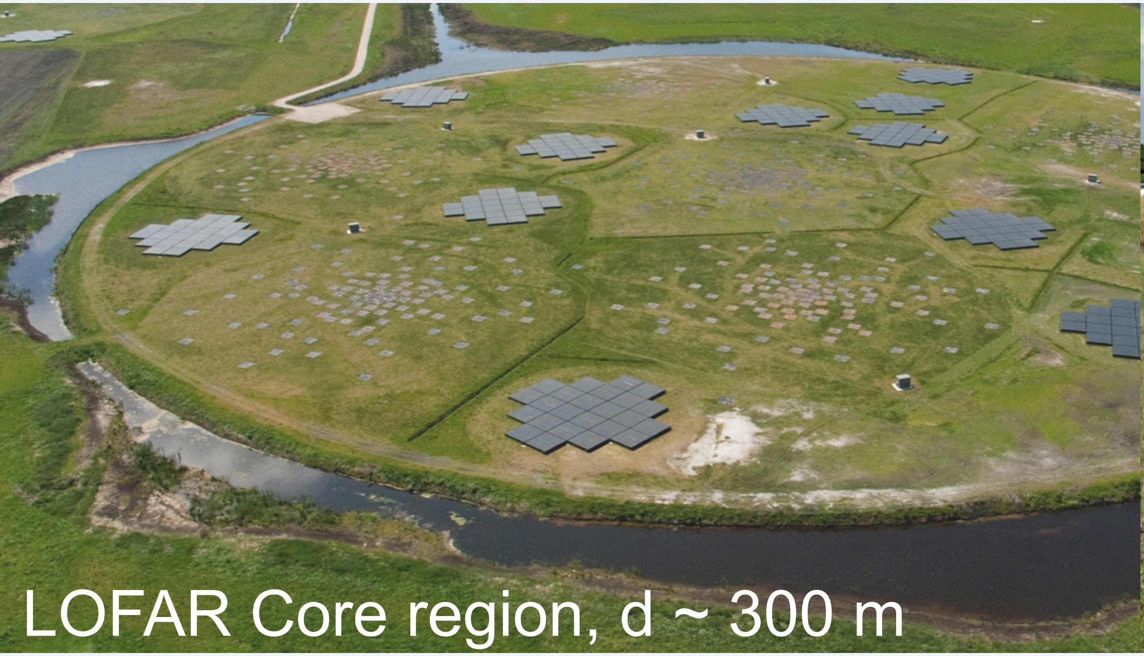
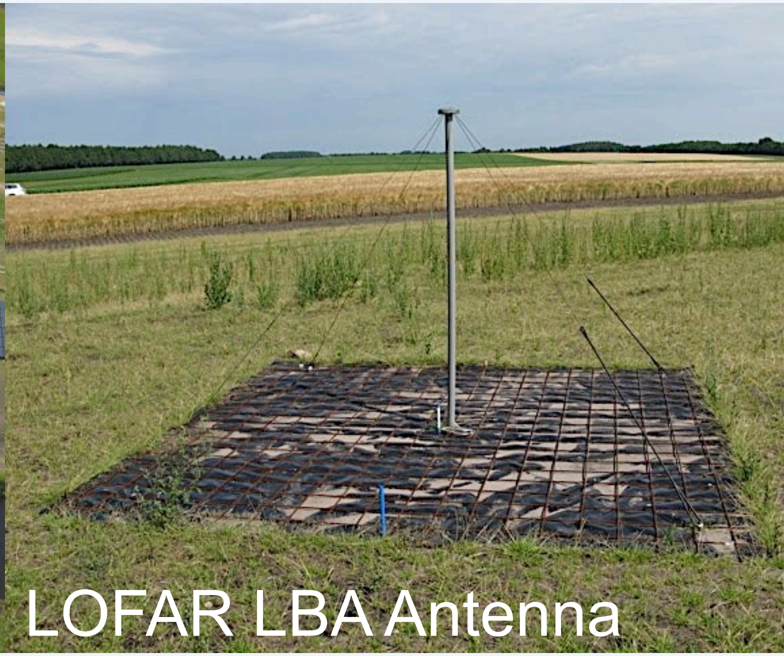
Polarized radio emission and radio wavefront shape of extensive air showers



