Precision radio detection of cosmic ray air showers

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LORA Scintillator

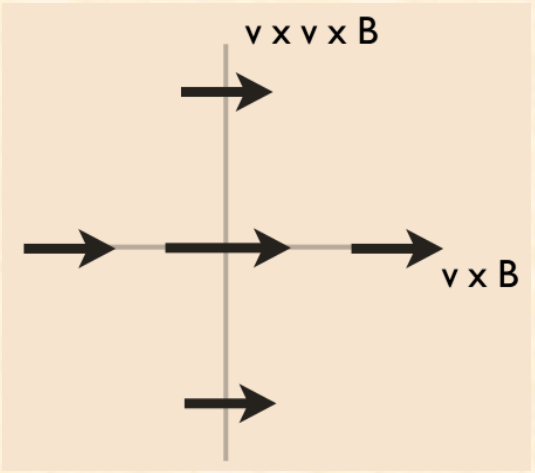
For the LOFAR Cosmic Ray KSP & Cosmic Lightning Project

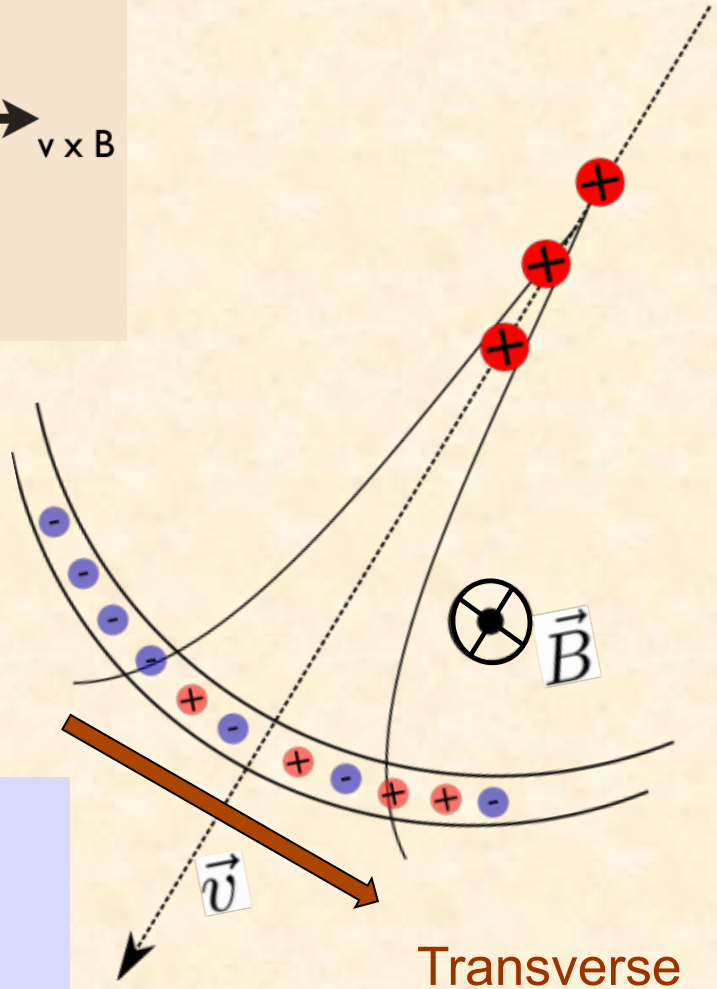
Multiple emission mechanisms

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

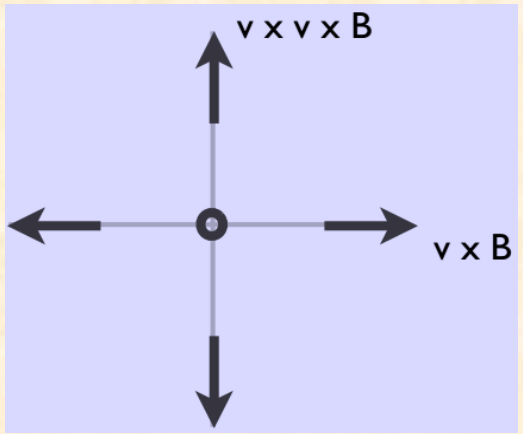
 # Charge excess:
- Negative charge buildup at shower front.
- Linearly polarized, Radially from shower axis

The full signal: $E = E\downarrow G + E\downarrow C$ modified by Time-compression effects.





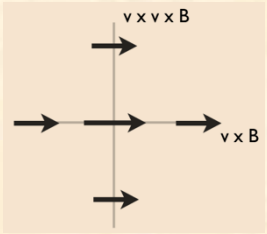
Transverse current



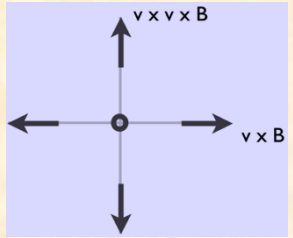
K. Werner et al., ApP 29 (2008) 393

Interpretation circular-polarization for fair weather

GeoMagnetic:



Charge eXcess:



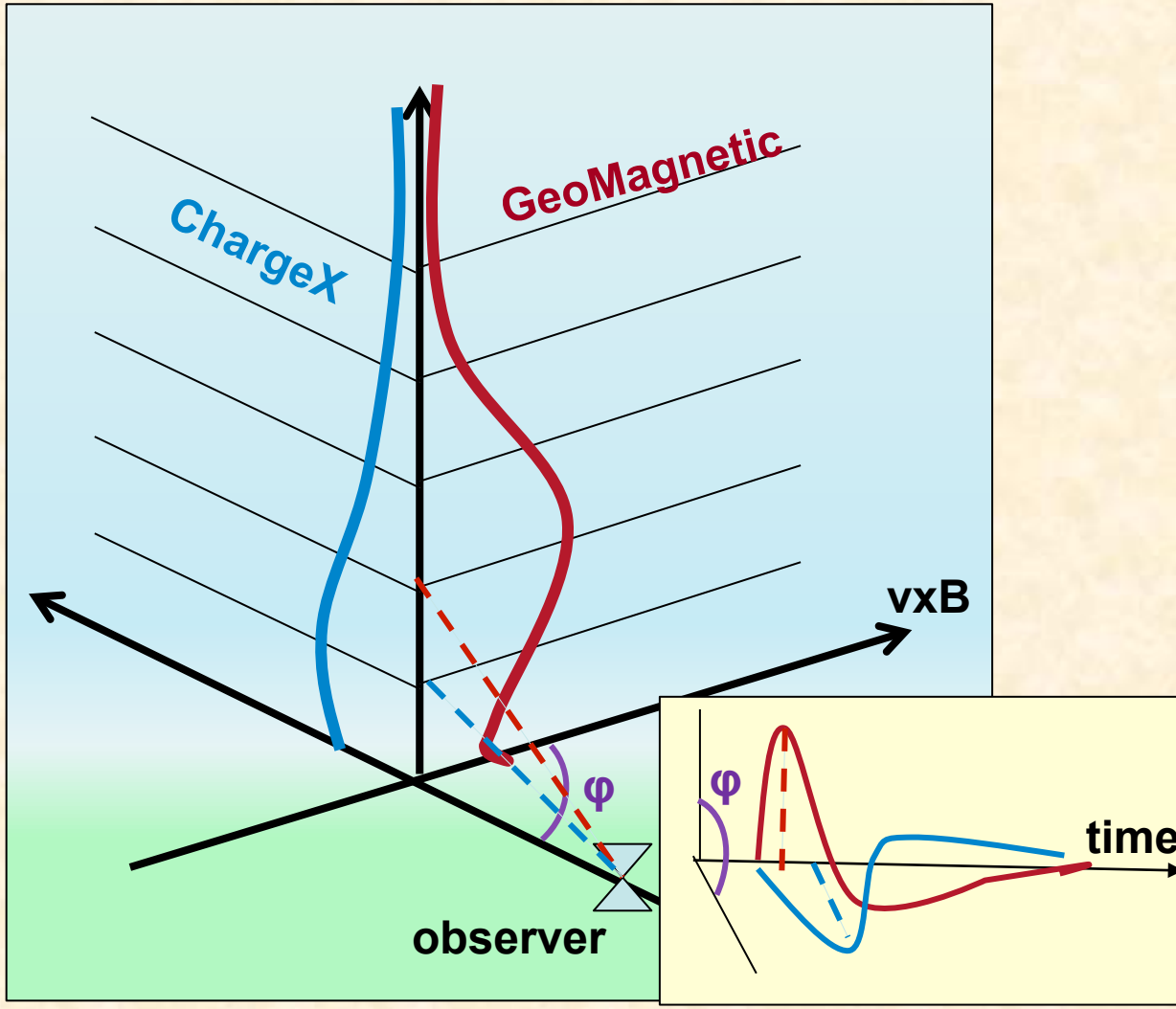
ChX Peaks lower in atmosphere than GM (physics)

