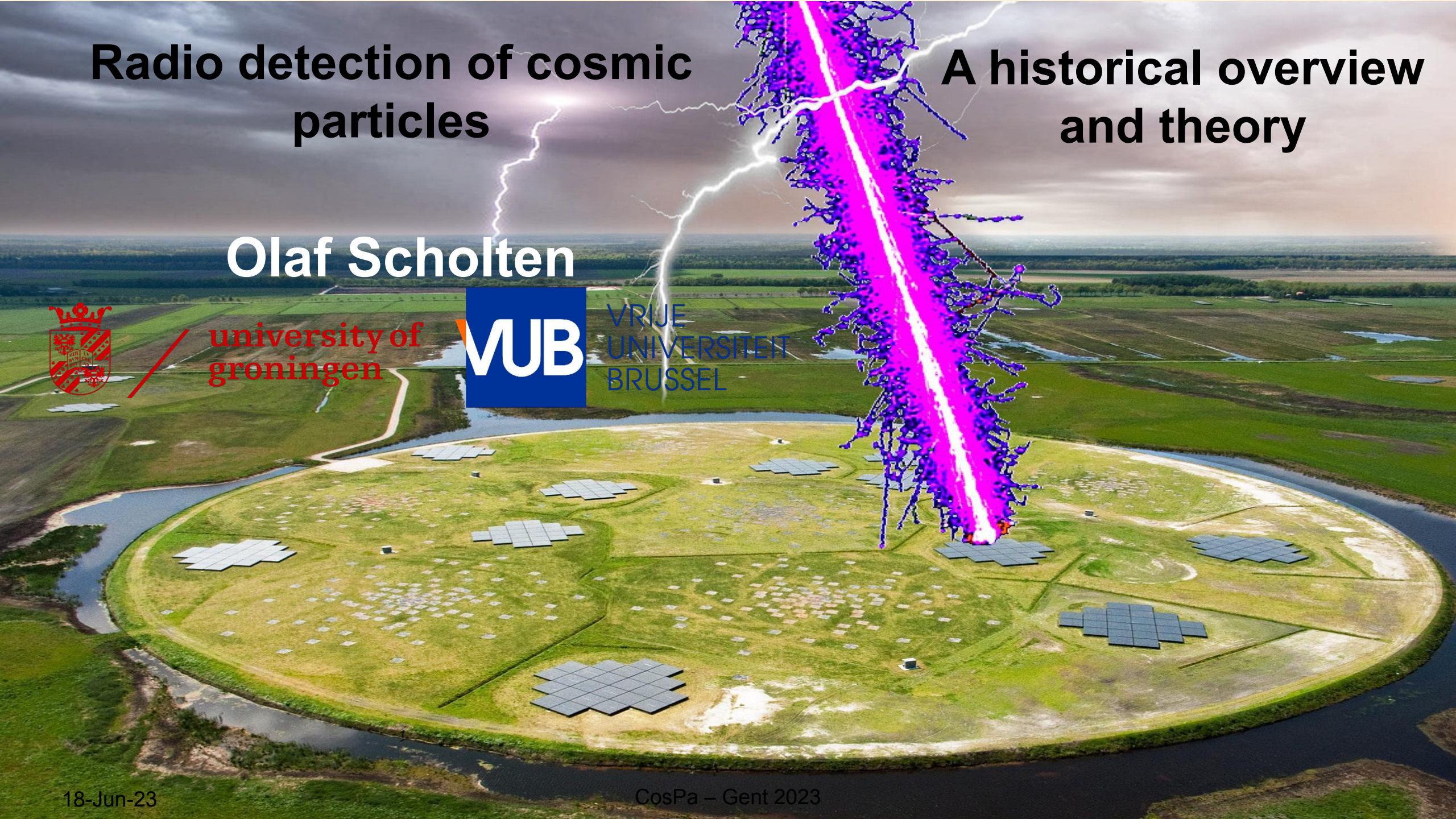
Radio detection of cosmic particles

A historical overview and theory

Olaf Scholten

university of groningen

VUB VRIJE UNIVERSITEIT BRUSSEL



Why UHECR & UHEν radio frequency detection? Towards multi-messenger astronomy

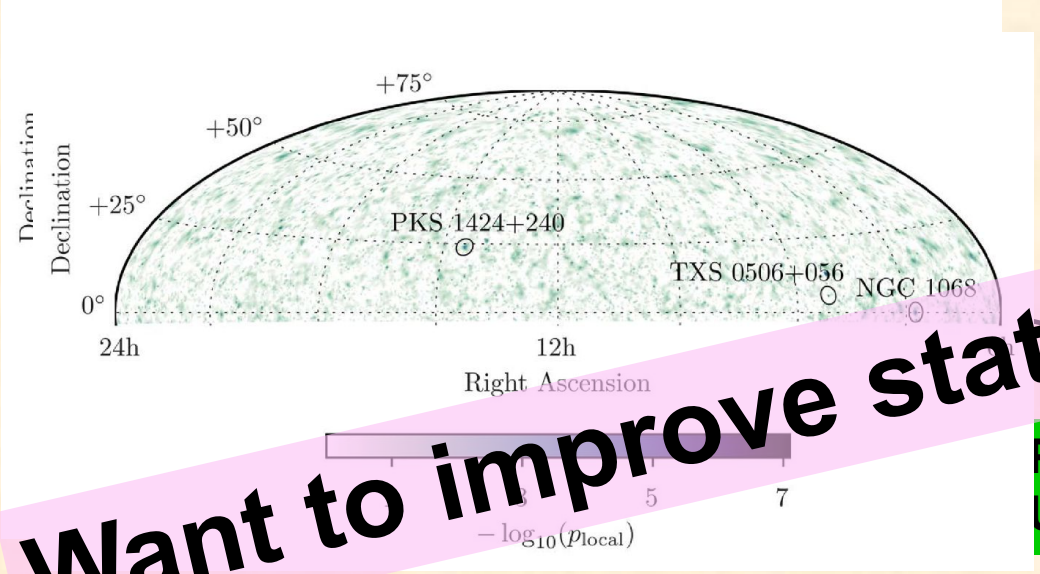
Prime example: Icecube Science article:

RESEARCH

NEUTRINO ASTROPHYSICS

Evidence for neutrino emission from the nearby active galaxy NGC 1068

IceCube Collaboration*†



Want to improve statistics & pointing accuracy

Peak intensity of UHEν from UHEν

M77 'Squid' UHEν

IceCube:
Neutrinos unveil hidden galactic activities
An obscured supermassive black hole may be producing high-energy cosmic neutrinos

