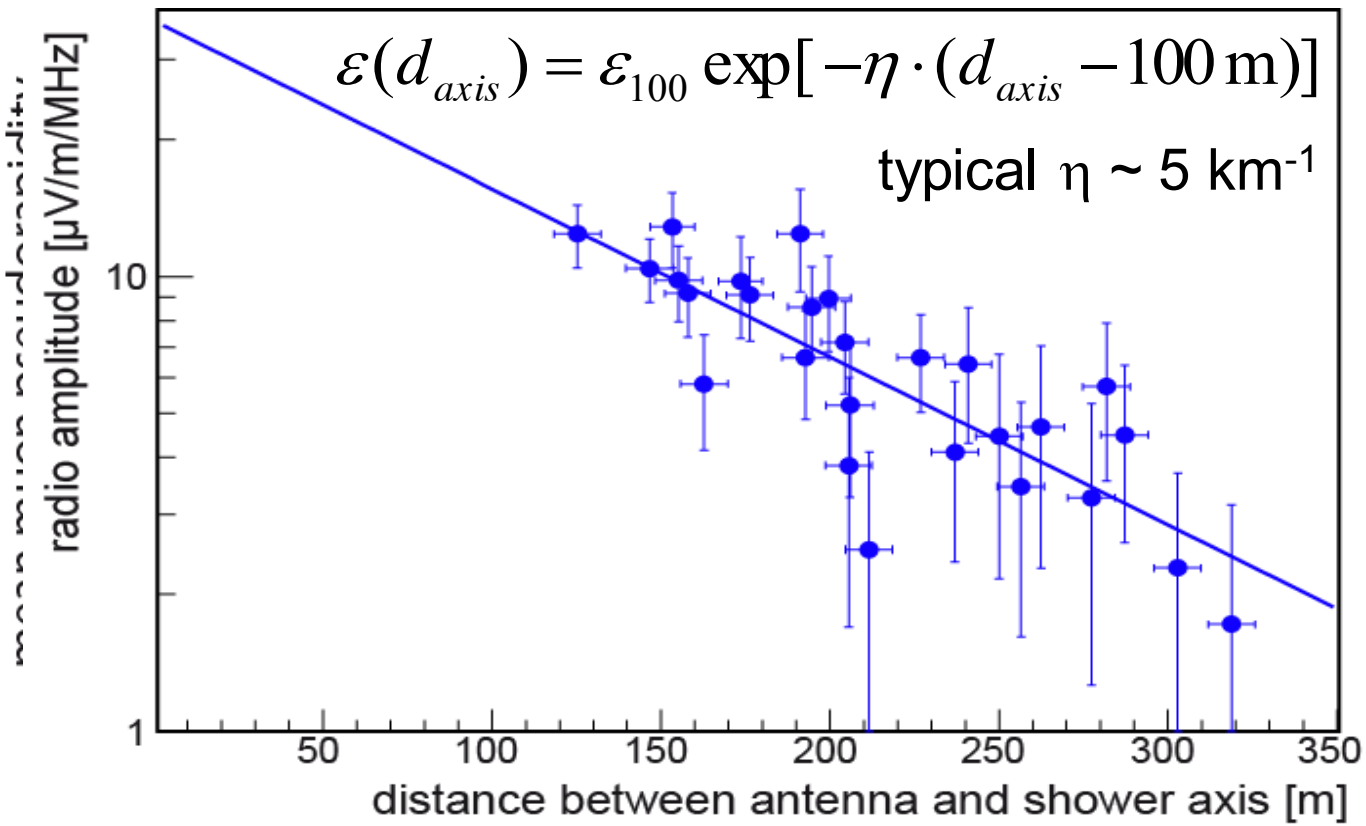


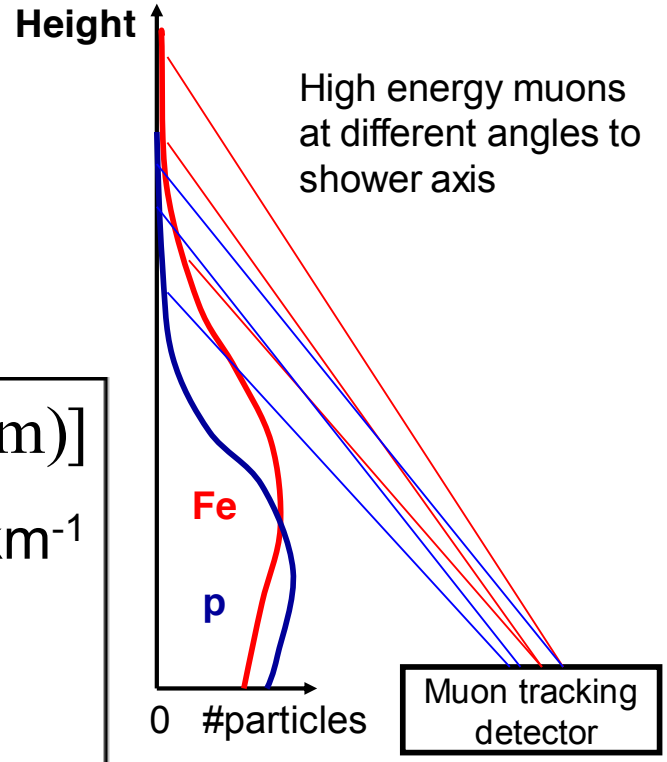


C. Glaser, ARENA (2012)

Mass (Type)