At 100 m, 30-80 MHz, delay = 1 ns

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

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

$$U + iV = \frac{2}{n}\sum_{0}^{n-1}\left(\mathcal{E}_{i,\vec{v}\times\vec{B}}\mathcal{E}^*_{i,\vec{v}\times\vec{v}\times\vec{B}}\right) .$$



Stokes parameter V is measure of circular polarization

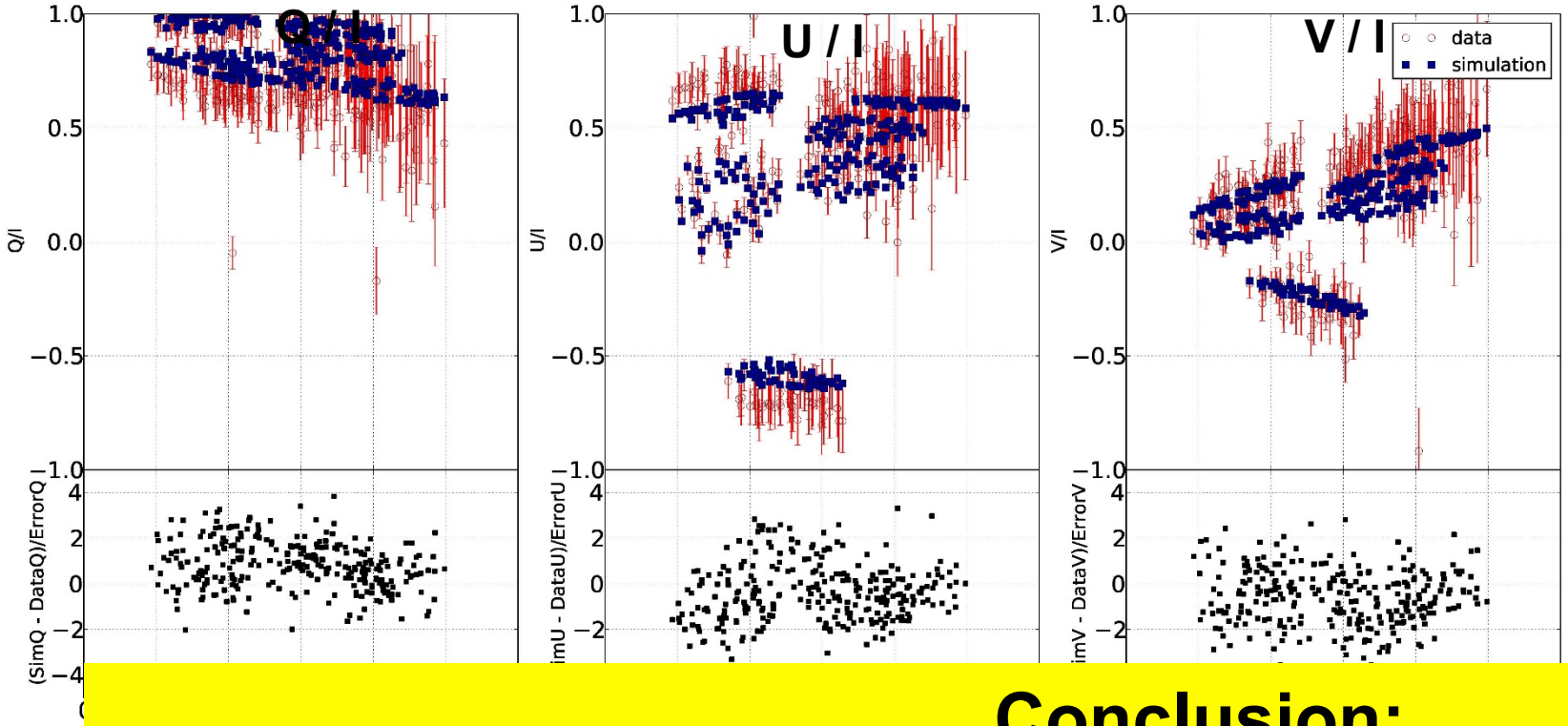
Slight delay between GM &ChX causes rotation in polarization

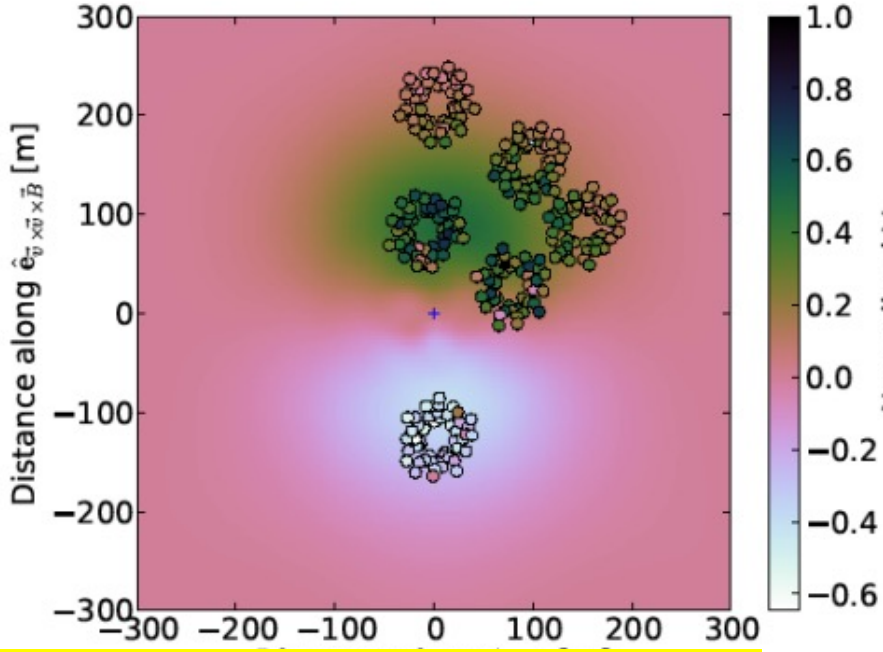
LOFAR data v.s. CoREAS

Transverse current is 1ns ahead of Charge excess pulse (@ 100m, 30-80 MHz)