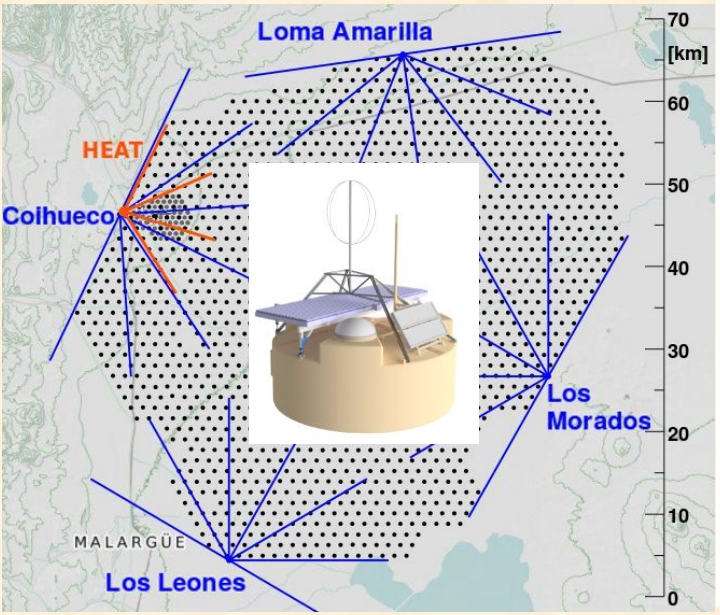
Statistics, thus large detectors: use radio emission from UHE-CR and -ν

Radio Frequency (RF):

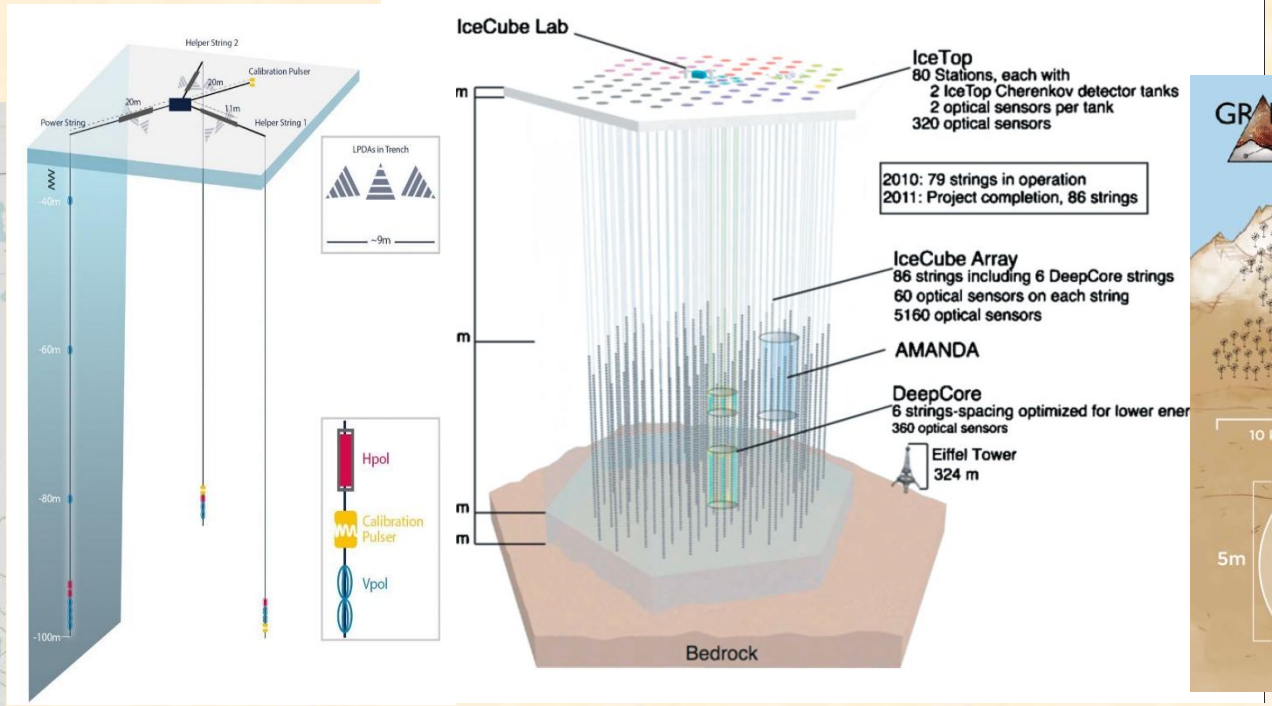
- Simple, cheap detectors
- RF waves are not attenuated in air & ice

Recent:
add-on or driving technology of major experiments, such as

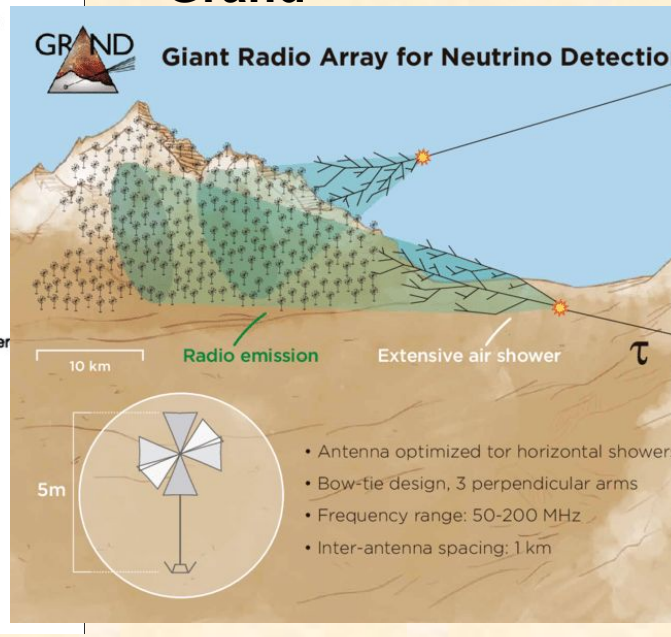
Pierre Auger Observatory



RNO-G & IceCube



Grand



Radio frequency observations

Jelley et al. 1965; Allan & Jones 1966: first detection of short pulses emitted by cosmic-ray induced air showers.