LOPES: mass sensitivity



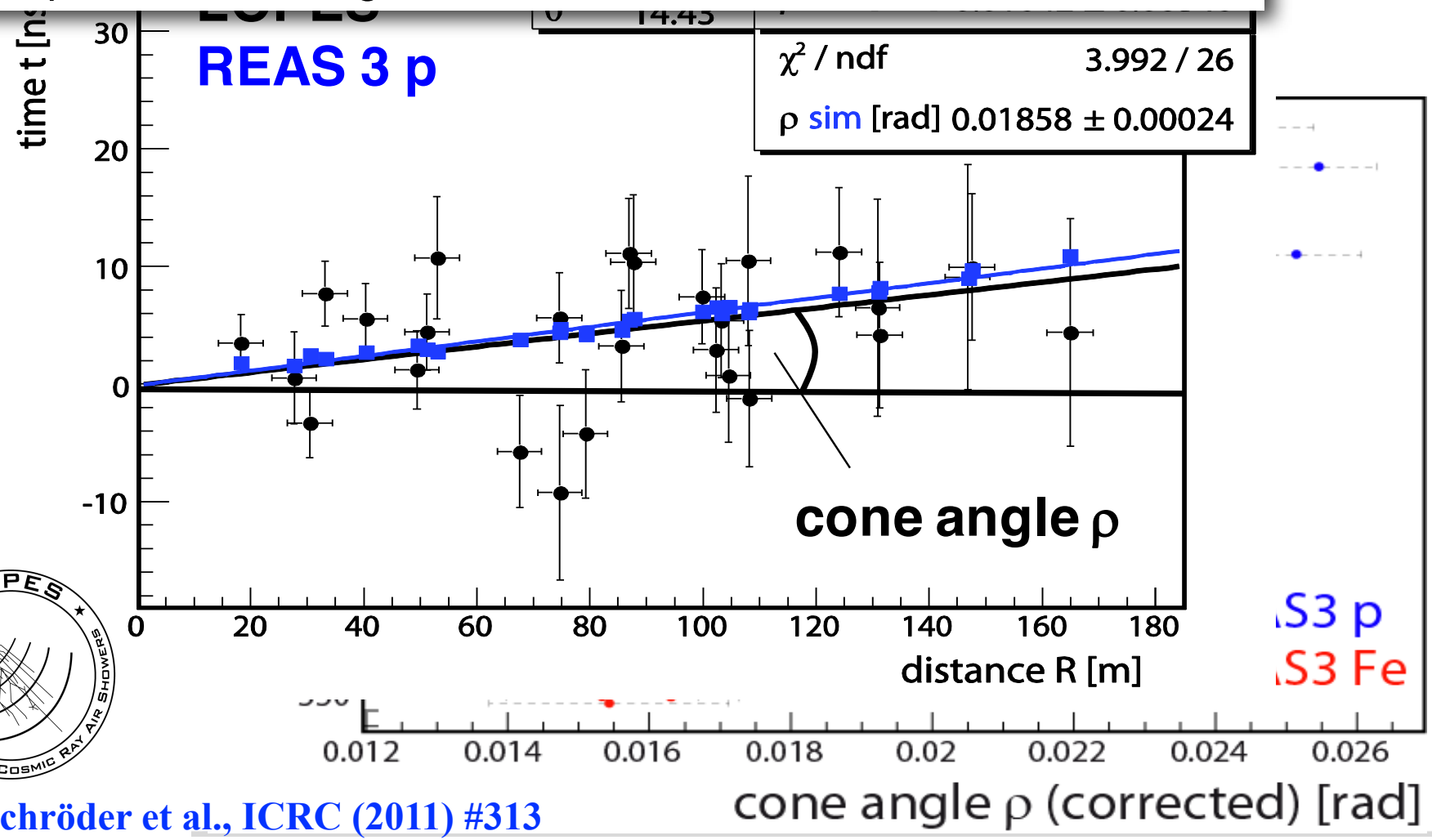


vents:
corr. for
istance
th angle

W.D. Apel et al., PRD 85 (2012) 071101 LOPES lateral slope [1/km]

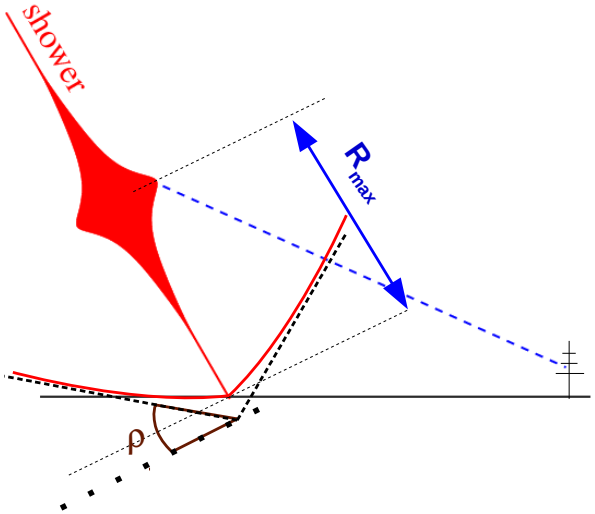
LOPES: Shape of Shower Front

- X_{max} proportional to ρ after correction for zenith angle
  - precision: ~30 g/cm² for REAS3 simulations without noise
  - precision: ~200 g/cm² for LOPES measurements

