The polarization of the radio emission in air showers with LOFAR

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For the

LOFAR, Key Science Project Cosmic Rays,

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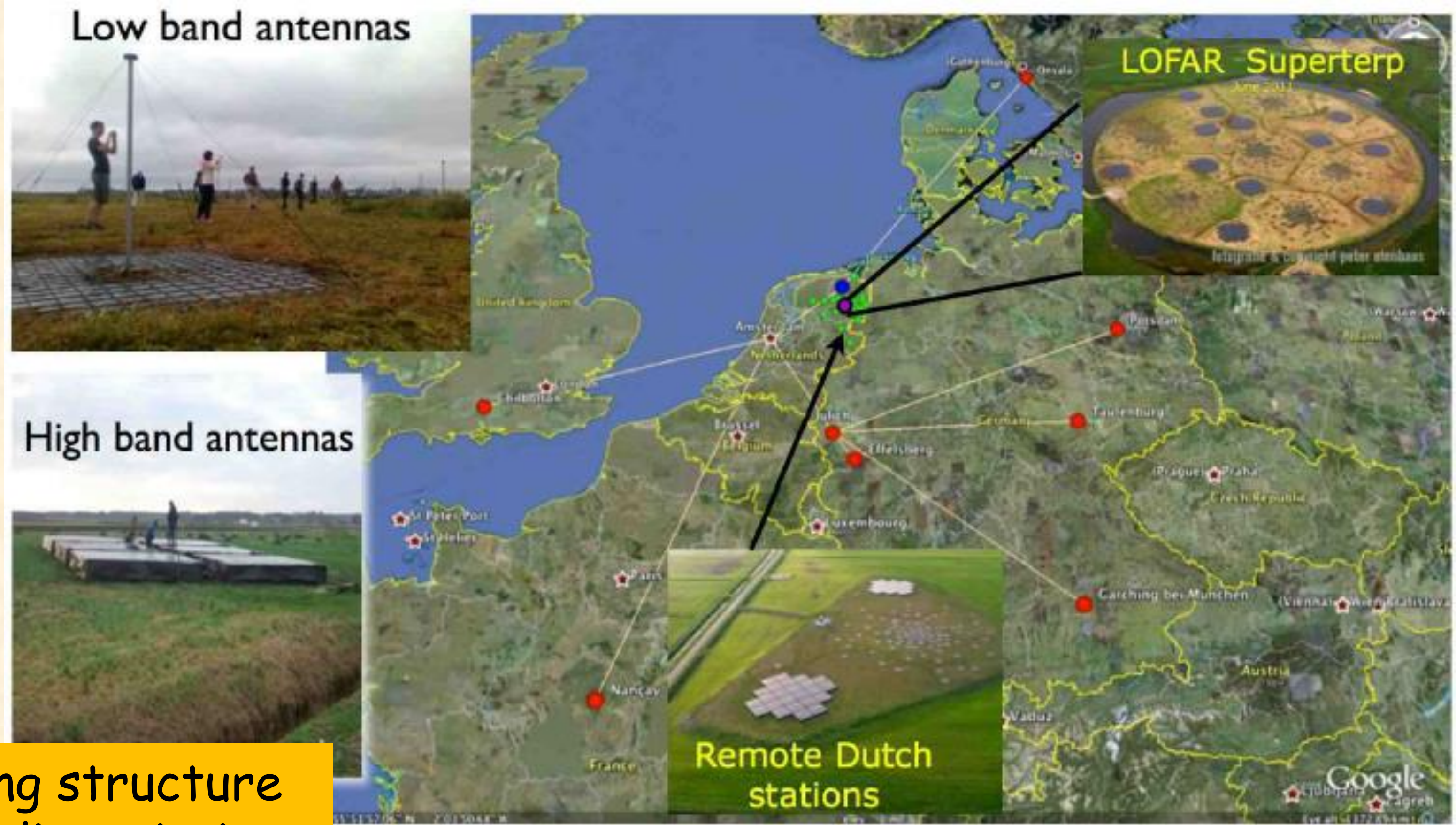
LOFAR

- First in a series of several contributions on LOFAR results
  - Jörg Hörandel
  - Anna Nelles
  - Stijn Buitink

- Quick overview LOFAR
- Details analysis: wait for Jörg, Anna & Stijn
- Here results Polarization observations