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Astroparticle Physics 19 (2003) 477–494

Astroparticle Physics

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2003, birth of modern RF air shower detection:

Detecting radio emission from cosmic ray air showers and neutrinos with a digital radio telescope

Heino Falcke [a,*], Peter Gorham [b]

Coherent emission, basic mechanisms

Coherent: intensity ~ (# particles)^2 ~ (shower energy)^2

In medium:

G.A. Askaryan,
Sov. Phys. JETP 14, 441 (1962); 21, 658 (1965)

Askaryan = Charge excess radiation:
- Negative charge buildup at shower front.
- Front moves faster than in-medium speed of light

In air:

F.D. Kahn and I. Lerche, Proc. Royal Soc. A289, 206 (1966)

Geomagnetic = Transverse current:
- Electrons & positrons have transverse drift, induced by geomagnetic field.

Modern modelling of radio signal

Need modelling of VHF emission from showers to extract direction, mass, energy.

A) Forward modeling (discussed here)

Have model for emission of radiation from particle shower and find best fit to data

- Microscopic (add emission from each electron) : CoREAS & ZHAires
- Macroscopic (calculate emission from moving charge cloud): EVA & MGMR

B) Parametrizations of radio footprint

C) Interferometric reconstruction

Trace back signal of each antenna to particle shower.

Microscopic Macroscopic approaches

Microscopic, full Monte Carlo (ZHAireS, CoREAS):

- Accounts for complete shower physics
- Minimum of approximations
- Monte Carlo based (random value for X_max)
- Very CPU intensive
- Difficult to get insight in physics

E. Zas, F. Halzen, and T. Stanev, Phys. Rev. D 45, 362 (1992)
J. Alvarez-Muñiz and E. Zas, Phys. Lett. B 411, 218 (1997)

T. Huege, H. Falcke, A & A 19, 412 (2003)

Macroscopic, semi analytic (MGMR):

- Not CPU intensive
- Predictive, steepest descent search, applicable to more complicated cases
- Insight in physics, understand importance of shower structure
- Parametrization of shower physics
- Approximations

O. Scholten, K. Werner, F. Rusydi, Astropart. Phys. 29, 94-103 (2008)

General mechanism of Radio emission

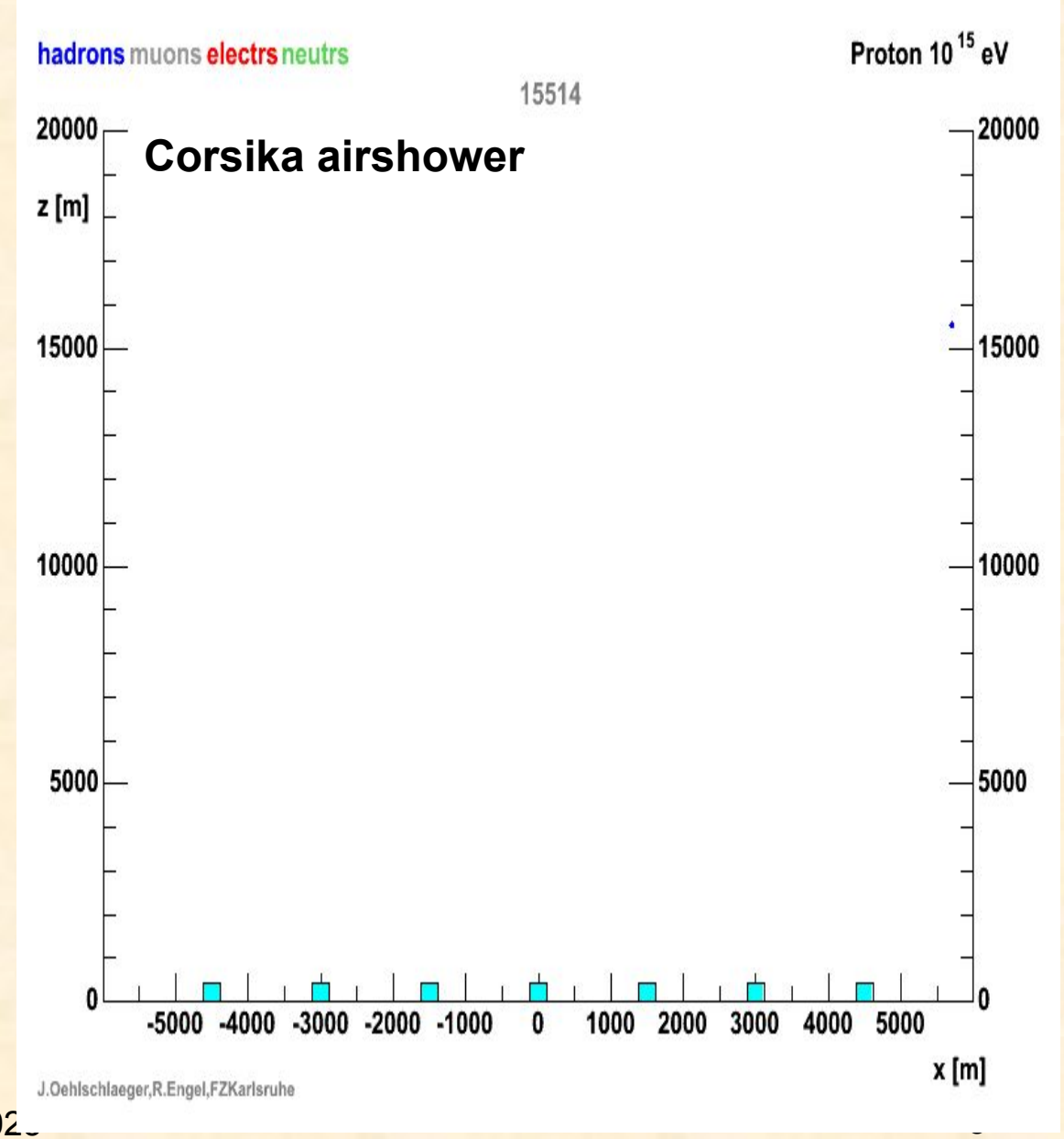
In medium (ice or rock):

Askarian effect (charged particle moving faster than in-medium speed of light)

In air:

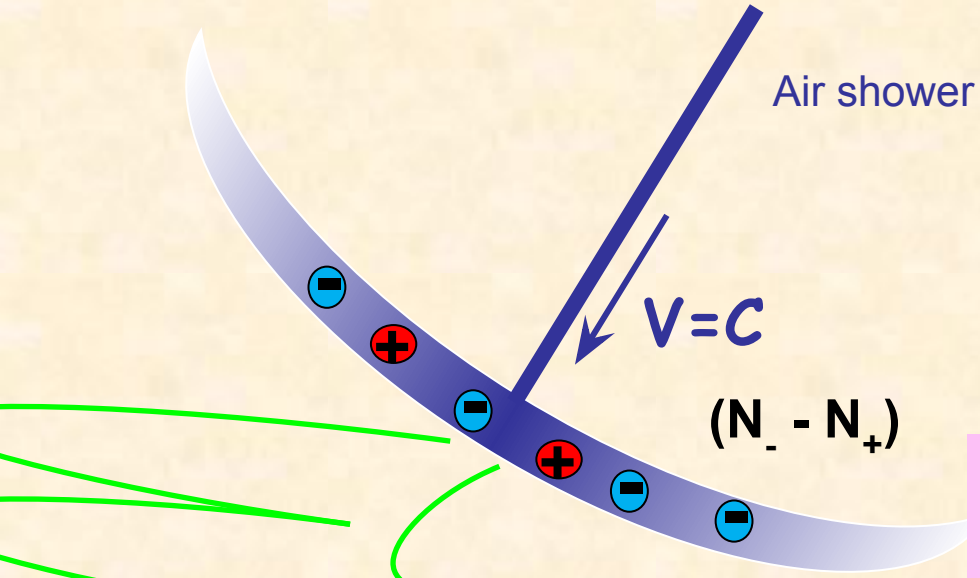
Askarian & Geomagnetic effects

(electric current induced by Lorentz force)



Two mechanisms can be distinguished

Charge excess



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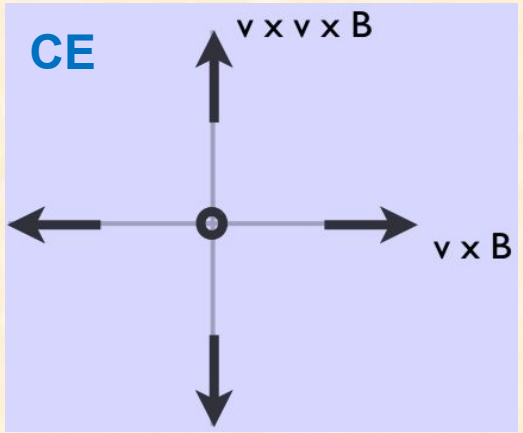


Linearly polarized, radially from shower axis

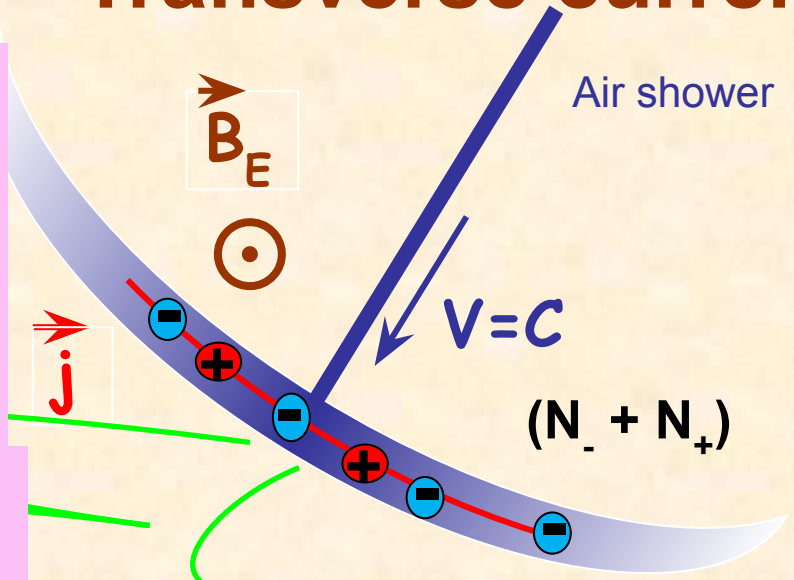
The full signal:

$$\vec{E} = \vec{E}_G + \vec{E}_C$$

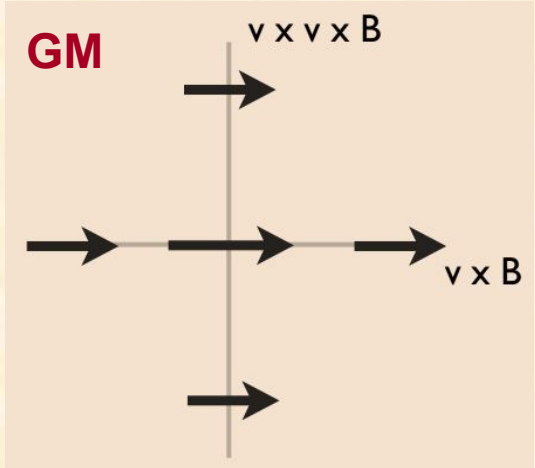
Time varying & Cherencov

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

Geomagnetic = Transverse current

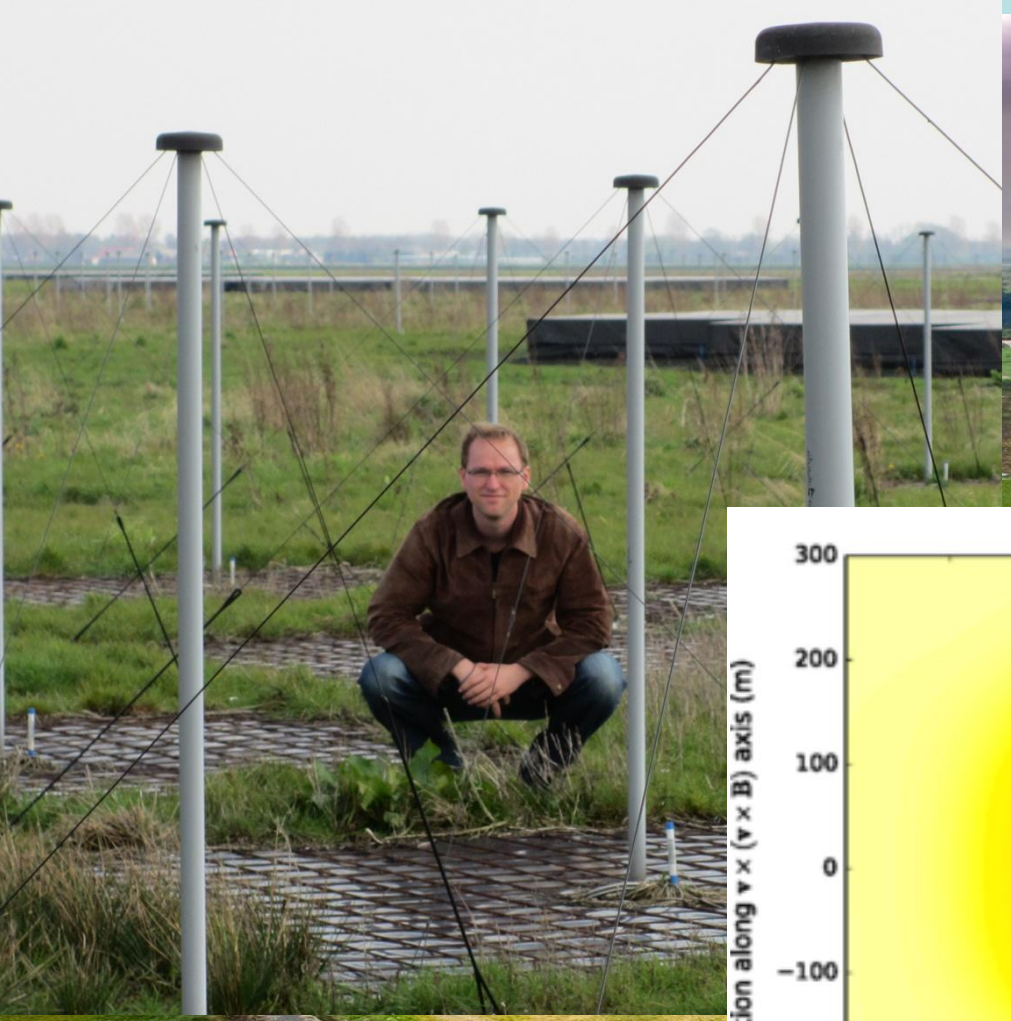


c/n

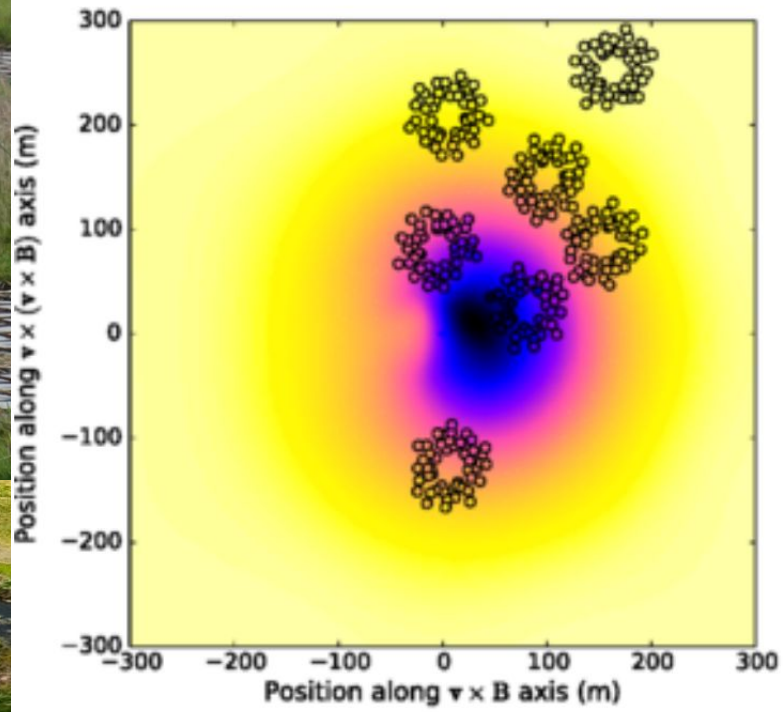


Linear polarization, along v x B

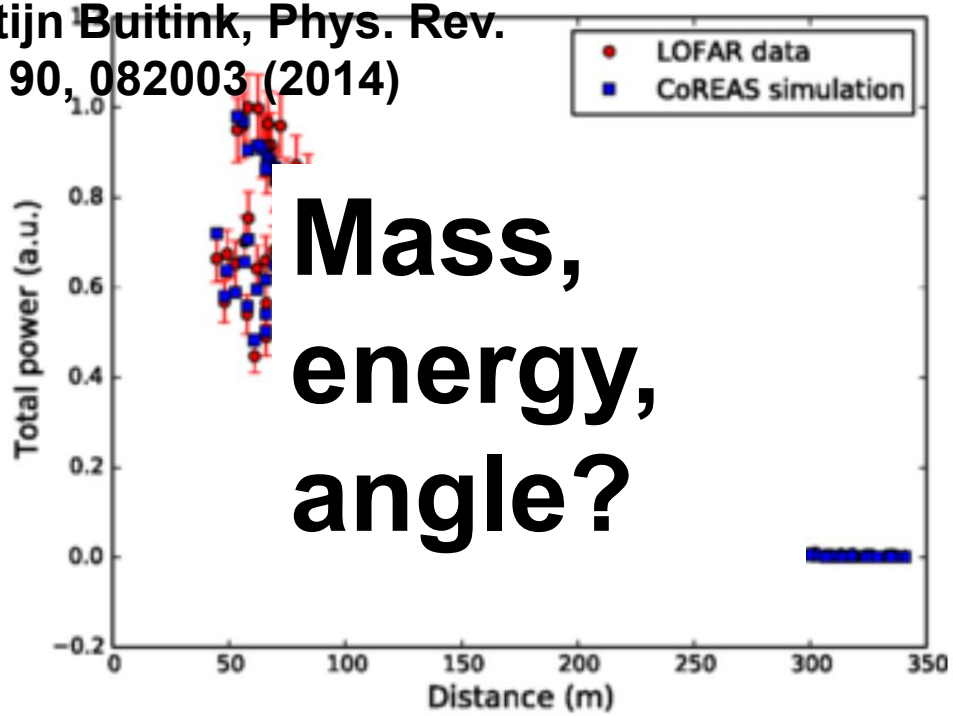