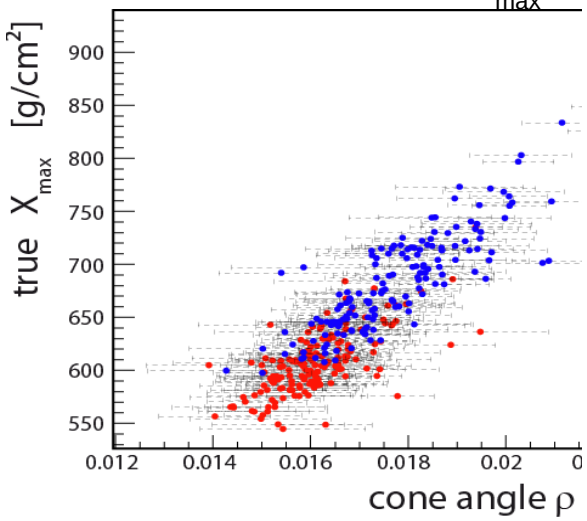


F.G. Schröder et al., ICRC (2011) #313

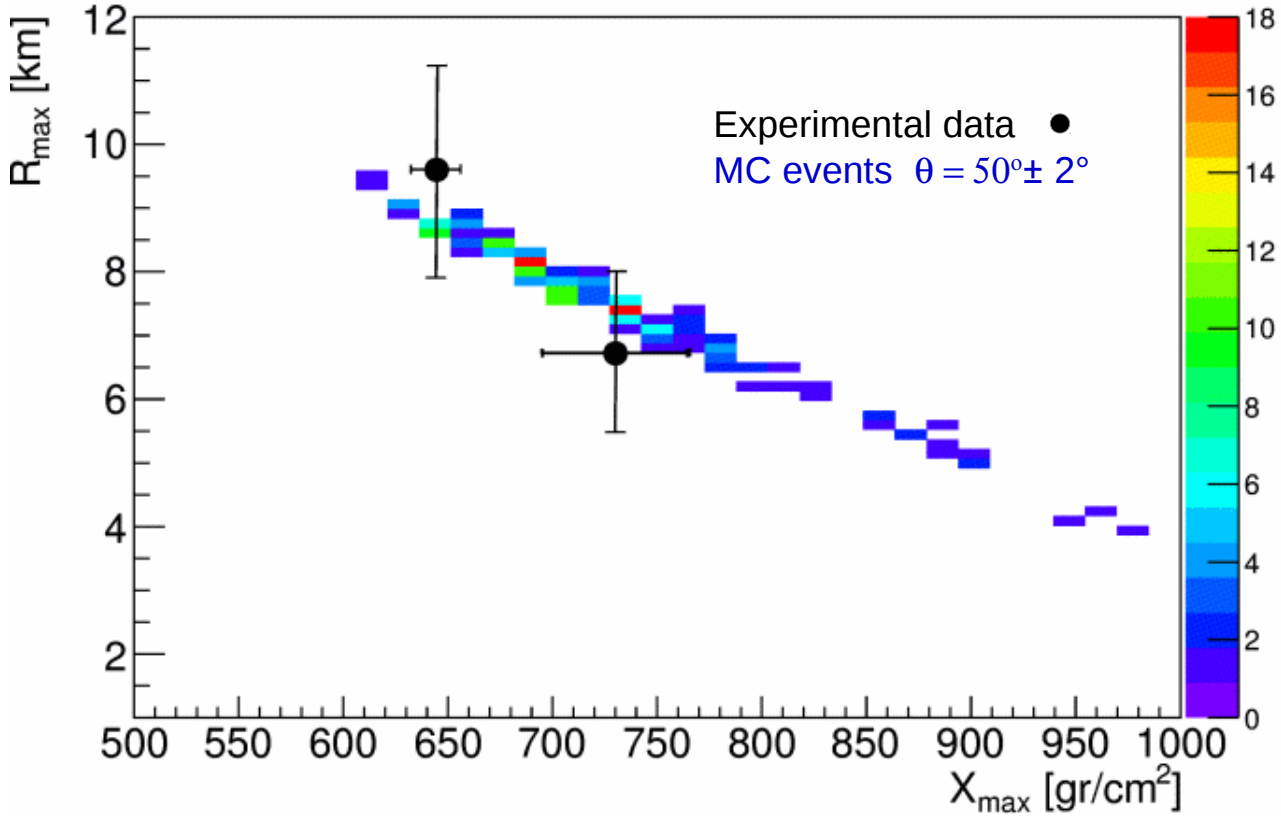
Depth of the shower maximum Xmax



Distribution of true X_{max} vs