Radio-detection; LOFAR

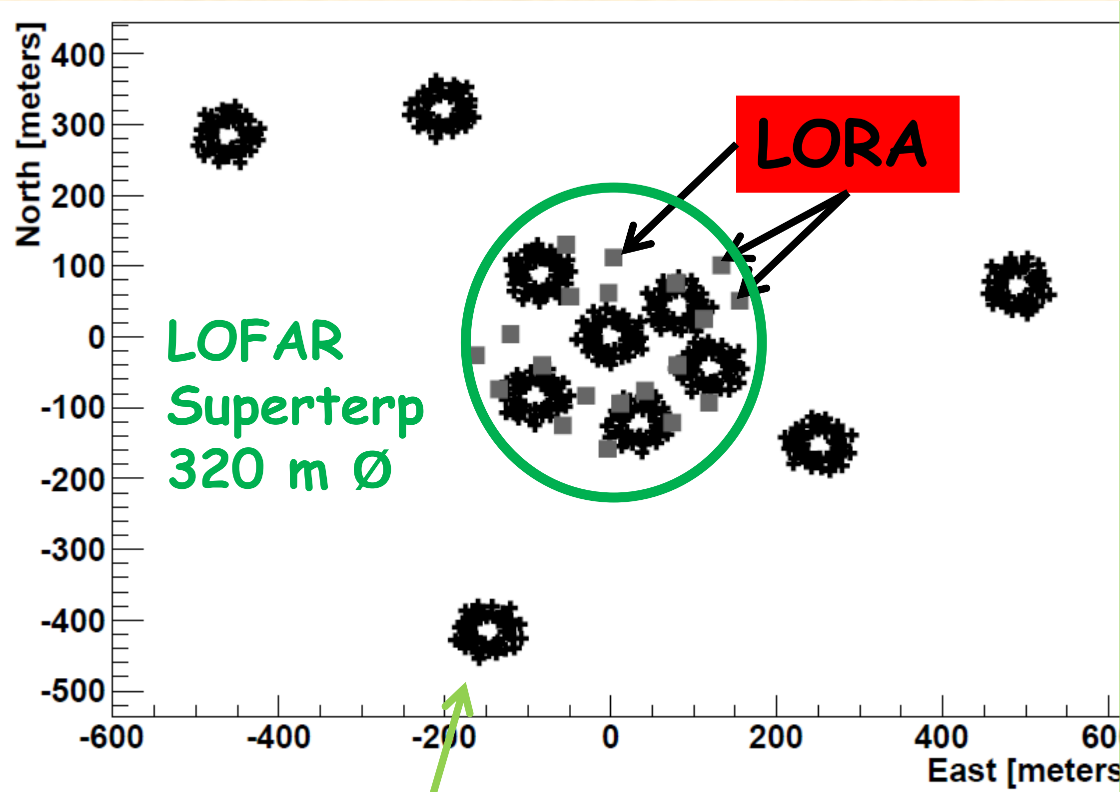
Main CR-workhorse:



Ring structure
Radio emission

Thousands of antennas, directed through software-interference
Low-band: 10-90 MHz;   High-band: 110-240 MHz

Included Stations



Each station: 48 dual pol. antennas

Detection method:

- Trigger signal from LORA scintillator detectors
  $E>10^{16}$ eV
- LOFAR Ring-buffers are read-out

Checks:

- Match arrival direction LORA & LOFAR
- RFI mitigation
- Thunderstorm check
- Core reconstruction

- 180-1 events left
- Each 192 – 528 antennas

Unfolding Antenna pattern

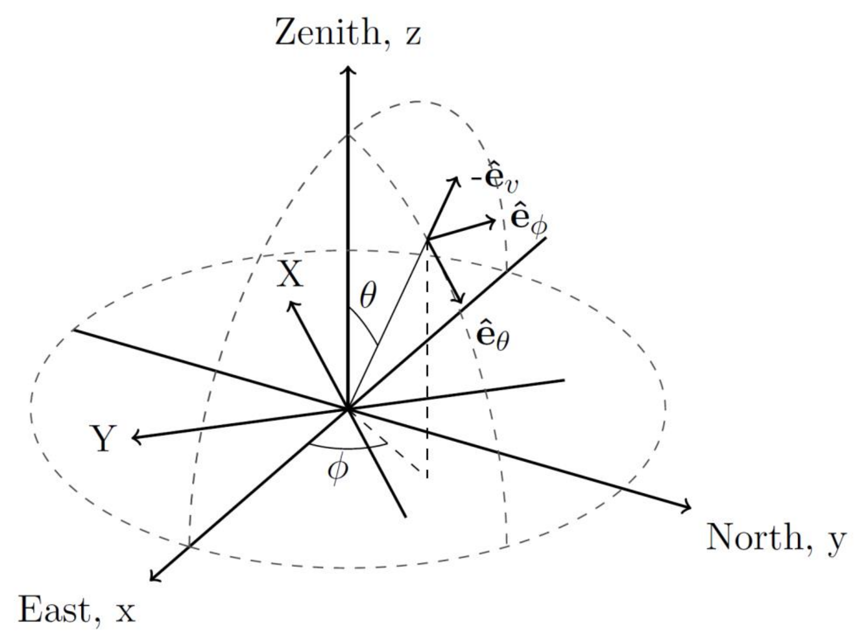
Antenna-simulation + electronics model

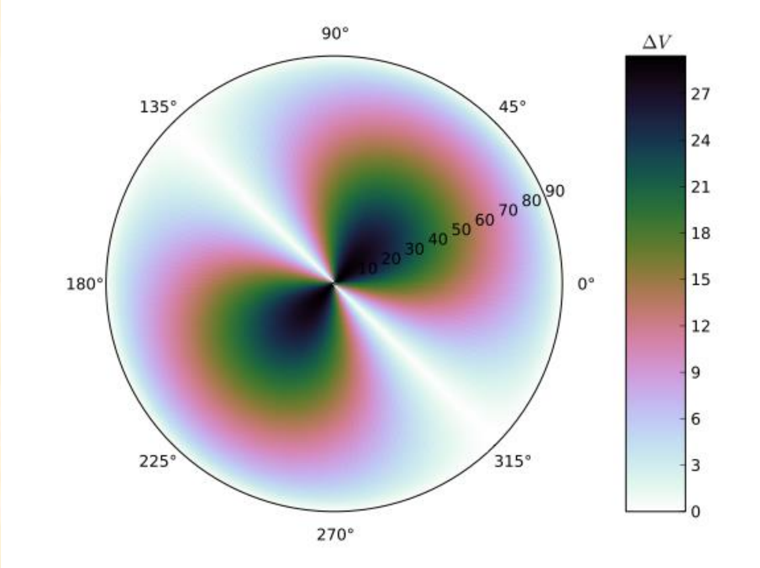
Complex direction and frequency dependent gain per polarization per dipole