Precision Measurement



Superterp, LOFAR core

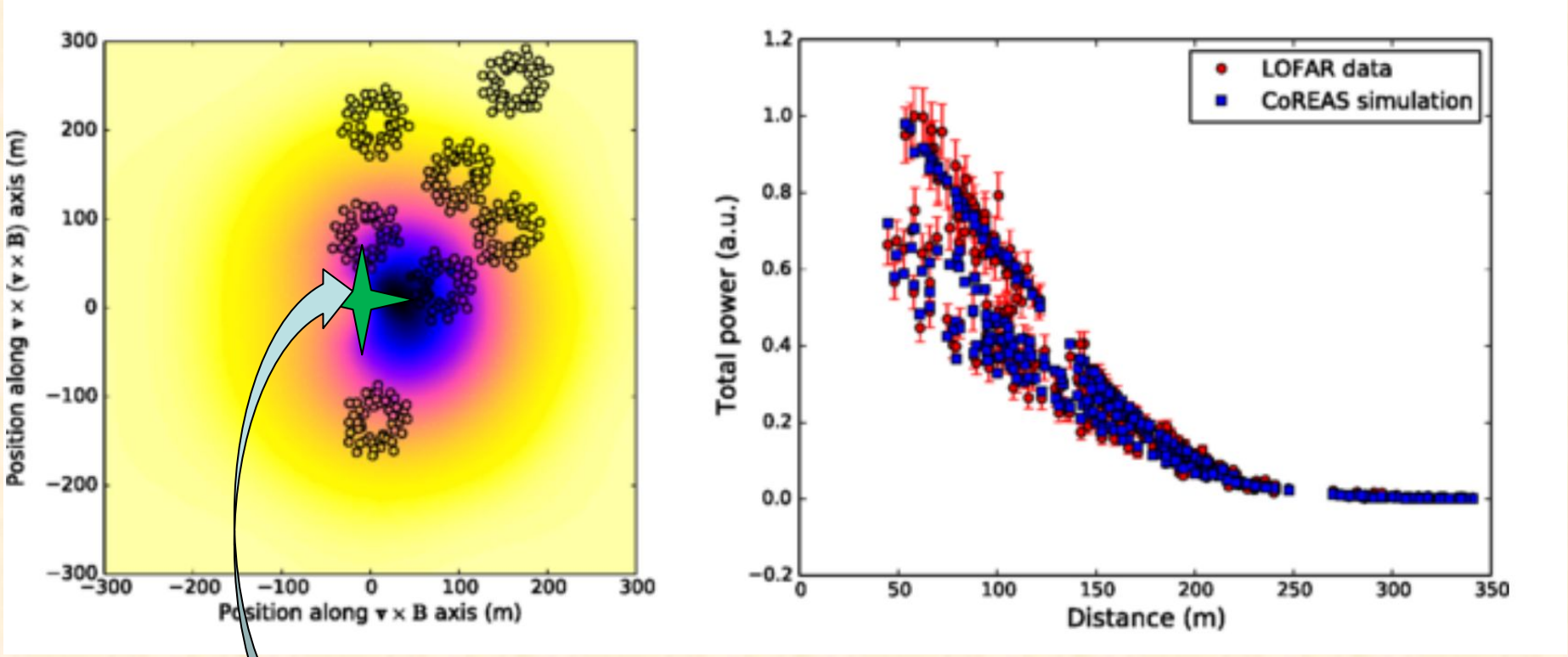


Stijn Buitink, Phys. Rev. D 90, 082003 (2014)



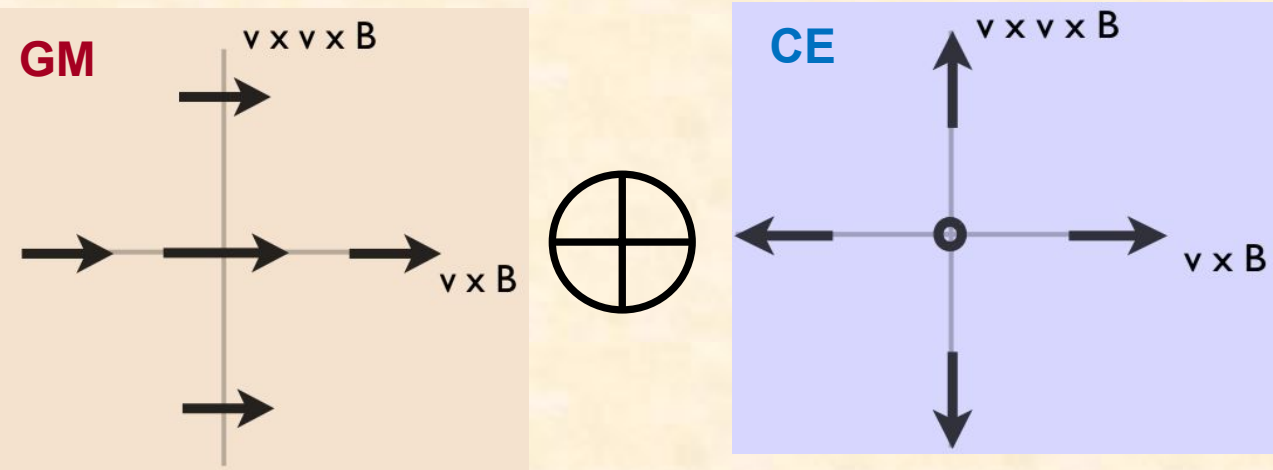
Mass, energy, angle?

Asymmetry intensity footprint



Core particle shower

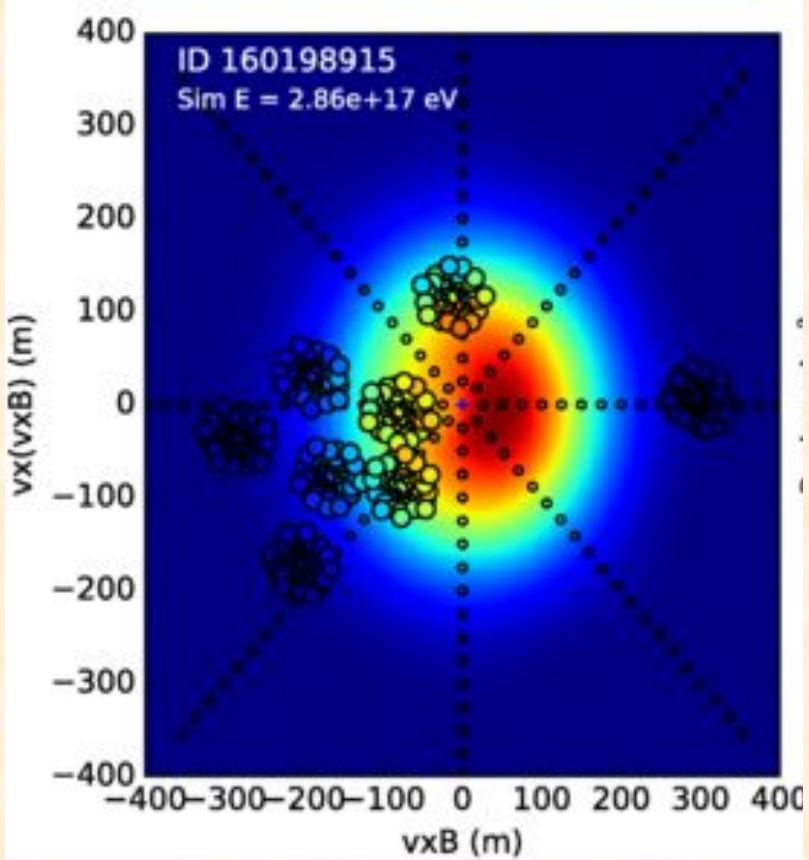
RF is asymmetric around particle core due to interference GM & CE