Distribution of R_{max} vs X_{max} for experimental data and MC

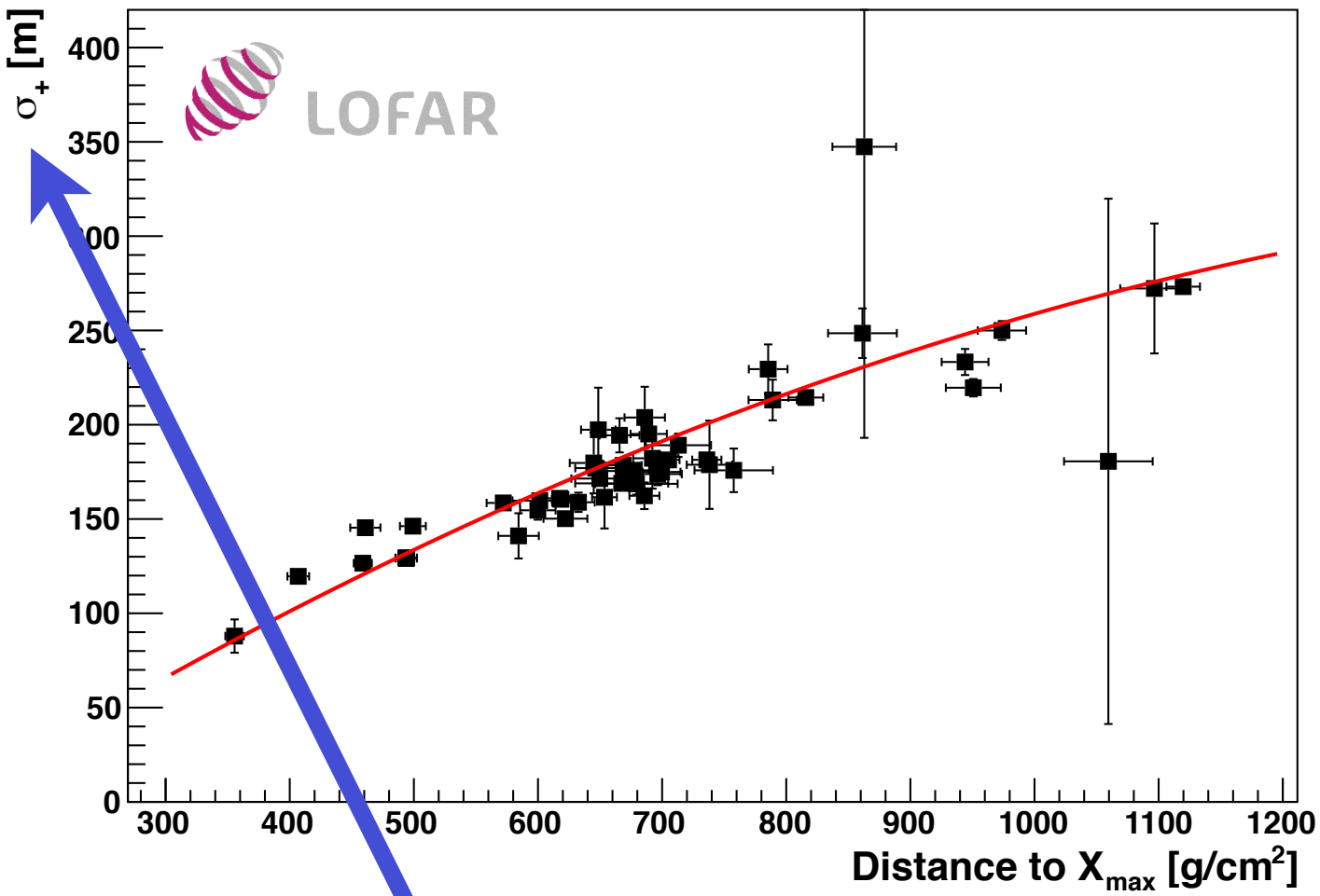


Q. Dorosti (ARENA 2014)

Experimental data: super-hybrid events

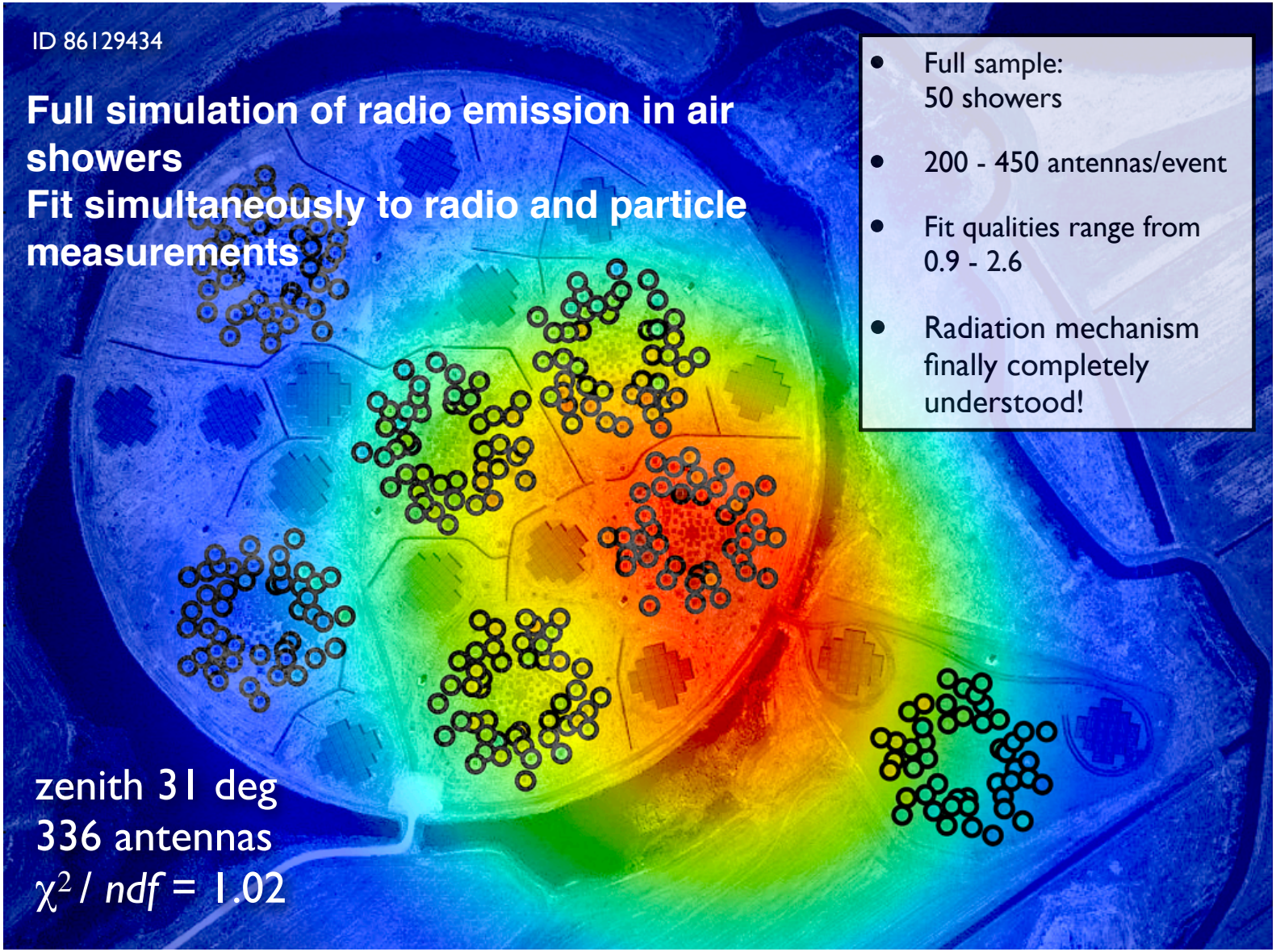
Particle type/mass

distance to Xmax



$$P(x',y') = A_+ \cdot \exp\left(\frac{-[(x'-X_+)^2+(y'-Y_+)^2]}{\sigma_+^2}\right) - A_- \cdot \exp\left(\frac{-[(x'-X_-)^2+(y'-Y_-)^2]}{\sigma_-^2}\right) + O$$