LOFAR Core region, d ~ 300 m



LOFAR LBA Antenna

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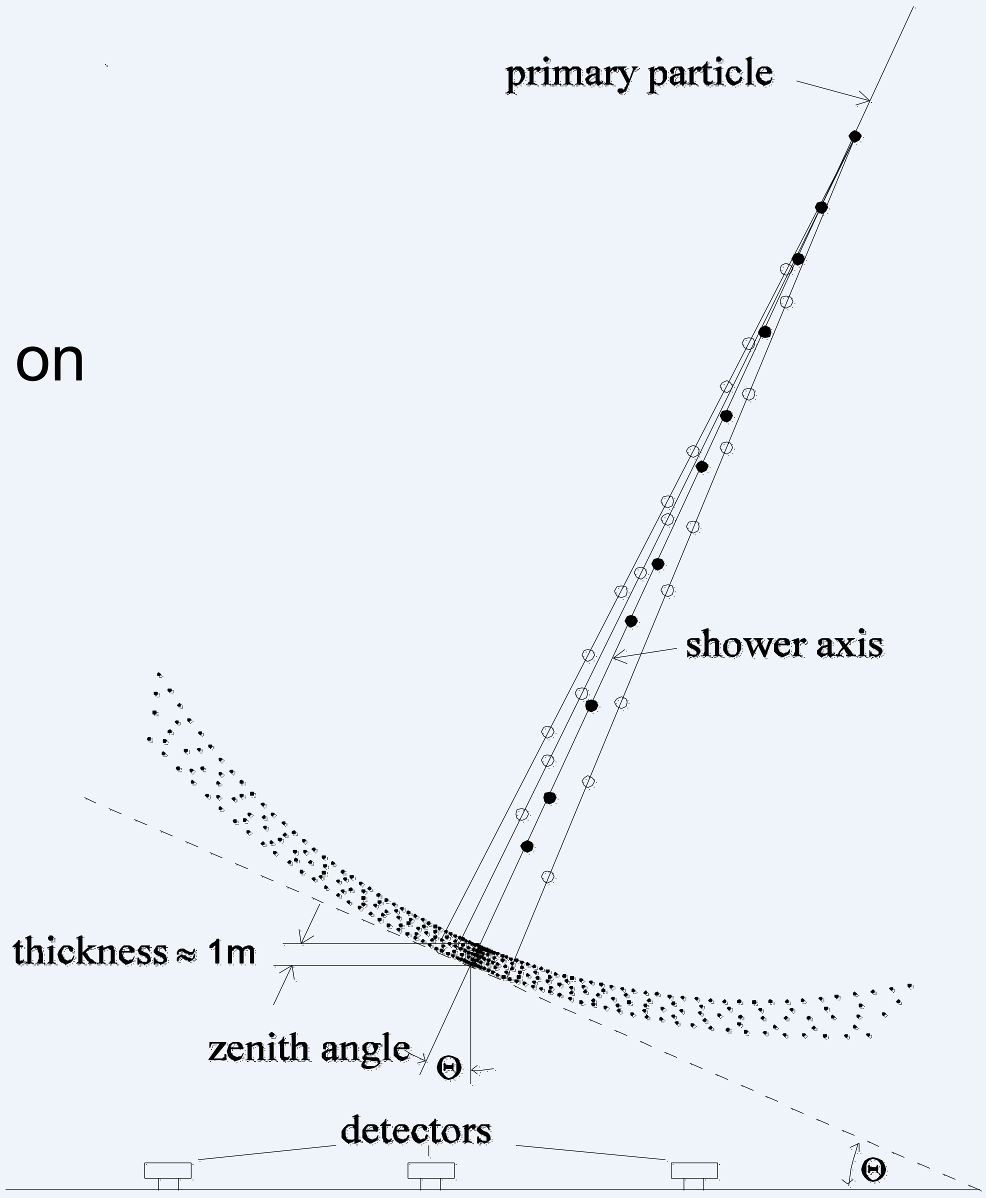
PoS (ICRC2015) 396

Radio pulses from air showers

Short (~10 to 100 ns) pulses from extensive air showers, primary energy > ~ 10^{17} eV

In 200 - 400 LOFAR antennas on the ground, we measure:

- Lateral distribution of
  - Signal power
  - Signal arrival time
    - ➢ Wavefront shape
  - Polarization
  - Spectrum / pulse shape



Arrival times for the radio signal

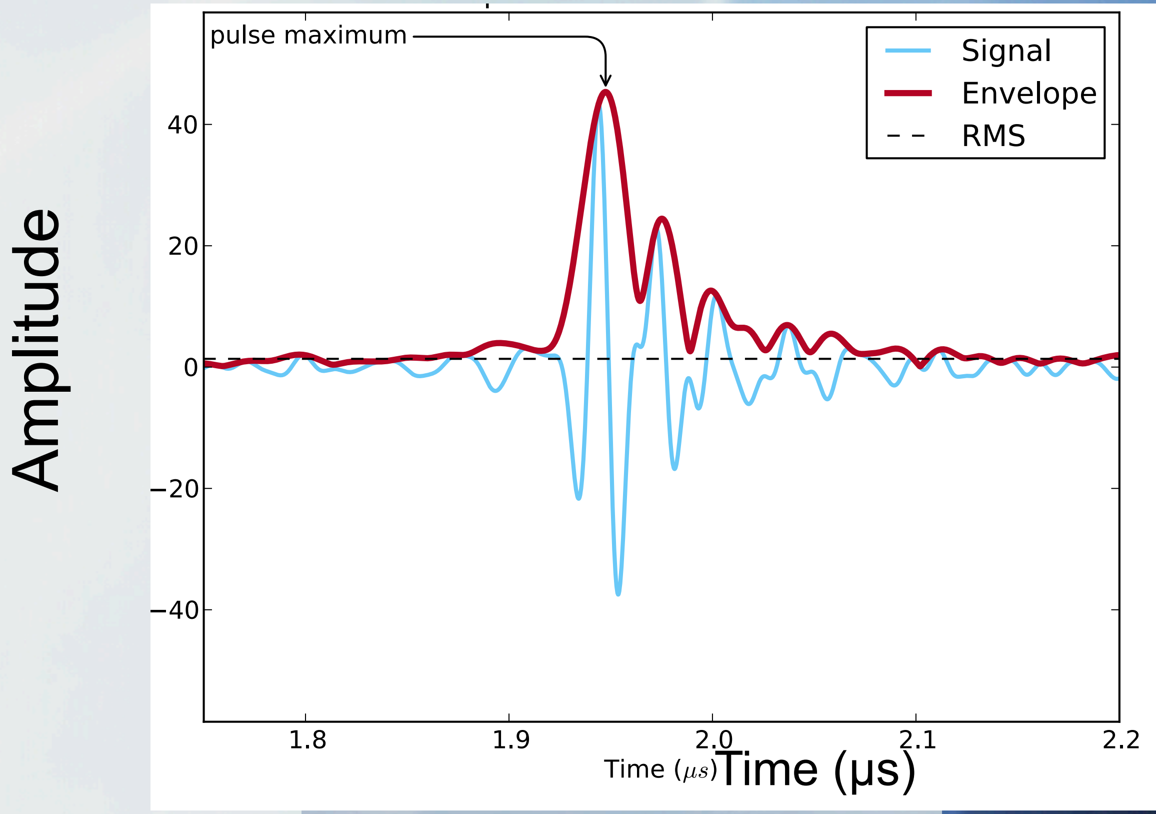
Measuring arrival time of pulse in individual antennas:

- Time series signal

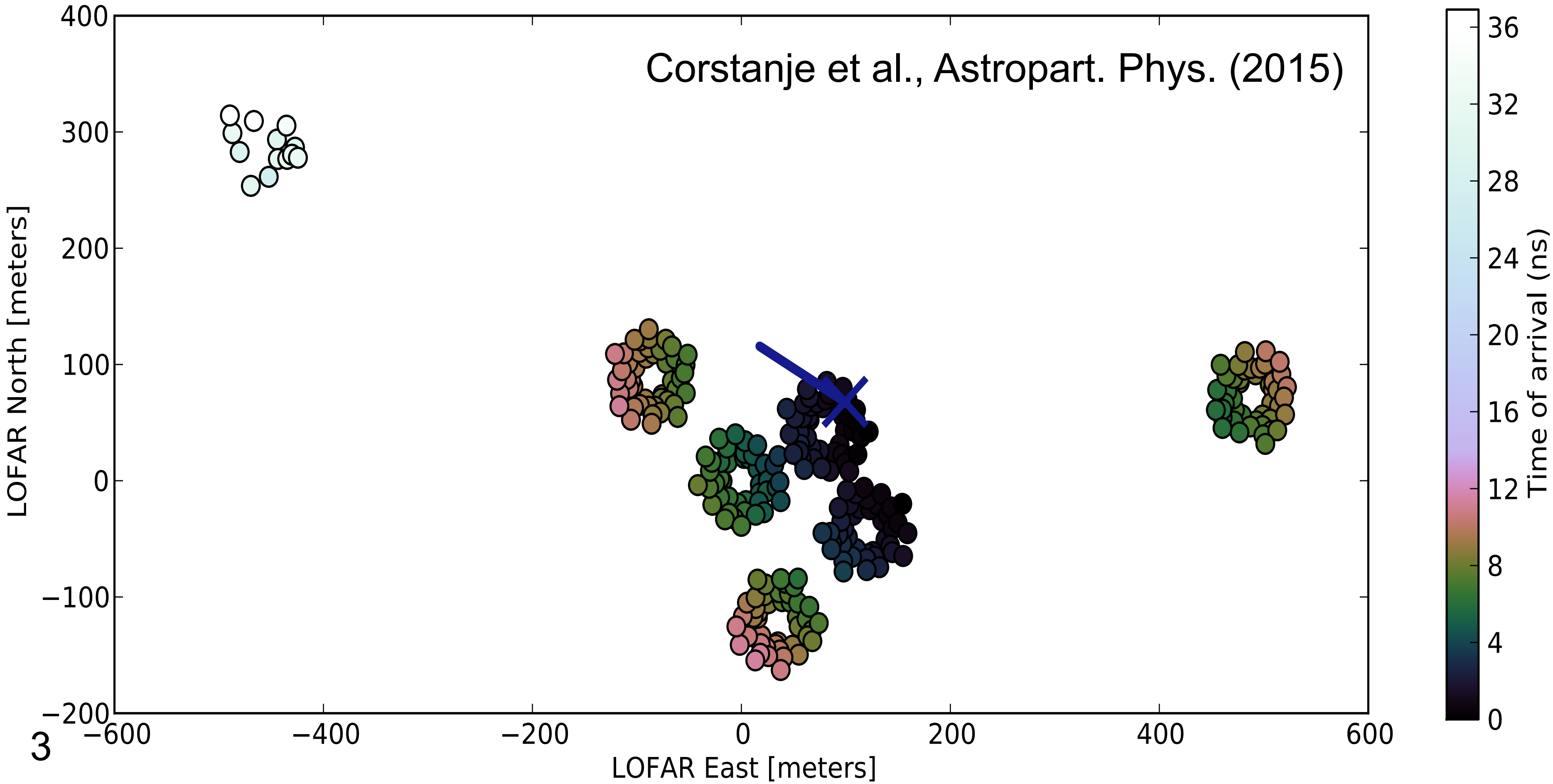
Apply Hilbert transform to get *Hilbert envelope*

- Define envelope maximum
  as 'the arrival time'