Interpolate to get 2x2 complex Jones matrix for pulse direction

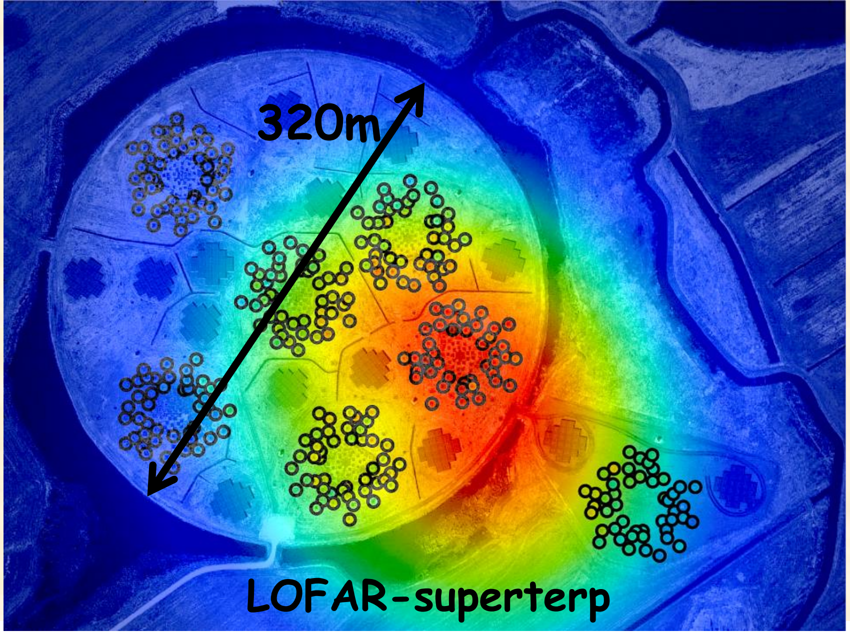
Invert and multiply to get **E**(t)