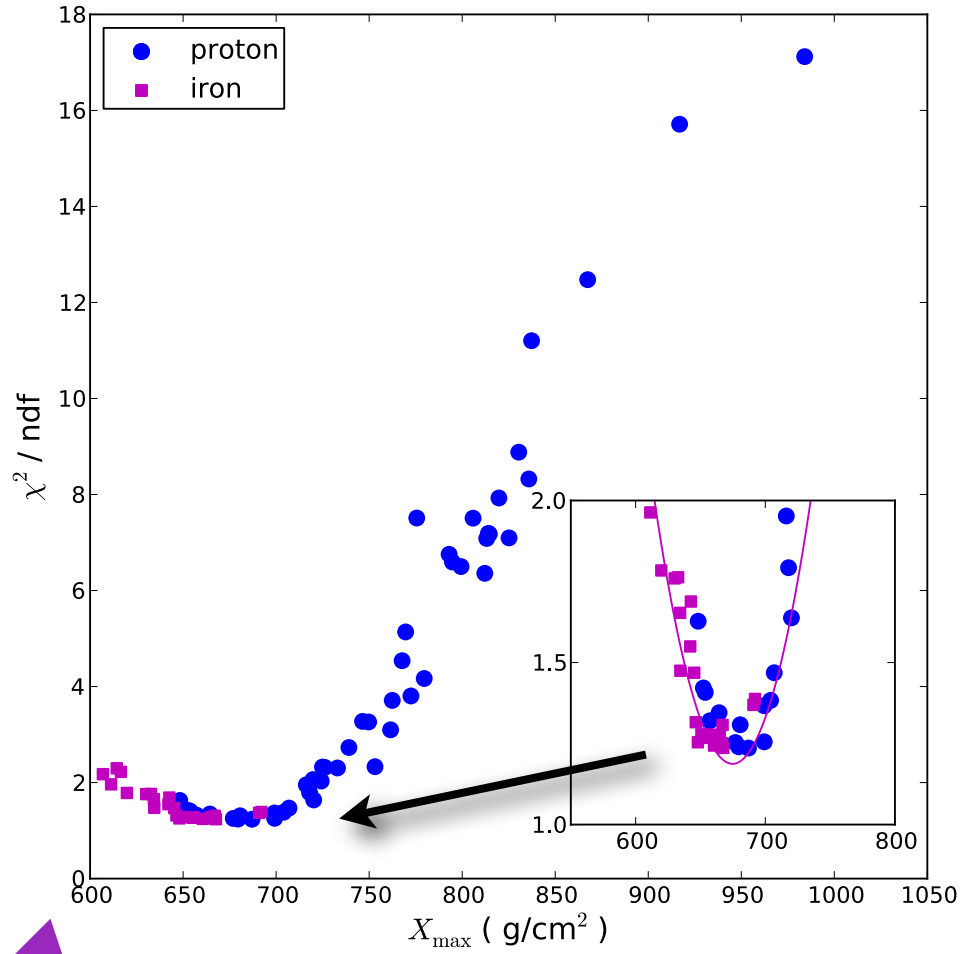
Reconstruction of the depth of the shower maximum (X_{max})



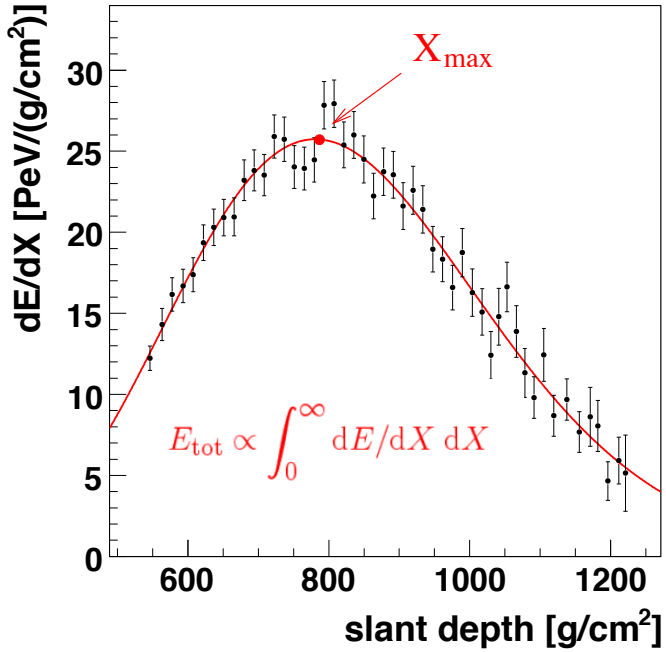
- Full sample: 50 showers
- 200 - 450 antennas/event
- Fit qualities range from 0.9 - 2.6
- Radiation mechanism finally completely understood!

S. Buitink et al, PRD in press, arXiv:1408.7001

Reconstruction of the depth of the shower maximum (X_{max})



- For each measured shower: Simulate many proton and iron showers
- Fit each simulation intensity pattern to the data
- Reconstruct depth of shower maximum: Xmax
- Uncertainty < 20 g/cm² !!



S. Buitink et al, PRD in press, arXiv:1408.7001

Precision measurements of the radio emission from extensive air showers

- lateral distribution - not rotational symmetric parametrization with two Gaussian functions
- Cherenkov ring in 120 - 240 MHz band
- shape of radio wavefront --> hyperboloid
- polarization --> emission processes (charge excess fraction)
- properties of cosmic rays from radio data
  - direction
  - energy
  - particle type/mass