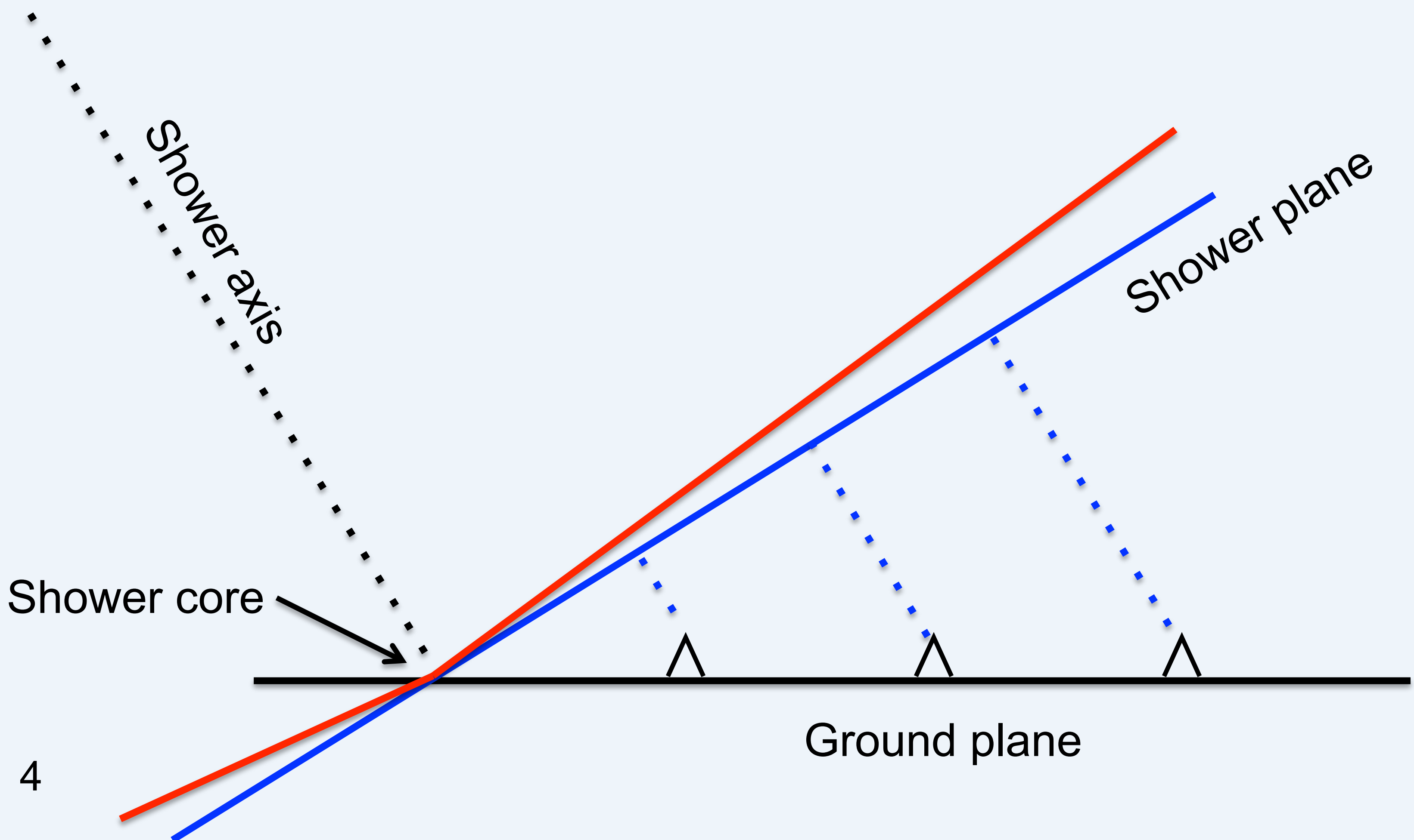
$$\sigma_t = \frac{12.7}{SNR} \text{ ns} < 5 \text{ ns!}$$



Arrival times after subtracting plane-wave solution



Shower plane projection



Wavefront in the shower plane

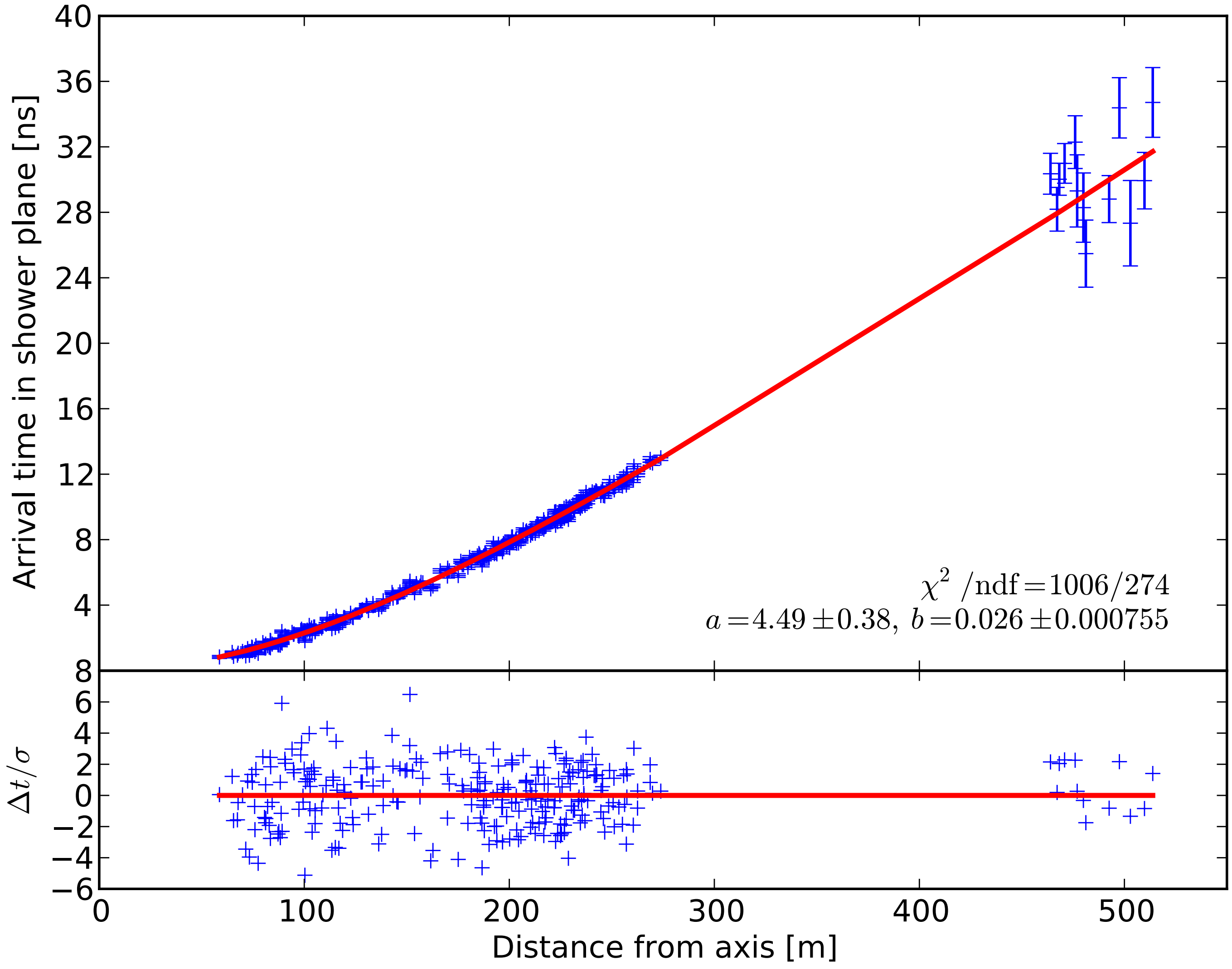
- Project antennas into shower plane
  - Shower axis position: fixed using power-LDF
  - Shower axis direction unknown to desired accuracy: **free fit parameters**