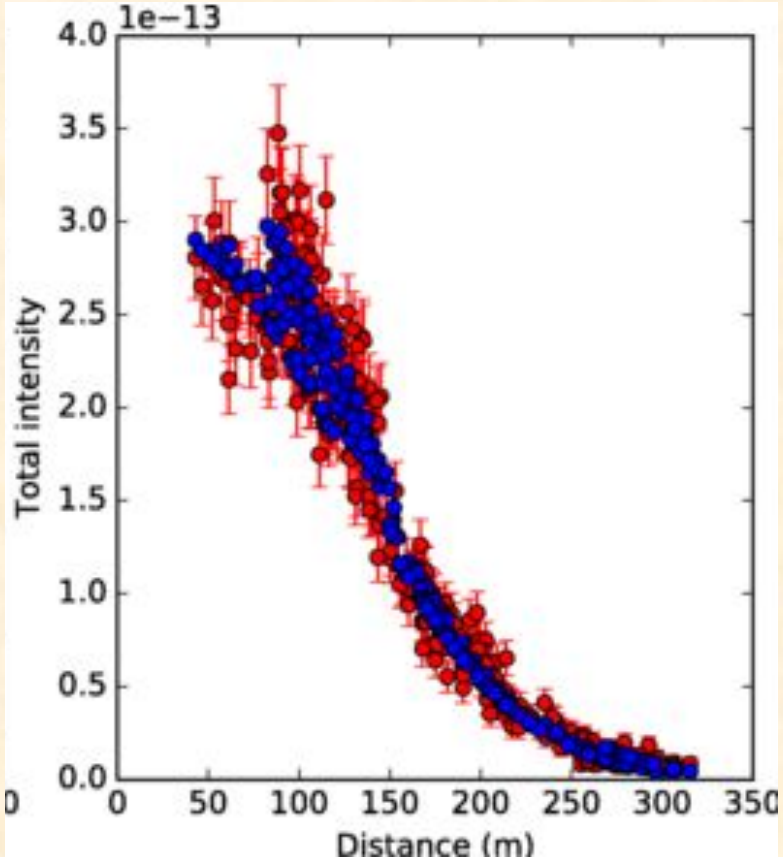


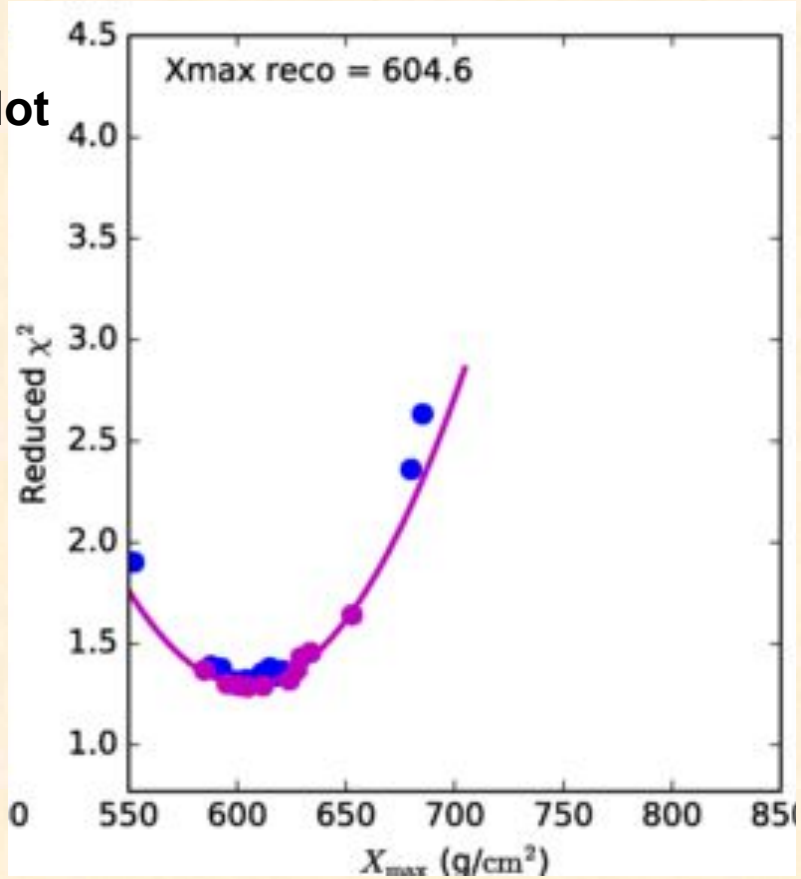
Microscopic (CoREAS) approach

For each measured event:
Perform about 30 CoREAS calculations and plot mean-square deviation from data v.s. X_max