Linear polarization direction

Circular polarization

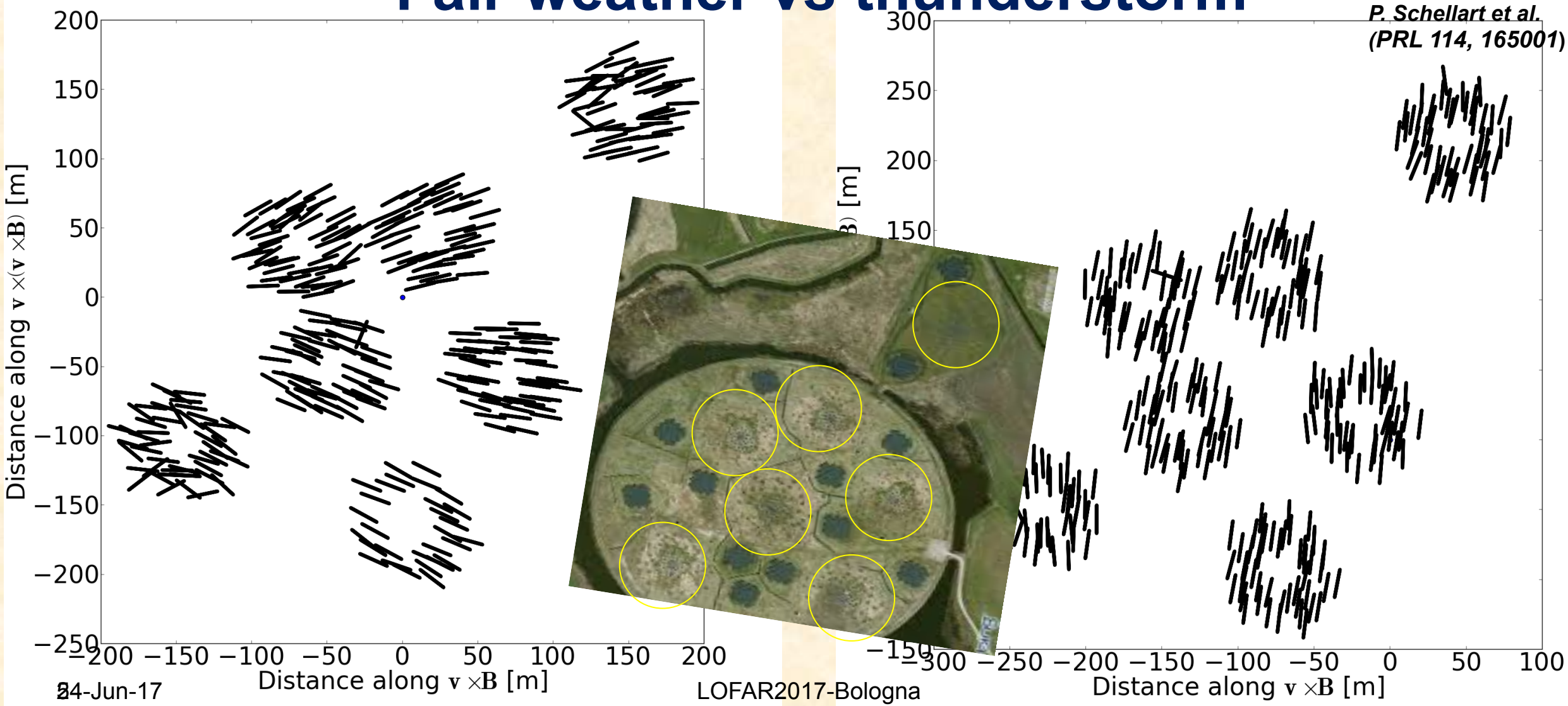




Conclusion:
even the very subtle circular polarization is well understood & accurately measured at LOFAR

Observations; polarization footprint

Fair weather vs thunderstorm



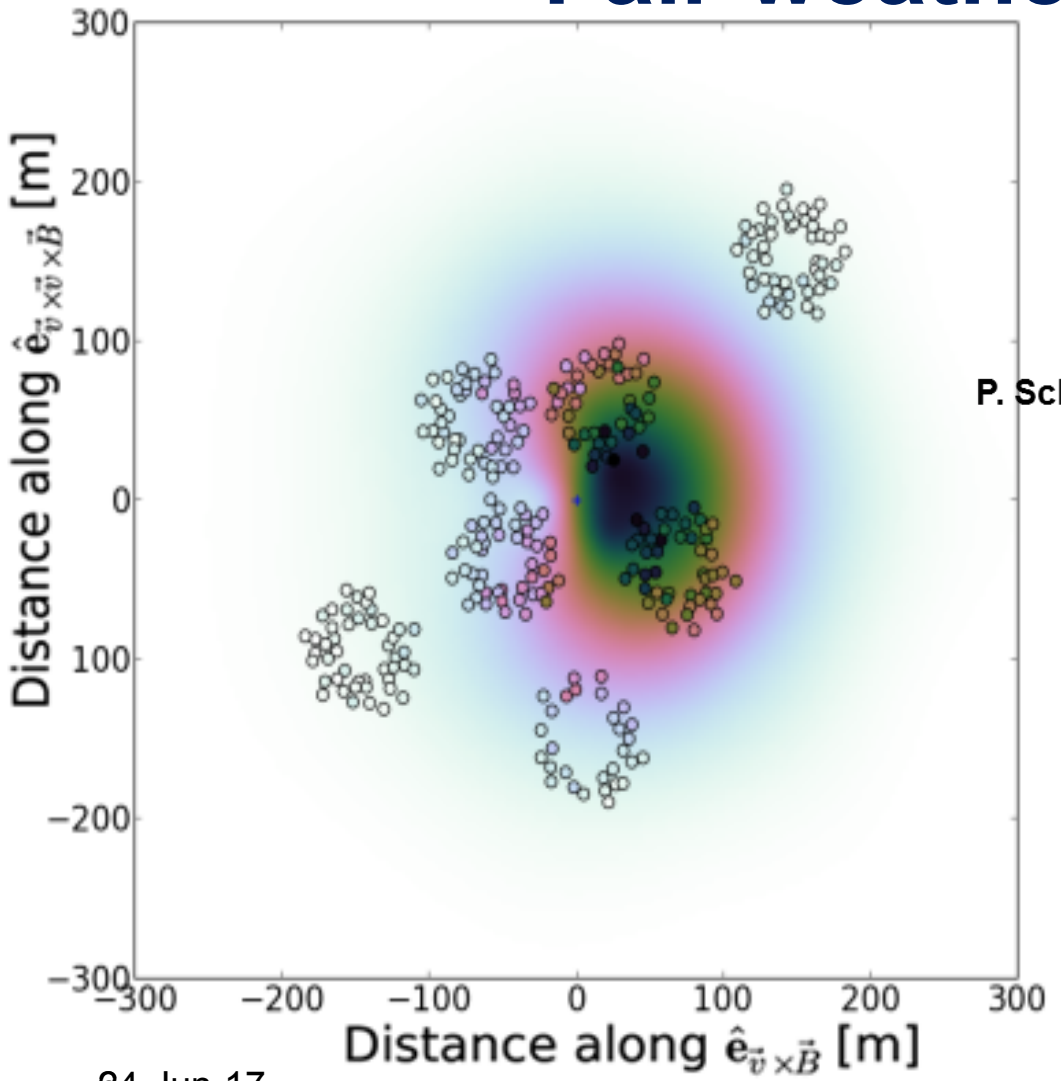
P. Schellart et al.
(PRL 114, 165001)