- Wavefront: arrival times as function of distance from shower axis

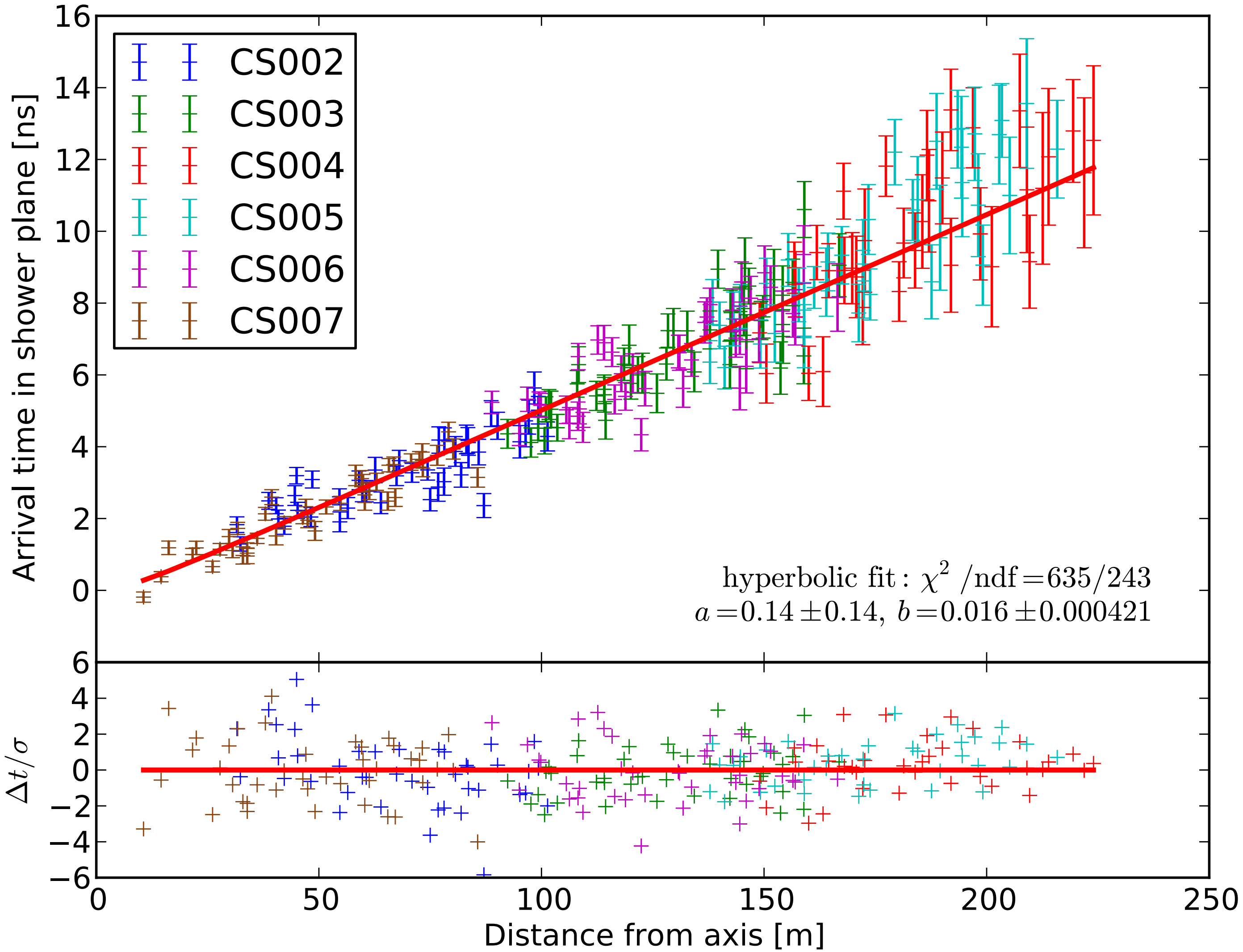
- Nested fitting (**5** parameters):
  - Optimize shower axis **direction** (2)
    - Optimize **curve-fit** (3)

Best-fitting hyperbolic shape

Corstanje et al., Astropart. Phys. (2015)