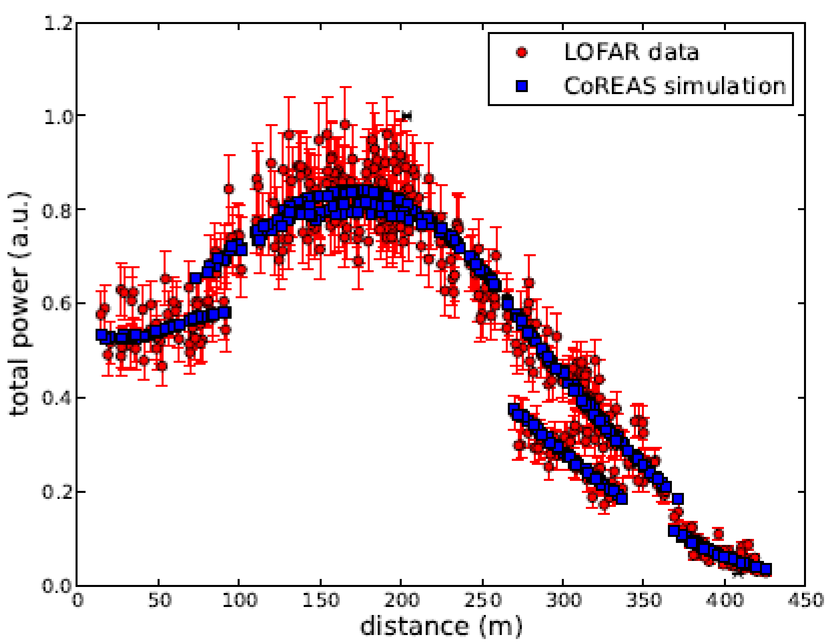
Project to the shower plane

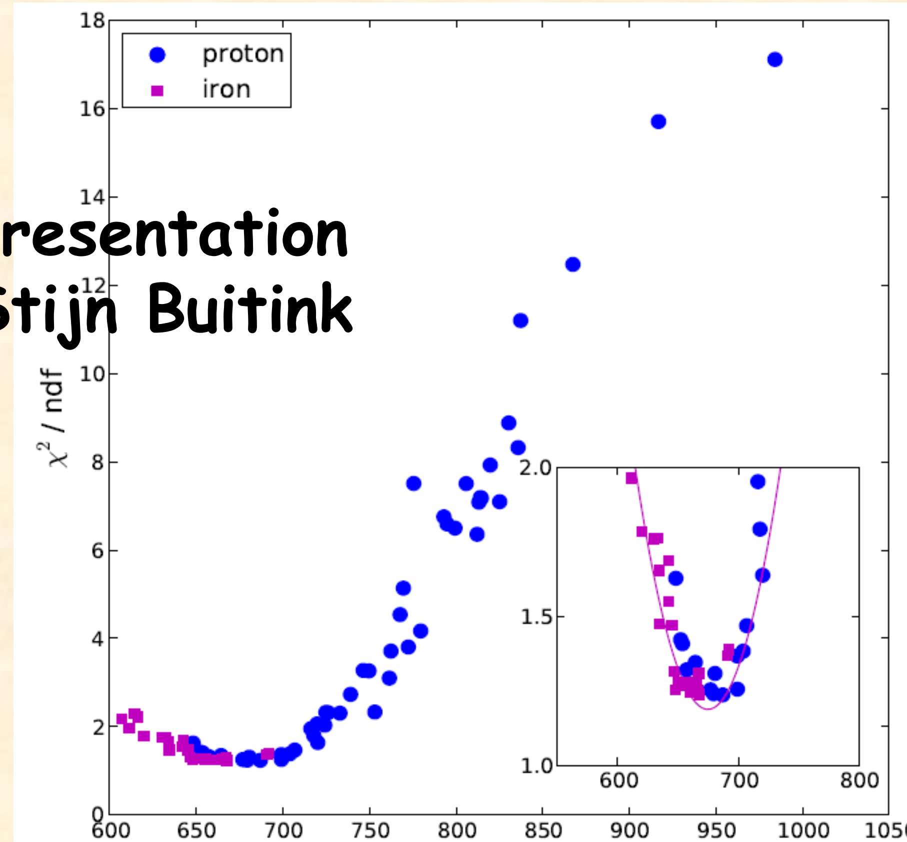




LOFAR
CR-radio detection





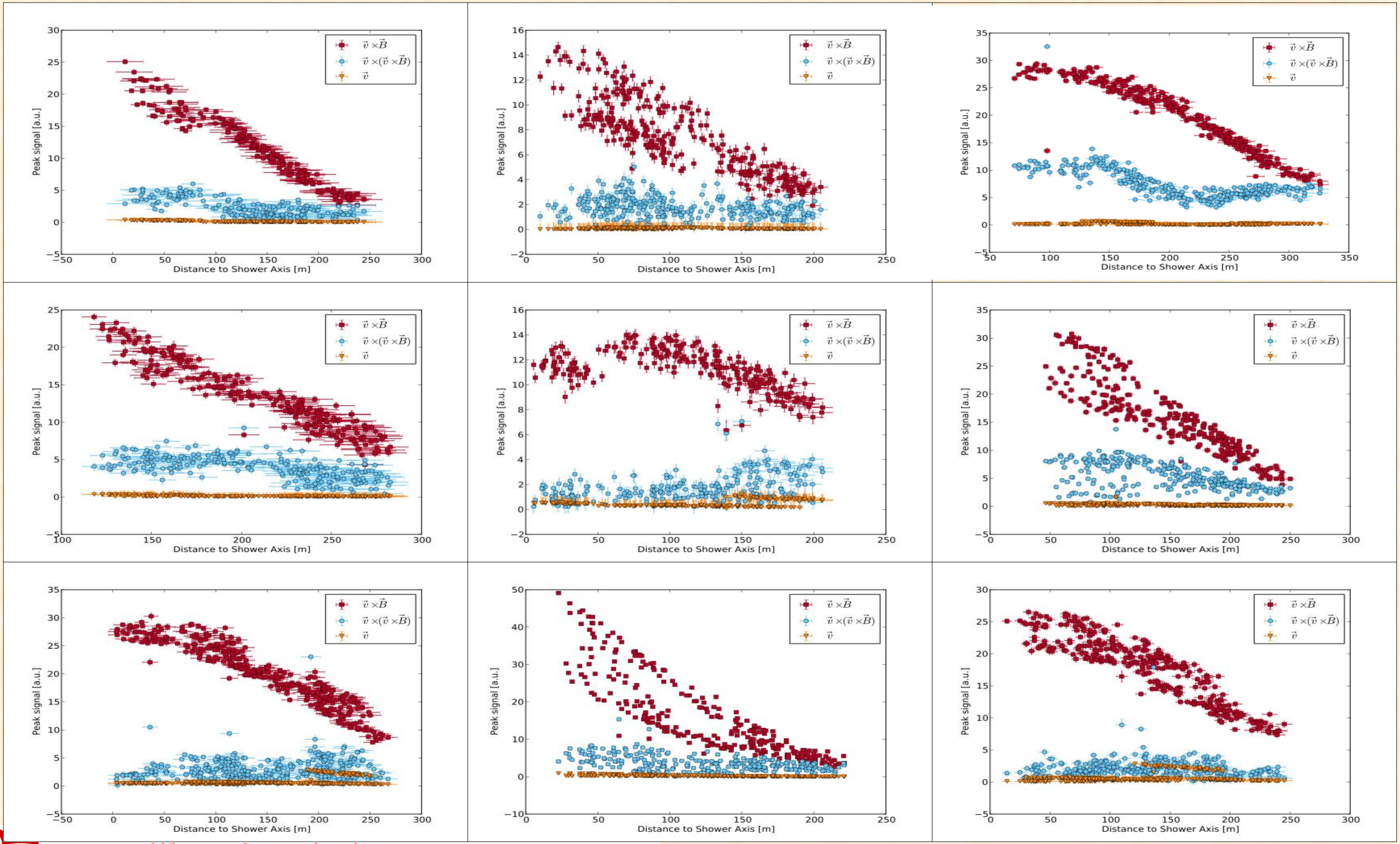


Presentation Stijn Buitink

X_{max} resolution = 20 g/cm^2

Complex polarization signature

There is a lot of information here...