Observations; intensity footprint

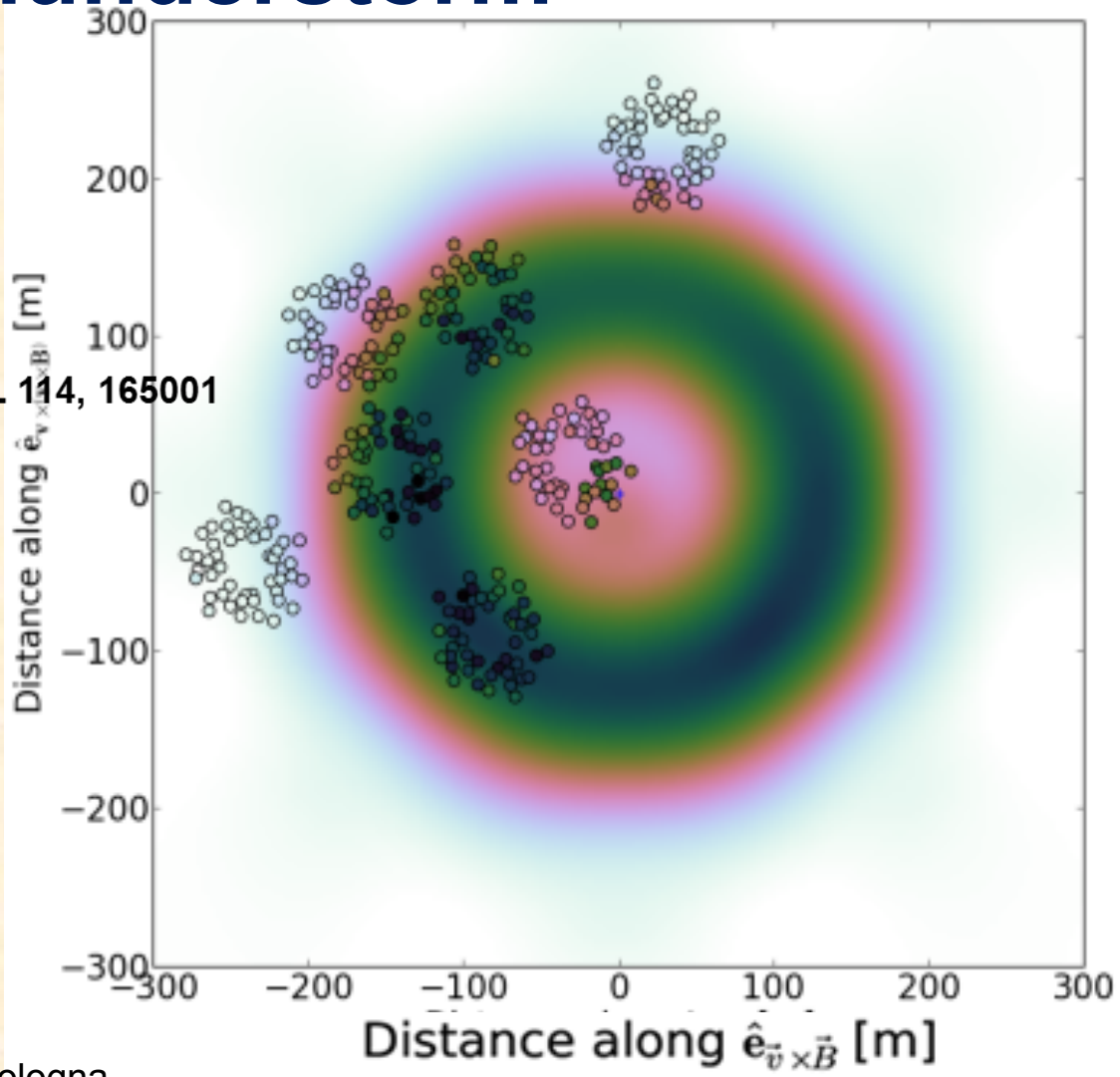
S. Buitink et al.
PRD 90, 082003 (2014)