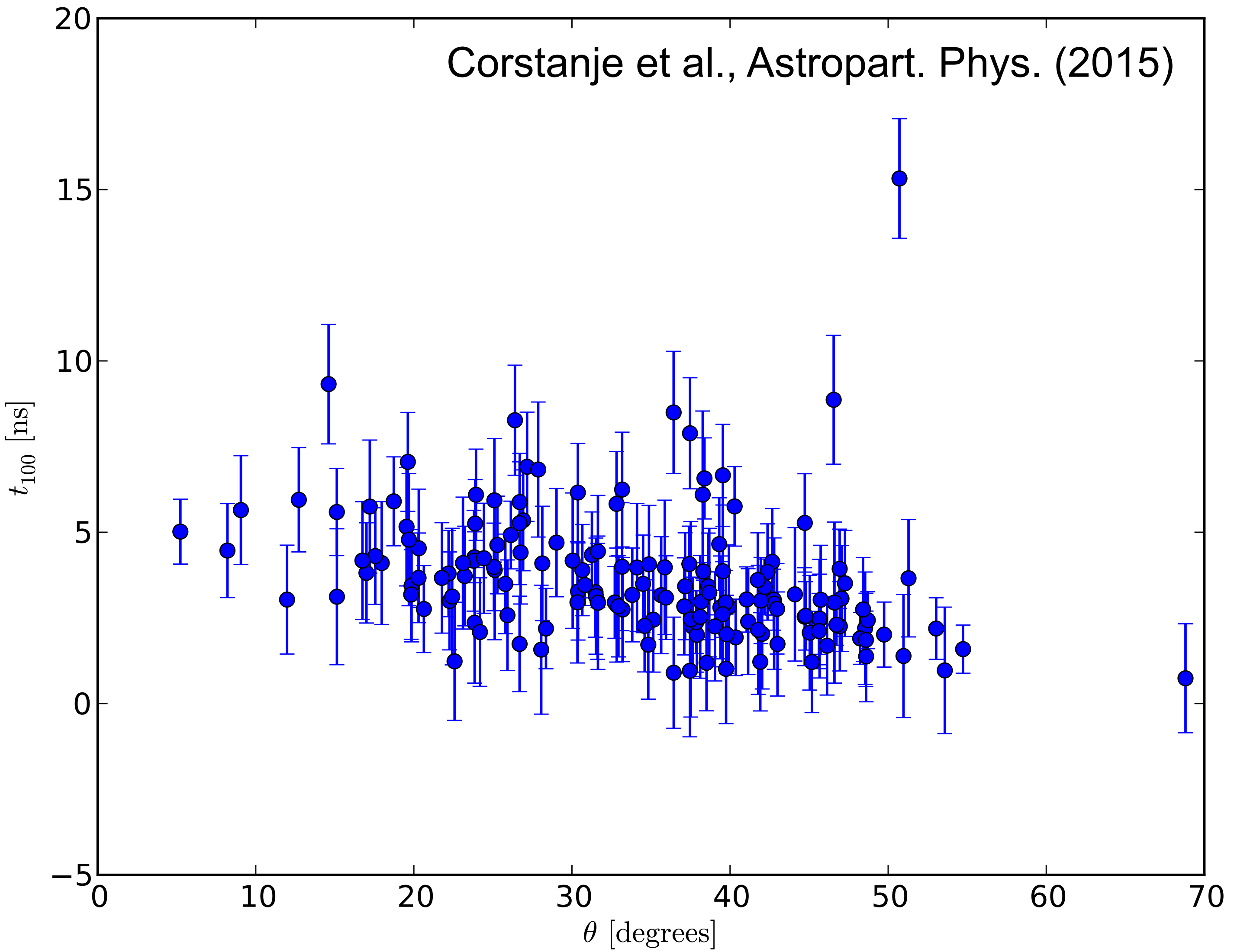
Conical-shaped example



Correlation with zenith angle

Time lag at 100 m from shower core

Decreases with zenith angle



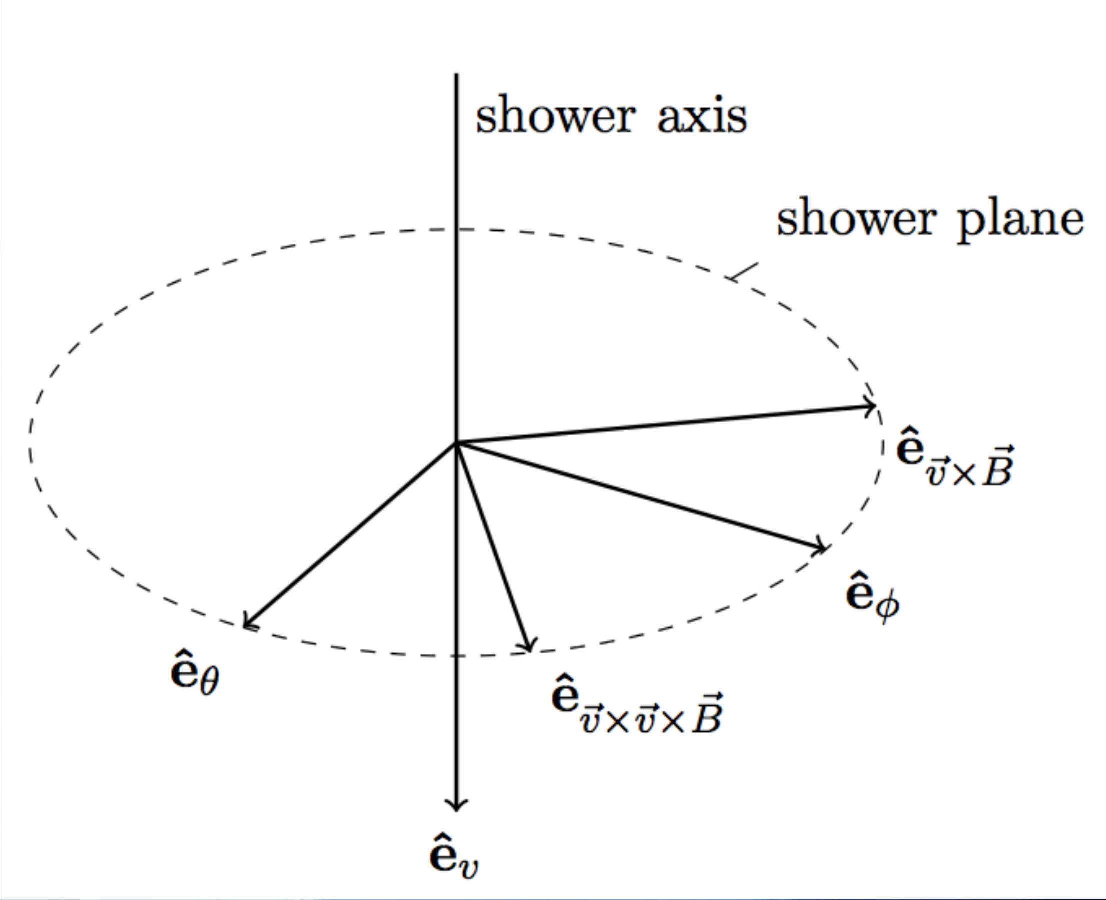
Polarization measurements

- Each LOFAR antenna offers two polarizations (NE-SW and NW-SE)
- Projected to 'on-sky' polarization when accounting for antenna model (Jones matrix)
- Polarizations further rotated to align with v x B and v x (v x B),

  v is shower axis

  B is magnetic field

Schellart et al., JCAP (2014)



Radio emission mechanisms

- Geomagnetic contribution,
  electric field aligned to v x B: $\vec{E}_G(\vec{r}) = E_G\,\hat{\mathbf{e}}_{\vec{v}\times\vec{B}}$