Introduce Stokes parameters

$\hat{E}$ is Hilbert transform

$$I = \frac{1}{n}\sum_{i=0}^{n-1}(E^2_{i,\vec{v}\times\vec{B}} + \hat{E}^2_{i,\vec{v}\times\vec{B}} + E^2_{i,\vec{v}\times\vec{v}\times\vec{B}} + \hat{E}^2_{i,\vec{v}\times\vec{v}\times\vec{B}}),$$

$$Q = \frac{1}{n}\sum_{i=0}^{n-1}(E^2_{i,\vec{v}\times\vec{B}} + \hat{E}^2_{i,\vec{v}\times\vec{B}} - E^2_{i,\vec{v}\times\vec{v}\times\vec{B}} - \hat{E}^2_{i,\vec{v}\times\vec{v}\times\vec{B}}),$$

$$U = \frac{2}{n}\sum_{i=0}^{n-1}(E_{i,\vec{v}\times\vec{B}}E_{i,\vec{v}\times\vec{v}\times\vec{B}} + \hat{E}_{i,\vec{v}\times\vec{B}}\hat{E}_{i,\vec{v}\times\vec{v}\times\vec{B}}),$$

$$V = \frac{2}{n}\sum_{i=0}^{n-1}(\hat{E}_{i,\vec{v}\times\vec{B}}E_{i,\vec{v}\times\vec{v}\times\vec{B}} - E_{i,\vec{v}\times\vec{B}}\hat{E}_{i,\vec{v}\times\vec{v}\times\vec{B}}).$$

Derived quantities:

Polarisation degree

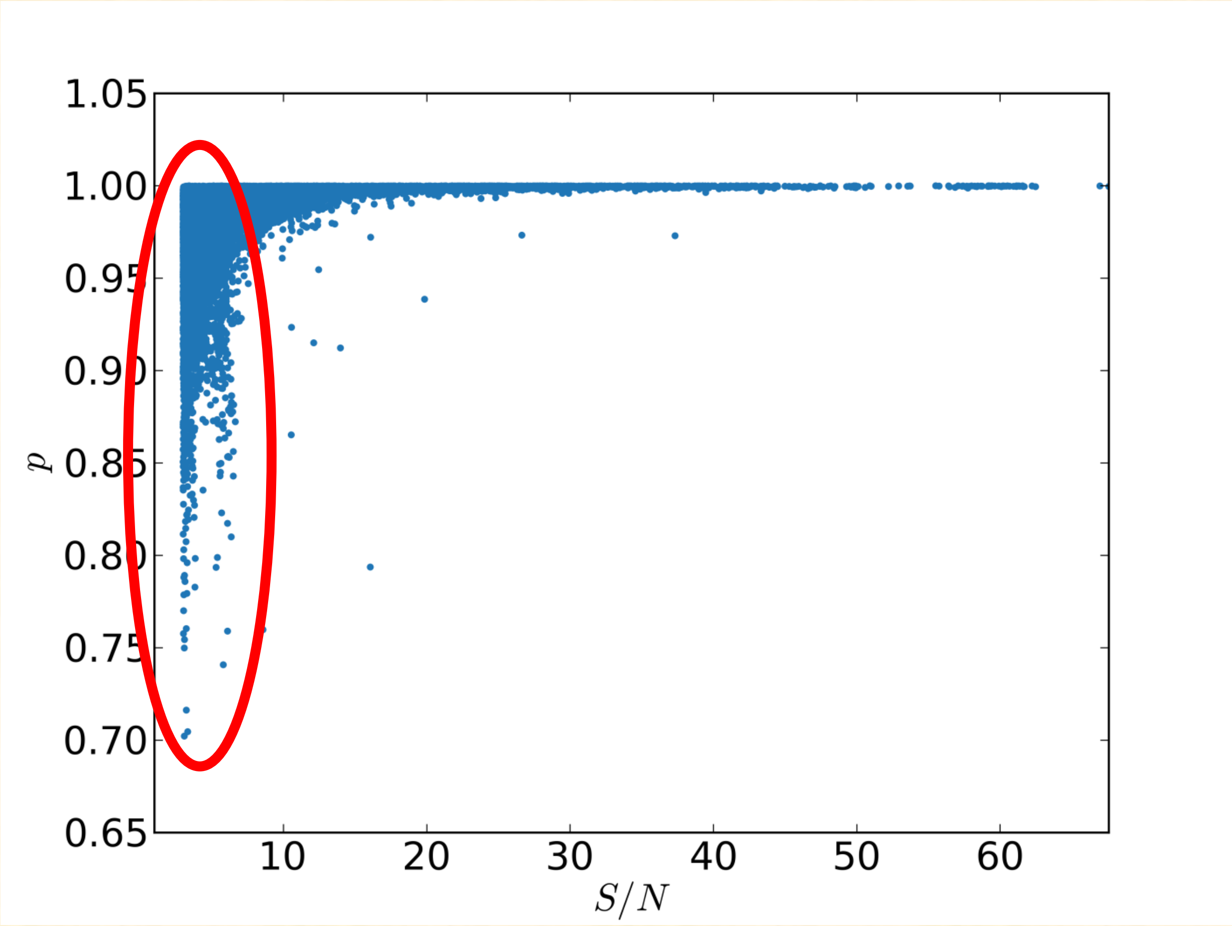
$$p = \frac{\sqrt{Q^2 + U^2 + V^2}}{I}$$