Fair weather vs thunderstorm

P. Schellart et al.,
PRL 114, 165001 (2015)

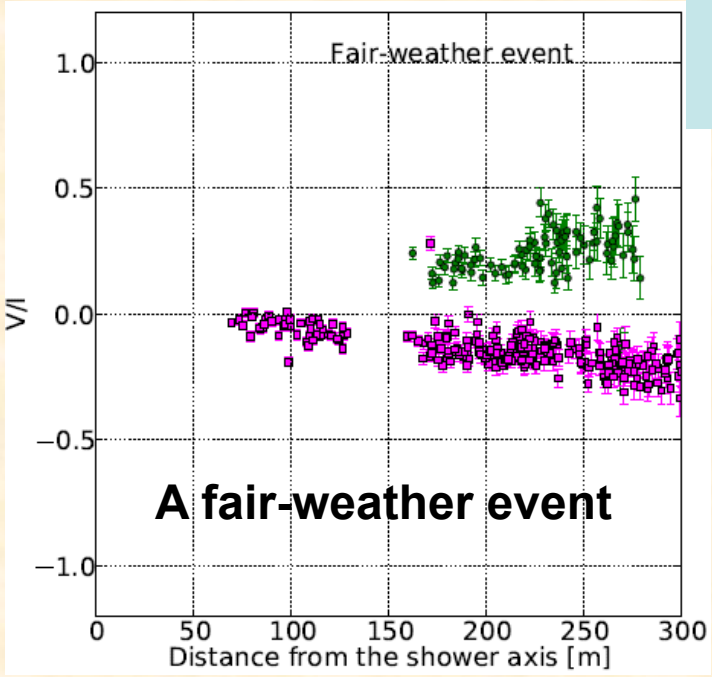


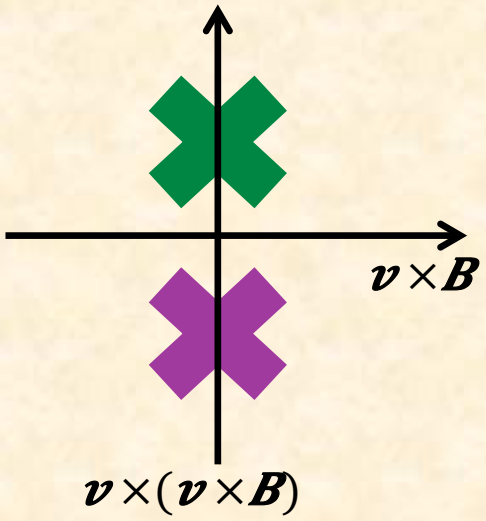
P. Schellart et al., PRL 114, 165001

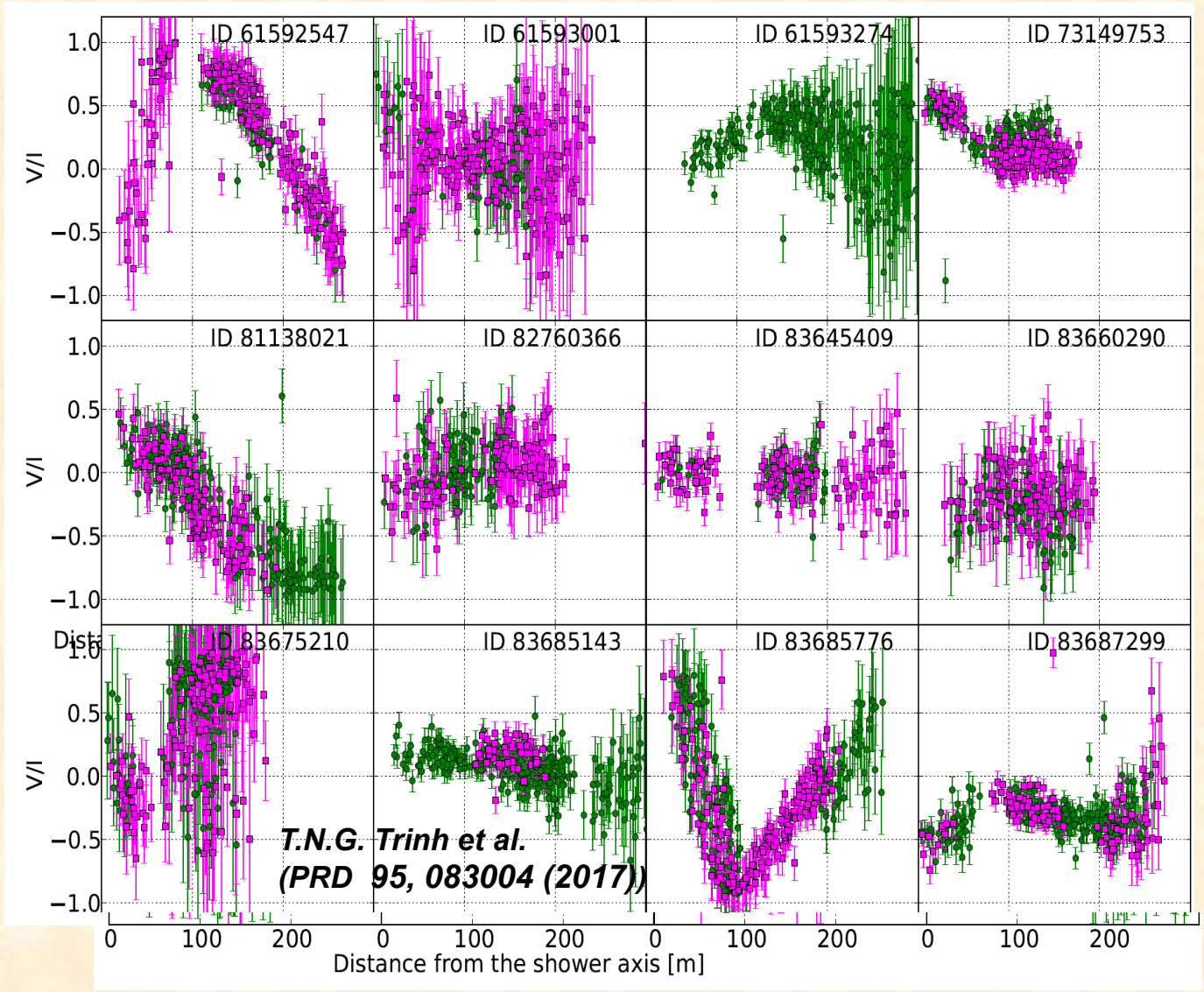


Observations; circular polarization

Fair weather vs thunderstorm

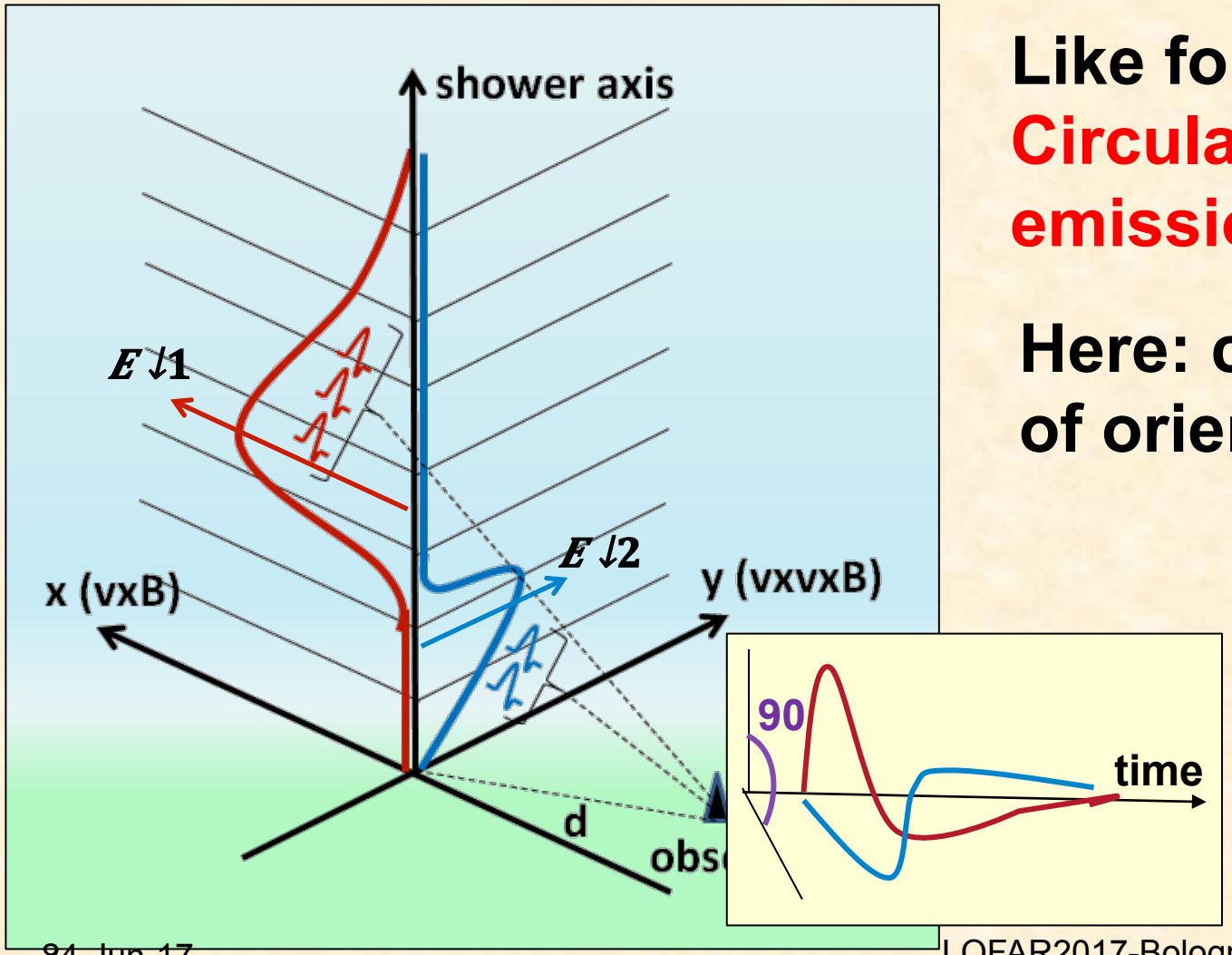