- Charge-excess contribution: electric field radially outward from shower core:

$$\vec{E}_C(\vec{r}) = E_C \cos\phi\,\hat{\mathbf{e}}_{\vec{v}\times\vec{B}} + E_C \sin\phi\,\hat{\mathbf{e}}_{\vec{v}\times(\vec{v}\times\vec{B})}$$

- Assuming these contributions account for total E-field

- Charge-excess fraction: $a(\vec{r}) = \frac{E_C}{E_G}\sin\alpha$

where α is angle of magnetic field with shower axis

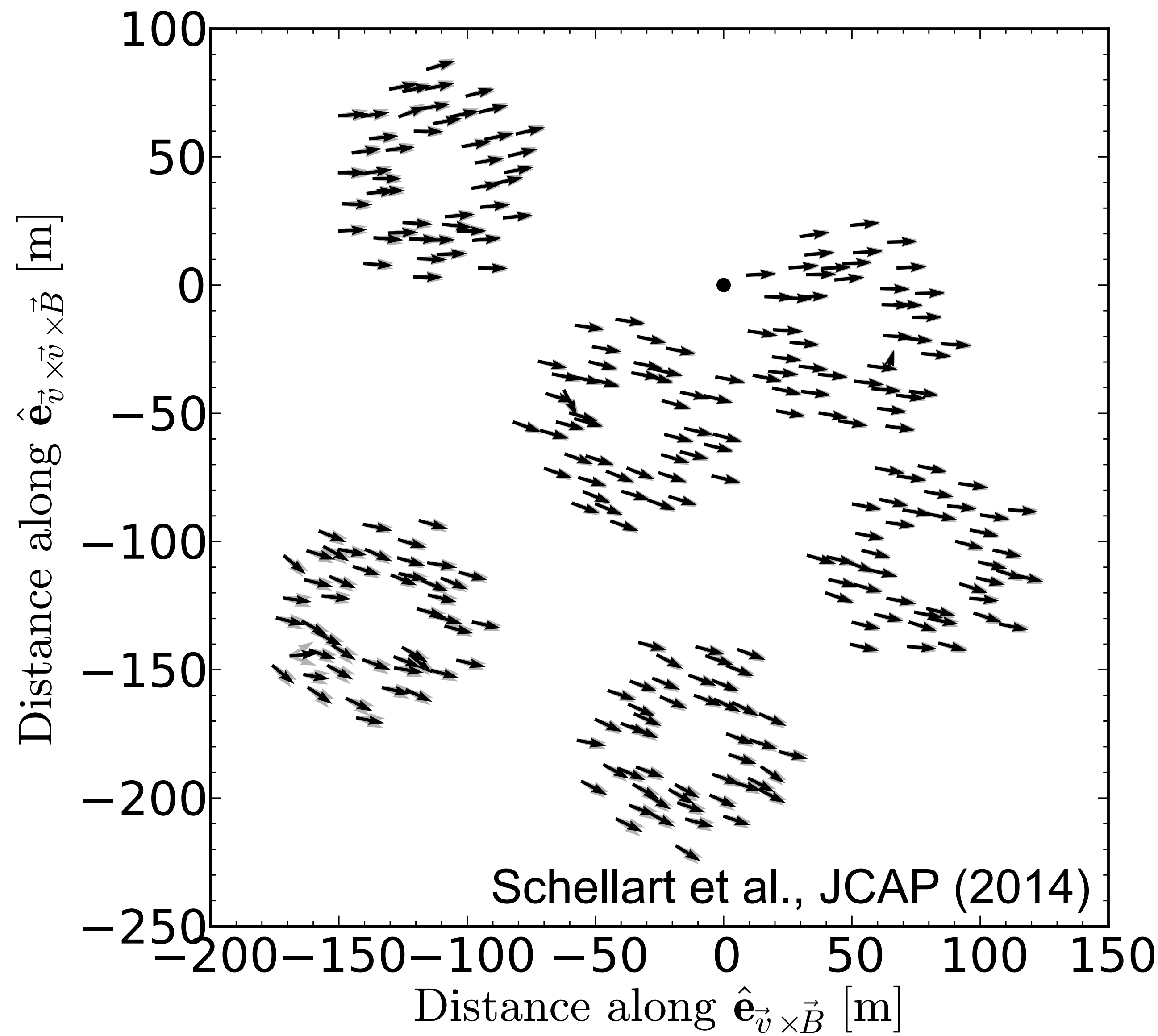
Example polarization footprint

Mostly parallel to the v x B-axis

Small radial component, consistent with charge-excess component

Angle uncertainty:

$$\sigma \sim \frac{21^\circ}{SNR}$$



Polarization results

- Charge-excess fraction on average 11 %, spread of distribution is 4 %.

  Precision per air shower is about 2 %
- This depends on specific set of air showers, and on magnetic field and altitude of LOFAR

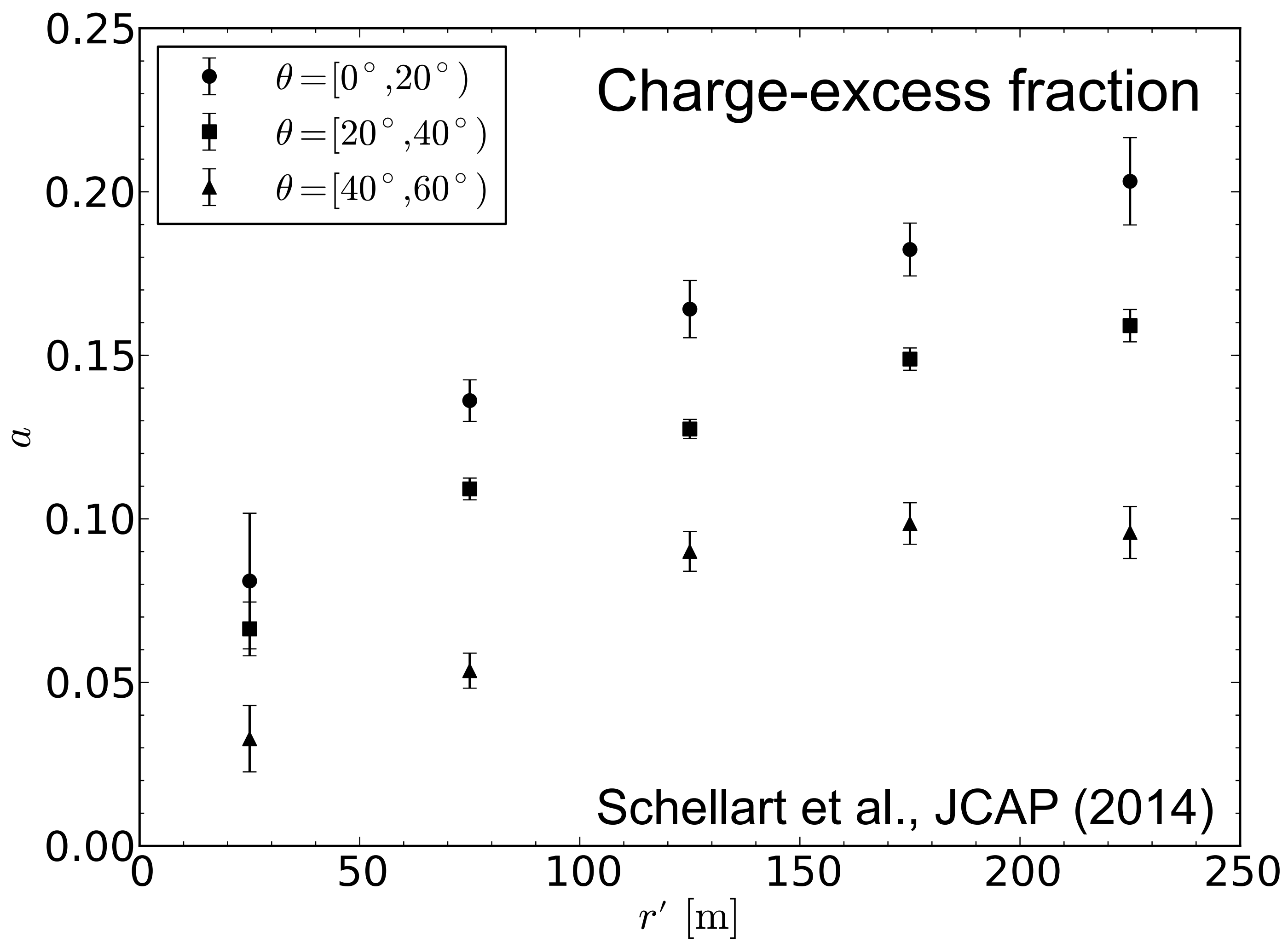
- Charge-excess fraction decreases with zenith angle, and increases with distance to shower axis, i.e. increases with opening angle from emission maximum

Variations with zenith angle and distance to shower axis

Decreases with zenith angle

Increases with distance to shower axis

Agrees with expectations from theory and CoREAS (qualitatively)



Conclusions

- With LOFAR, we have obtained high-precision measurements of polarization and radio wavefront shape
- Hyperbolic wavefront fits all cases, some of them also described by cone or parabola
- Polarization pattern well described by dominant geomagnetic contribution, and sub-dominant charge-excess component
- Qualitative agreement with theory and CoREAS simulations