Polarization angle

$$\psi = \frac{1}{2}\tan^{-1}\left(\frac{U}{Q}\right)$$

Almost 100% polarized

$$p = \frac{\sqrt{Q^2 + U^2 + V^2}}{I}$$



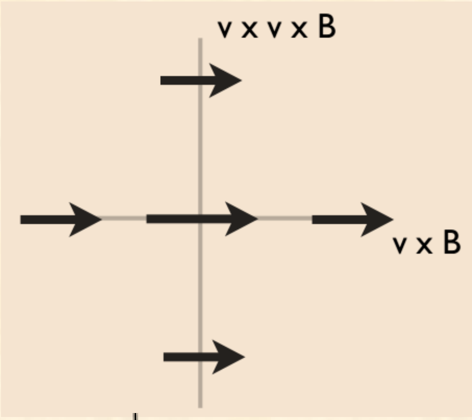
Only large deviation from p=1 for low S/N, as expected

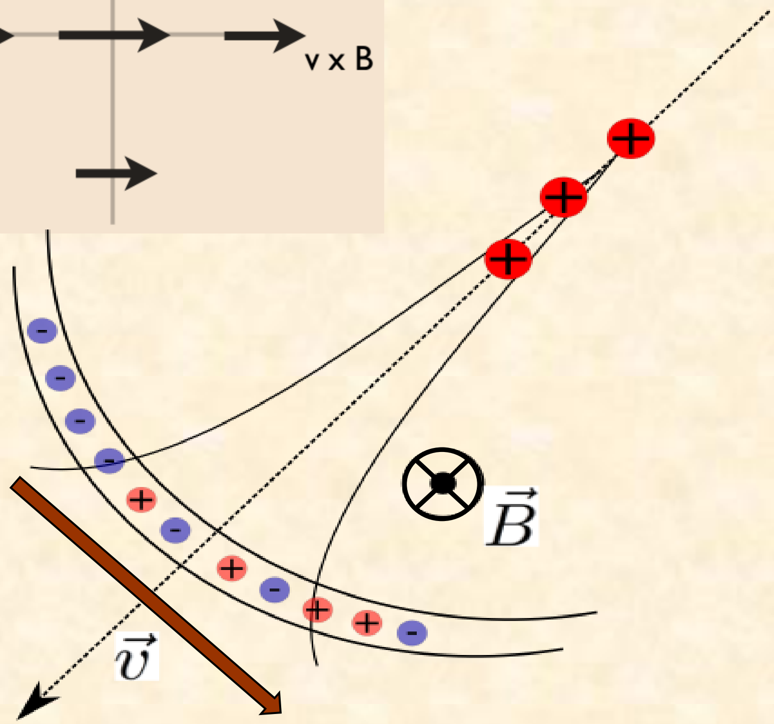
Multiple emission mechanisms

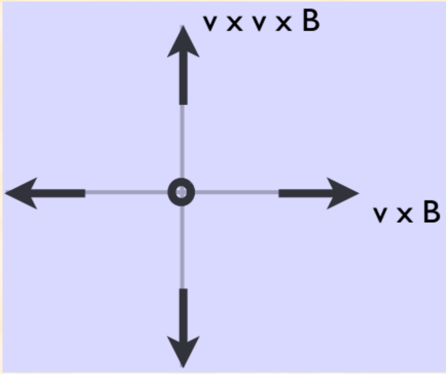
 # Geomagnetic:
- Electrons & positrons have transverse drift, induced by geomagnetic field.
- Linearly polarized, Unidirectional along v x B

 # Charge excess:
- Negative charge buildup at shower front.
- Linearly polarized, Radially from shower axis

The full signal: $\vec{E} = \vec{E}_G + \vec{E}_C$ modified by Time-compression effects.