Physics for thunderstorm events

Atmospheric fields induce electric currents in shower plasma

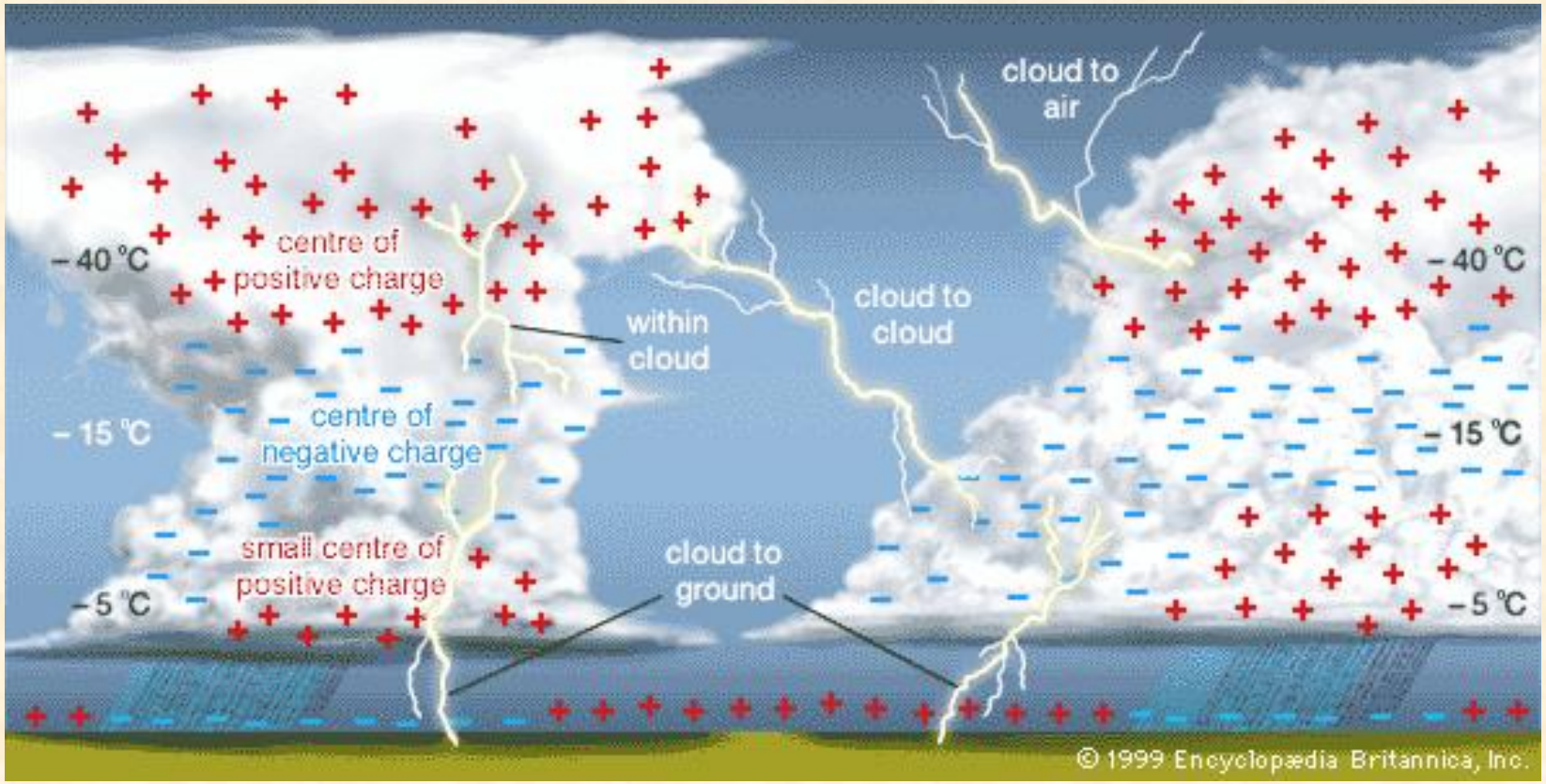


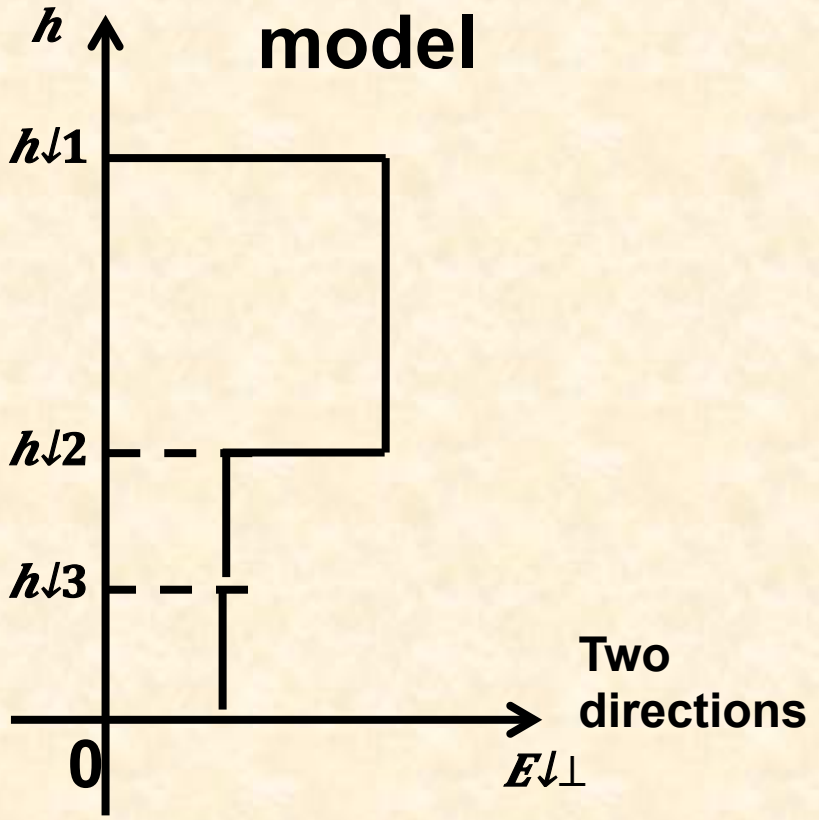
Like for Fair Weather:
Circular polarization due to emission-height differences.

Here: caused by height dependence of orientation of atmospheric fields.

Independent of observer position.