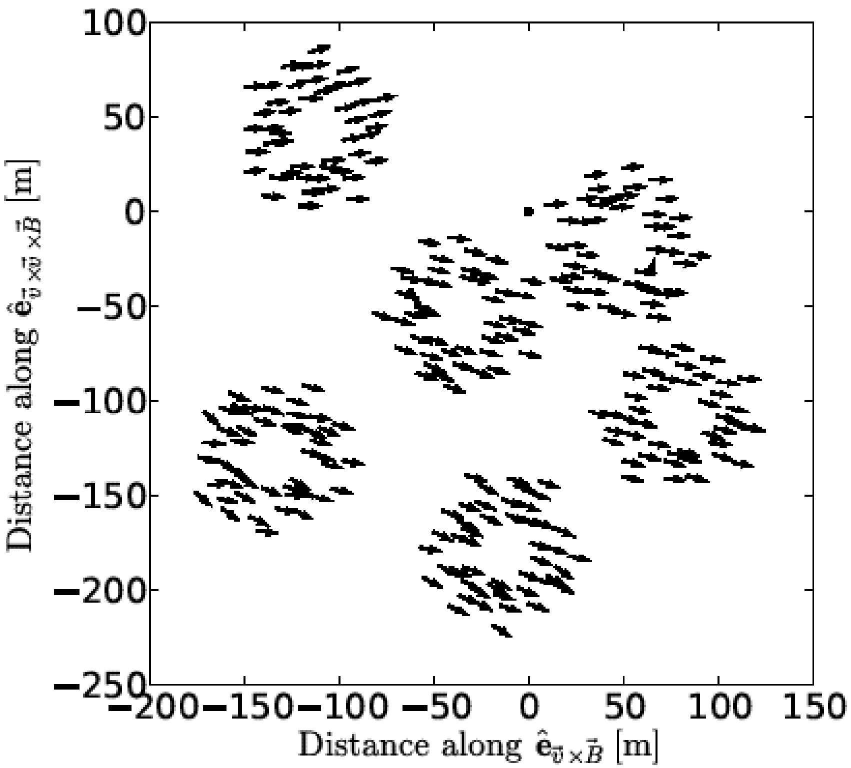


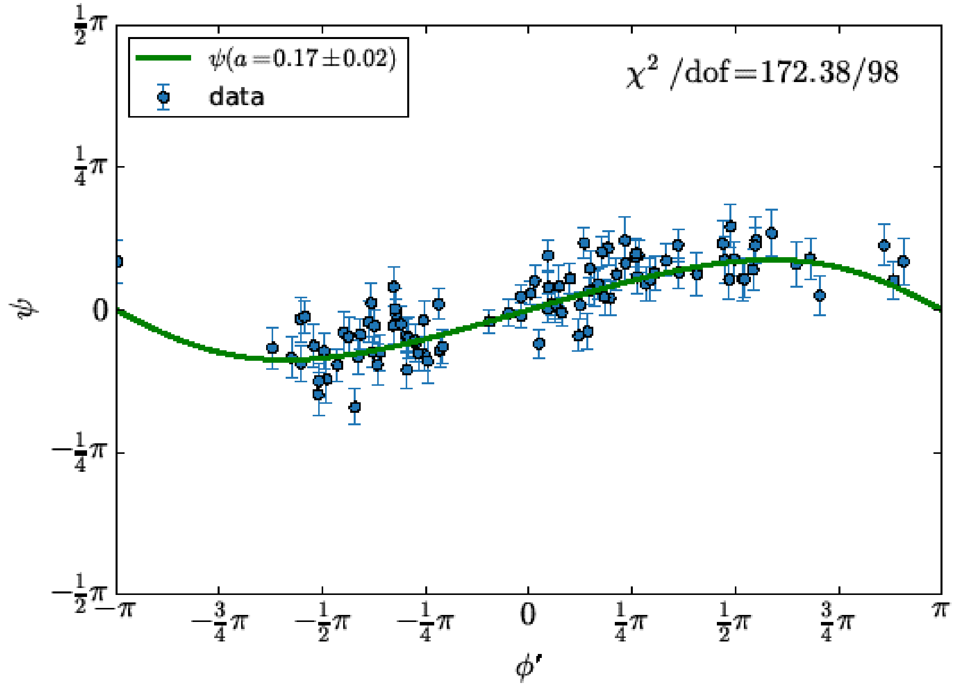
K. Werner et al., ApP 29 (2008) 393

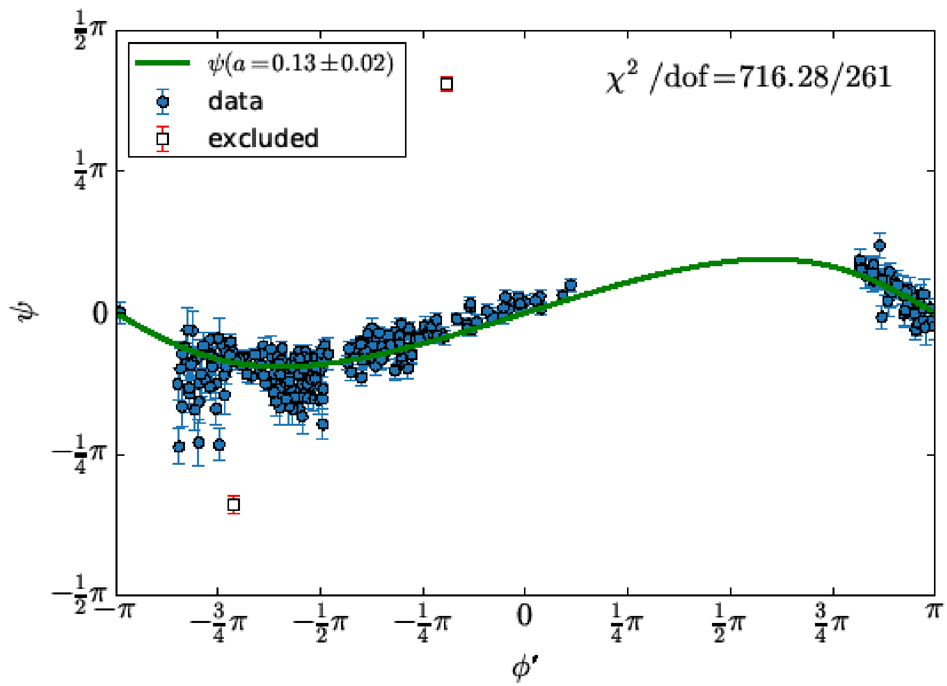
Polarization angle

$$\psi = \frac{1}{2}\tan^{-1}\left(\frac{U}{Q}\right)$$

Pim Schellart et al, arXiv:1406.1355





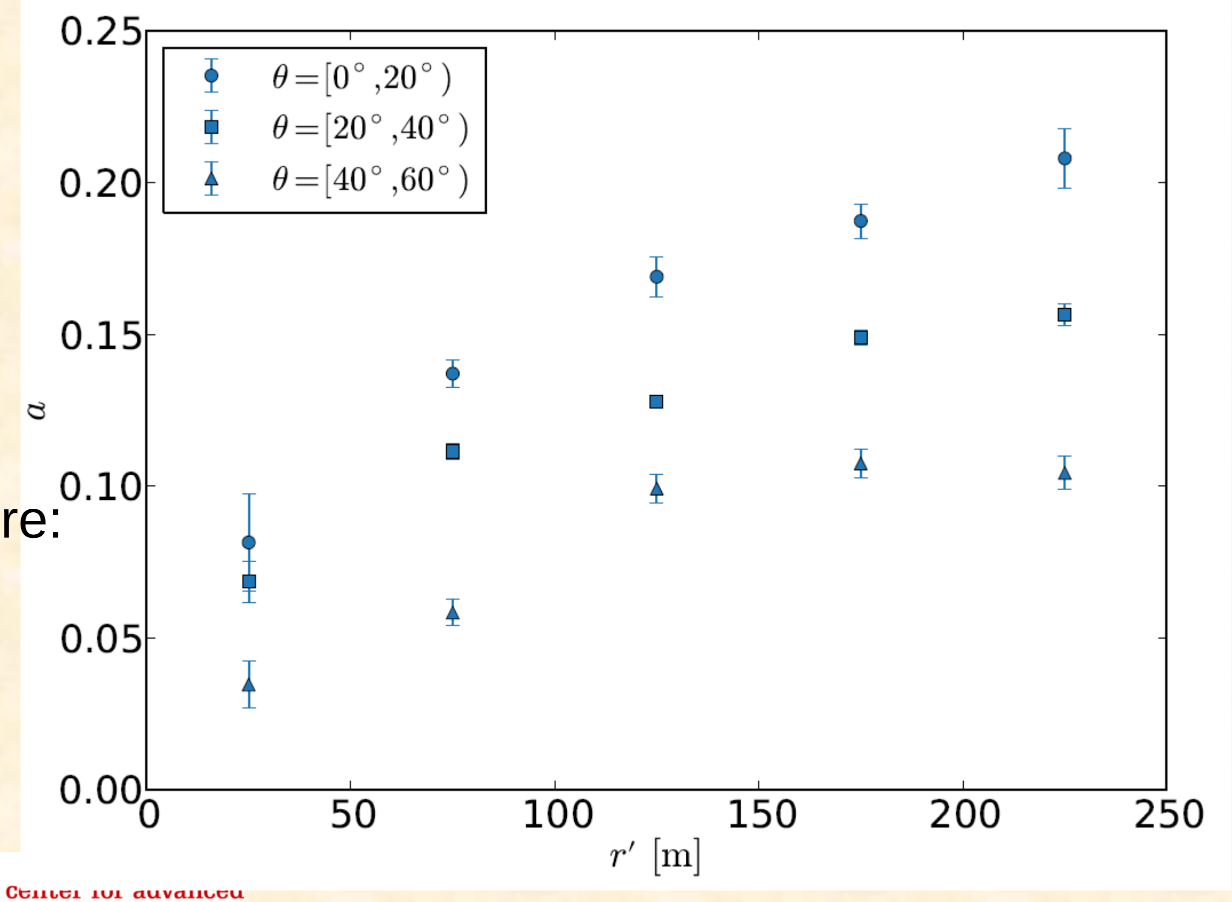


a ~ %'charge excess'

$$\vec{E}(t) = \vec{E}_{\mathrm{G}}(t) + \vec{E}_{\mathrm{C}}(t)$$
$$= (|\vec{E}_{\mathrm{G}}(t)| + |\vec{E}_{\mathrm{C}}(t)| \cos\phi')\hat{\mathbf{e}}_{\vec{v}\times\vec{B}} +$$
$$(|\vec{E}_{\mathrm{C}}(t)| \sin\phi')\hat{\mathbf{e}}_{\vec{v}\times\vec{v}\times\vec{B}}.$$

$$a \equiv \sin\alpha \frac{|E_{\mathrm{C}}|}{|E_{\mathrm{G}}|}$$

Data:
Pim Schellart et al,
arXiv:1406.1355



Simple interpretation, at core:
ChX (radial pol) vanishes
GeoM finite at
(de Vries et al, ApP 45 (2013) 23, arXiv:1304.1321).

Conclusions

- LOFAR provides unmatched antenna density (ideal for model verification, complementary to other experiments)
- All data processed with a fully automated pipeline (Schellart, Nelles et al. A&A 560, A98 (2013))
- Accurate timing (arXiv: 1404.3907; accepted in ApP)
- Detailed measurements of CR signal polarization (Schellart et al. arXiv:1406.1355)
- Radial dependence of ratio a ~ radial/unidirectional polarization can be determined accurately and in agreement with model prediction.
- For some (thunderstorm) events the unidirection polarization deviates from vxB.

Typical 'thunderstorm' pattern