Atmospheric electric fields



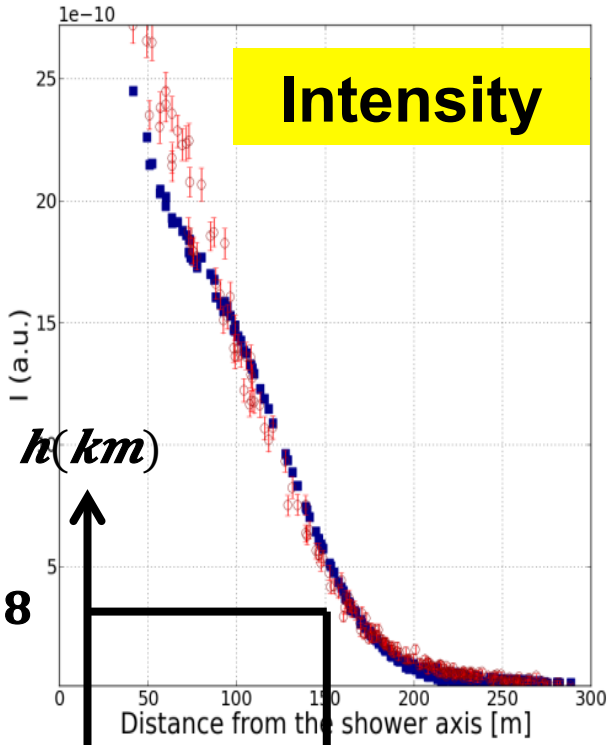


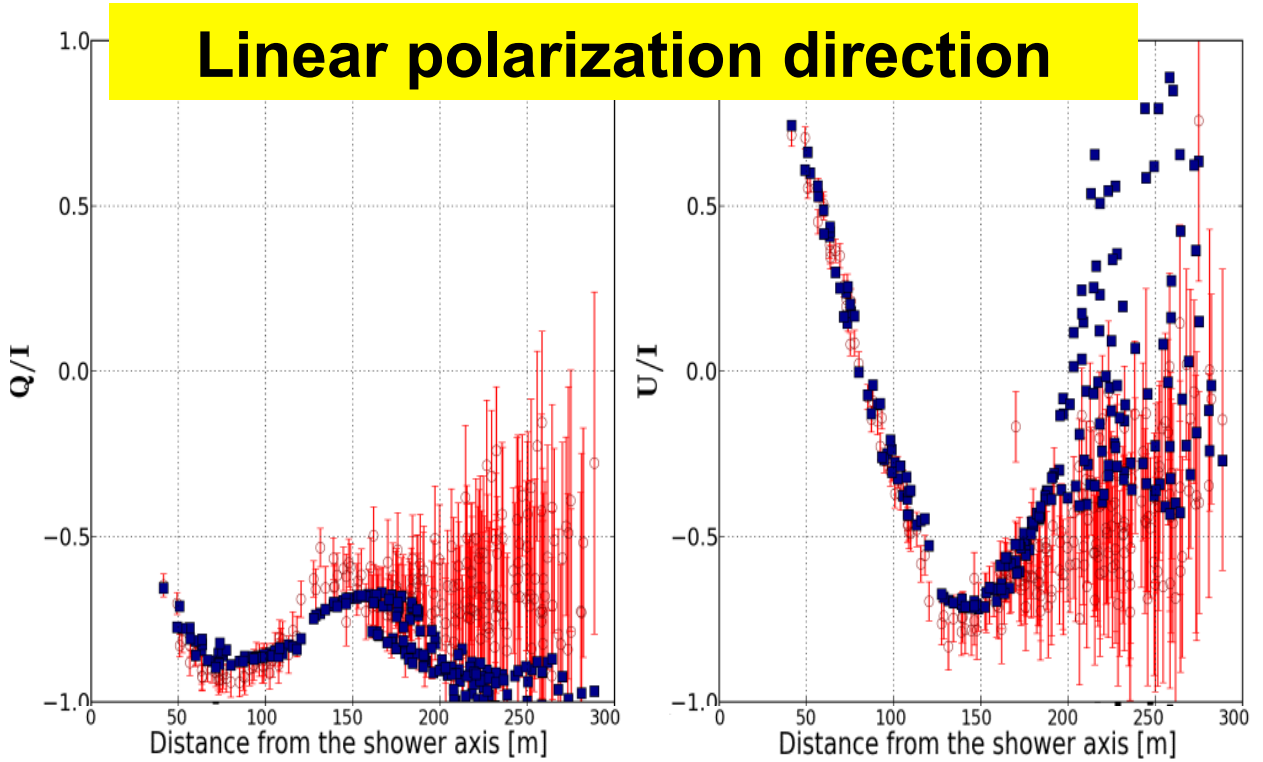
Challenge: **Many parameters → grid search cumbersome**

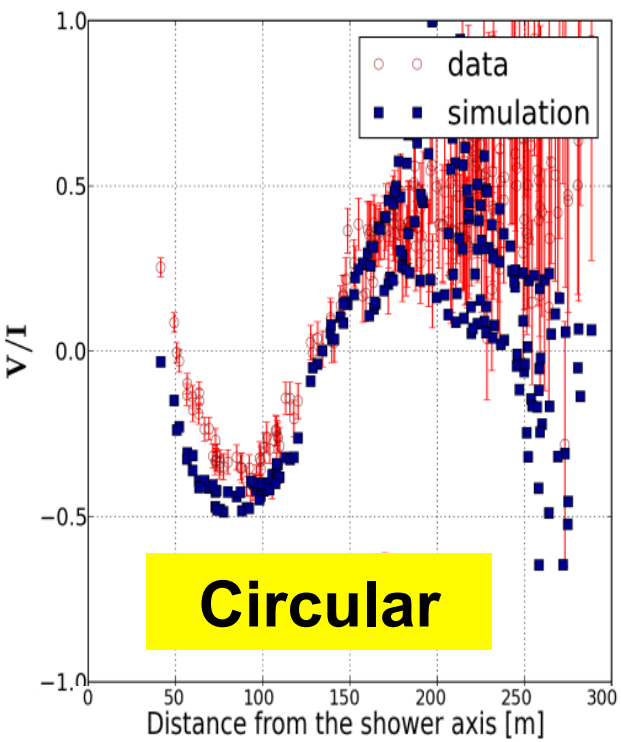
Levenberg-Marquardt minimization requires: Fast & Deterministic code

Semi-analytic approximation developed

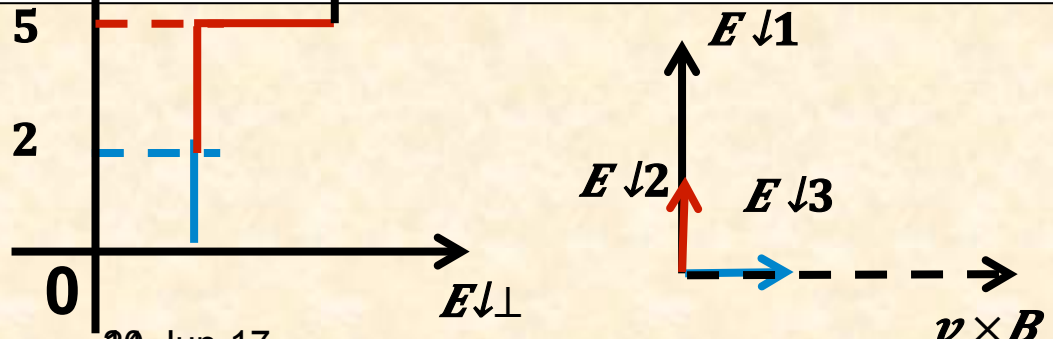
A reconstructed thunderstorm event







T.N.G. Trinh et al.
(PRD 95, 083004 (2017))



Layer	1	2	3
Height (km)	8–5	5–2	2–0
$\lvert \mathbf{E}_\perp \rvert$ (kV/m)	50	15	9
α (°)	98	98	8
$E_{\mathbf{v}\times\mathbf{z}}$ (kV/m)	46	13	4
$E_{\mathbf{v}\times(\mathbf{v}\times\mathbf{z})}$ (kV/m)	−22	−9	8

Conclusions

Radio emission from air showers is very well understood

Radio emission from air showers is accurately measured at LOFAR

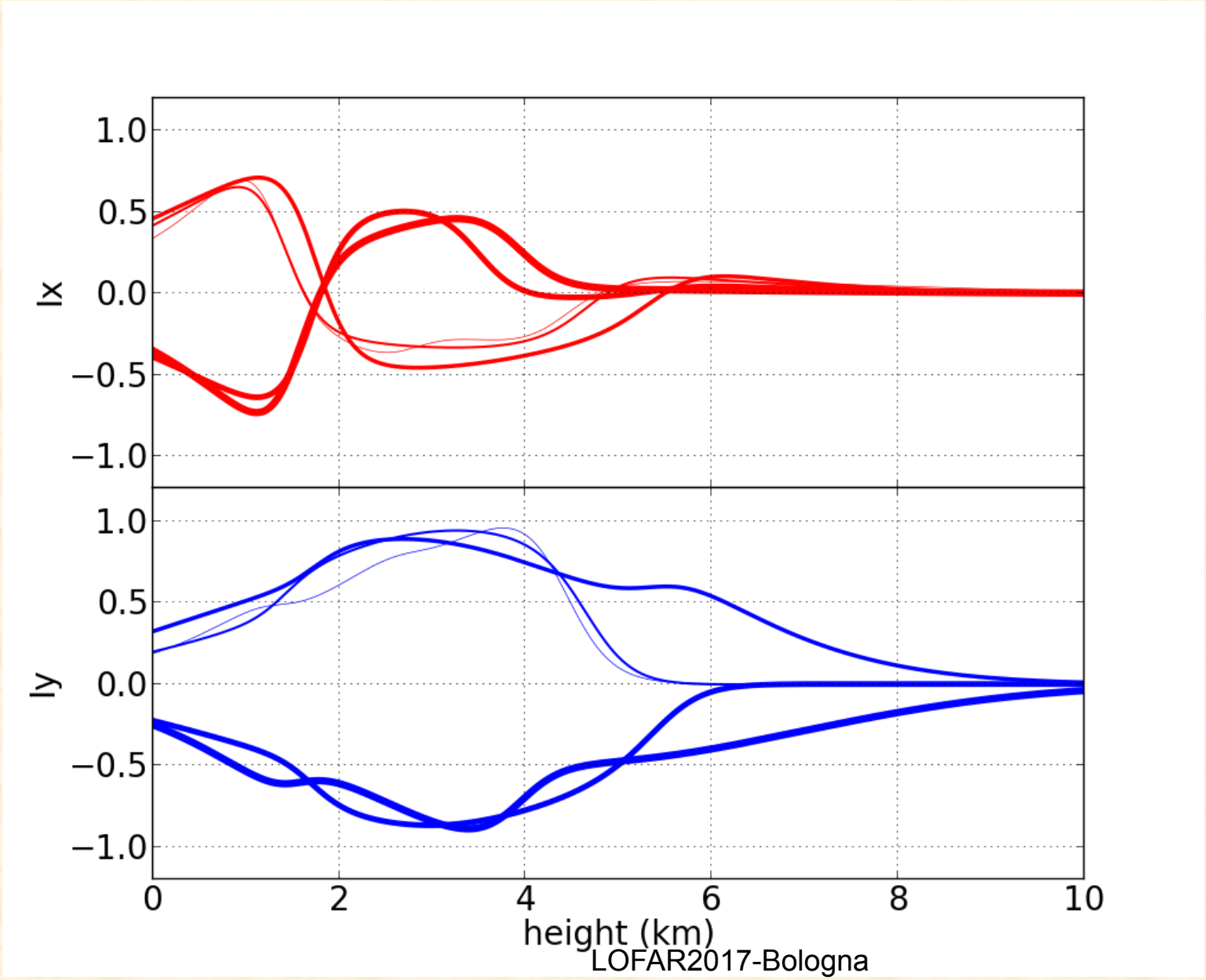
example of both: circular polarization for fair weather

Thus:

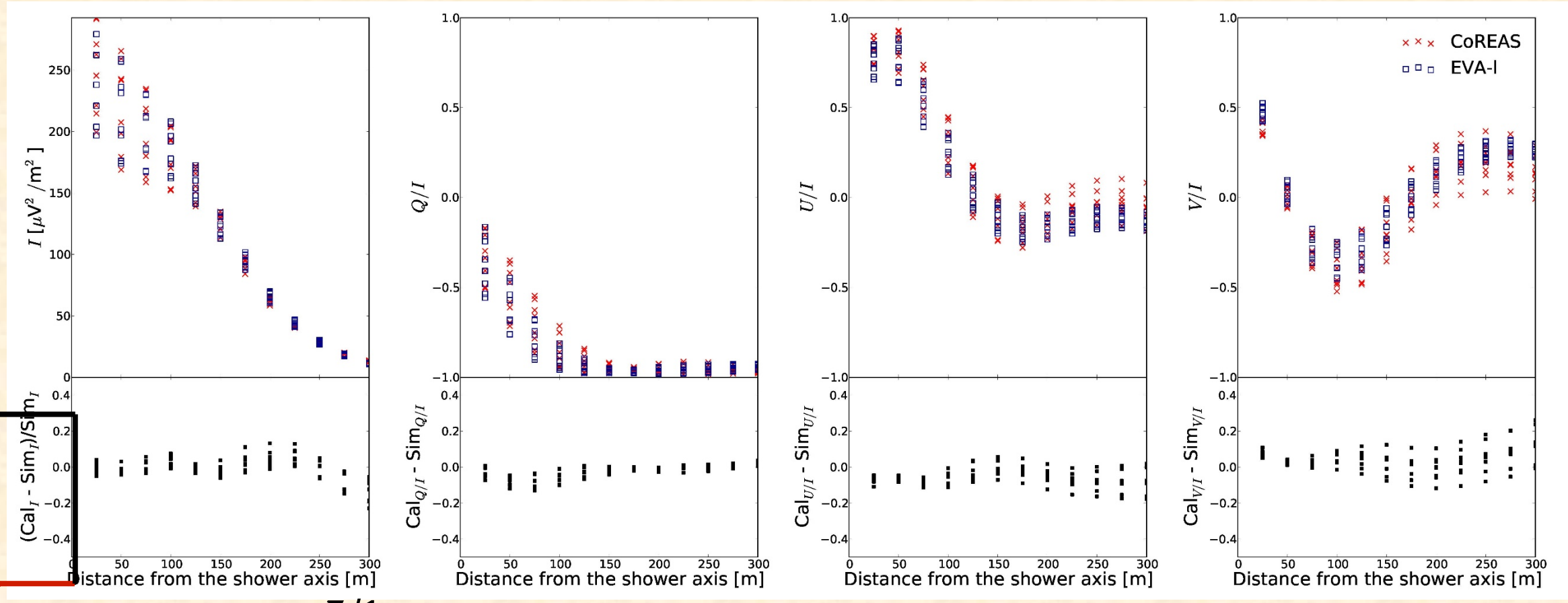
Radio-detection of air showers can be used as diagnostic tool

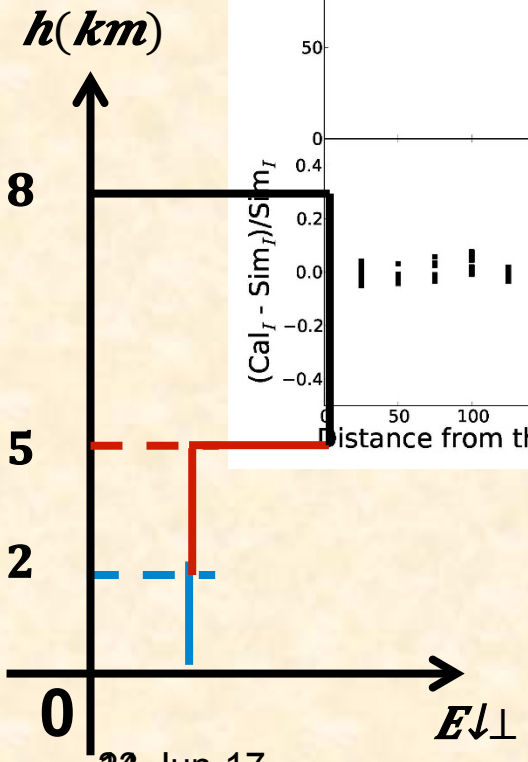
- **X-max**
- **atmospheric electric fields**

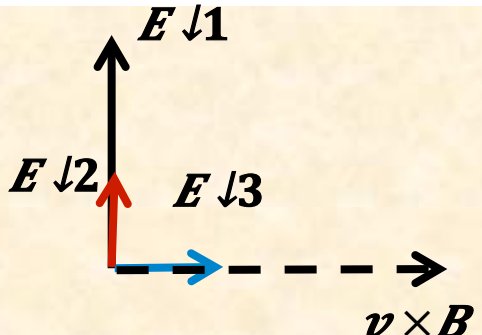
Uniqueness of the results



Analytic code vs CoREAS







Circular polarization distinguishes E3 to left or to right

Full polarization, Stokes

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

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

$$U + iV = \frac{2}{n}\sum_{0}^{n-1}\left(\mathcal{E}_{i,\vec{v}\times\vec{B}}\mathcal{E}^*_{i,\vec{v}\times\vec{v}\times\vec{B}}\right) .$$

Interesting results:

- **Fair weather:**

  confirmation of emission mechanisms

- **Thunderstorm:**

  Finite circular pol. near core due to changing atmospheric E-field

Stokes parameters: I, Q, U, V

Linear polarization angle: 2 φ =atan(U/Q)

Circular polarization = V/I