Minimum chi-square defines value X_max
Typical result



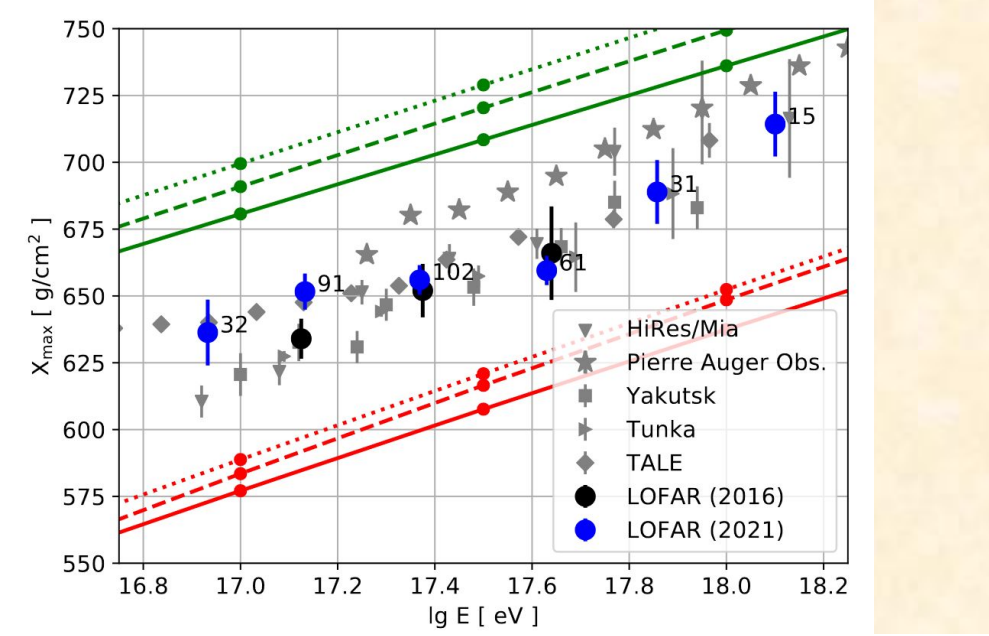


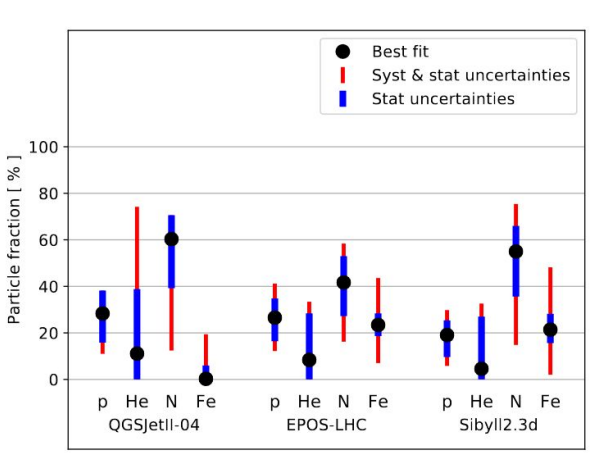


From A.Corstanje et al, PRD 103, 102006

Arthur's & Bjarni's results

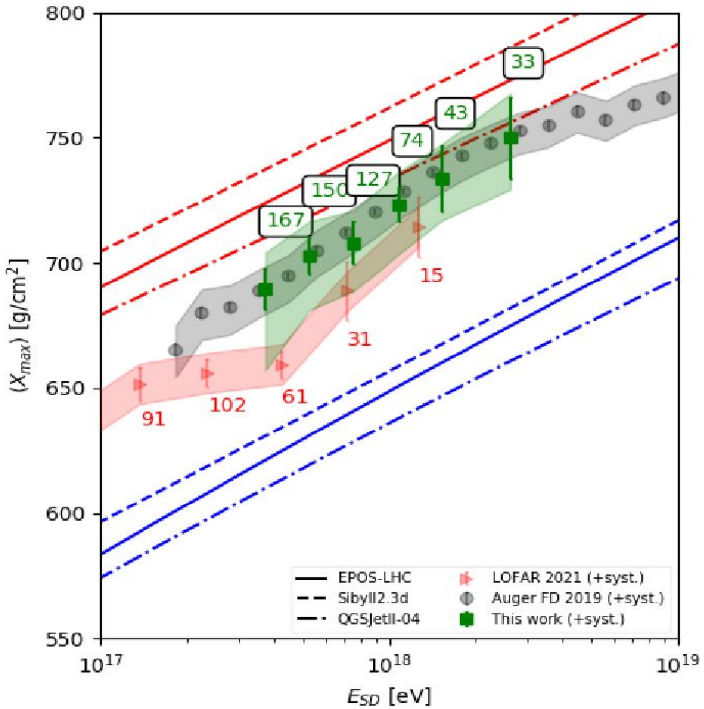
Arthur Corstanje (LOFAR)

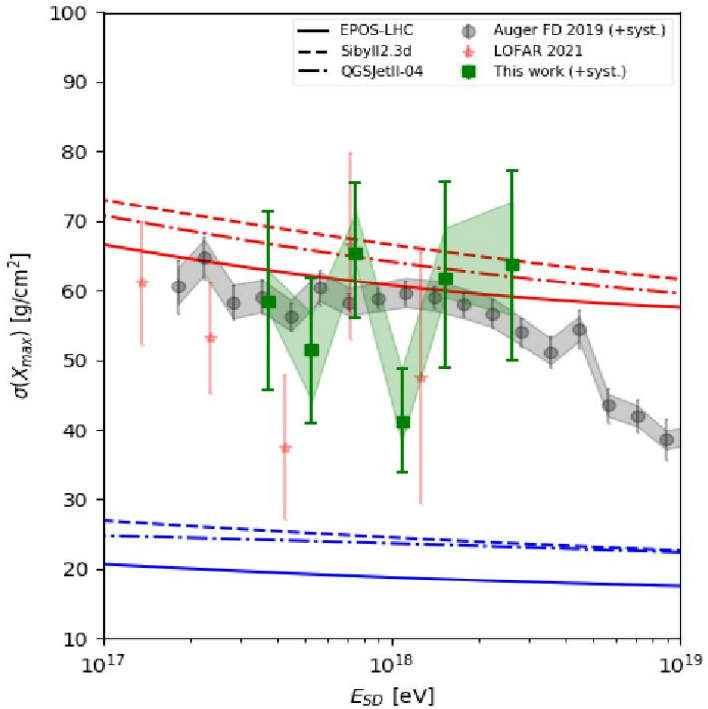




Physics:
Moderately heavy,
~ Nitrogen

Bjarni Pont (Pierre Auger Observatory, Engineering Radio Array)





Results obtained using CoREAS
Requires ~50 simulations per measured event
Each simulation ~ 24h CPU

Macroscopic approach

MGMR: radiation emitted from parametrized time-dependent charges & currents in air-shower pancake, moving with speed-of-light.

Fast & Insight in physics of radio emission:

Drift velocity proportional to inverse-square-root of air density:

$v_d \sim 1/\sqrt{\rho(\text{air})}$

Similar to terminal velocity of macroscopic particle in medium.

Maximum charge excess (proportional to ρ(air)) deeper in atmosphere then maximum of current. Slight arrival time (=phase) difference causes circular polarization of radio signal.

Stokes parameters: I, Q, U, V

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

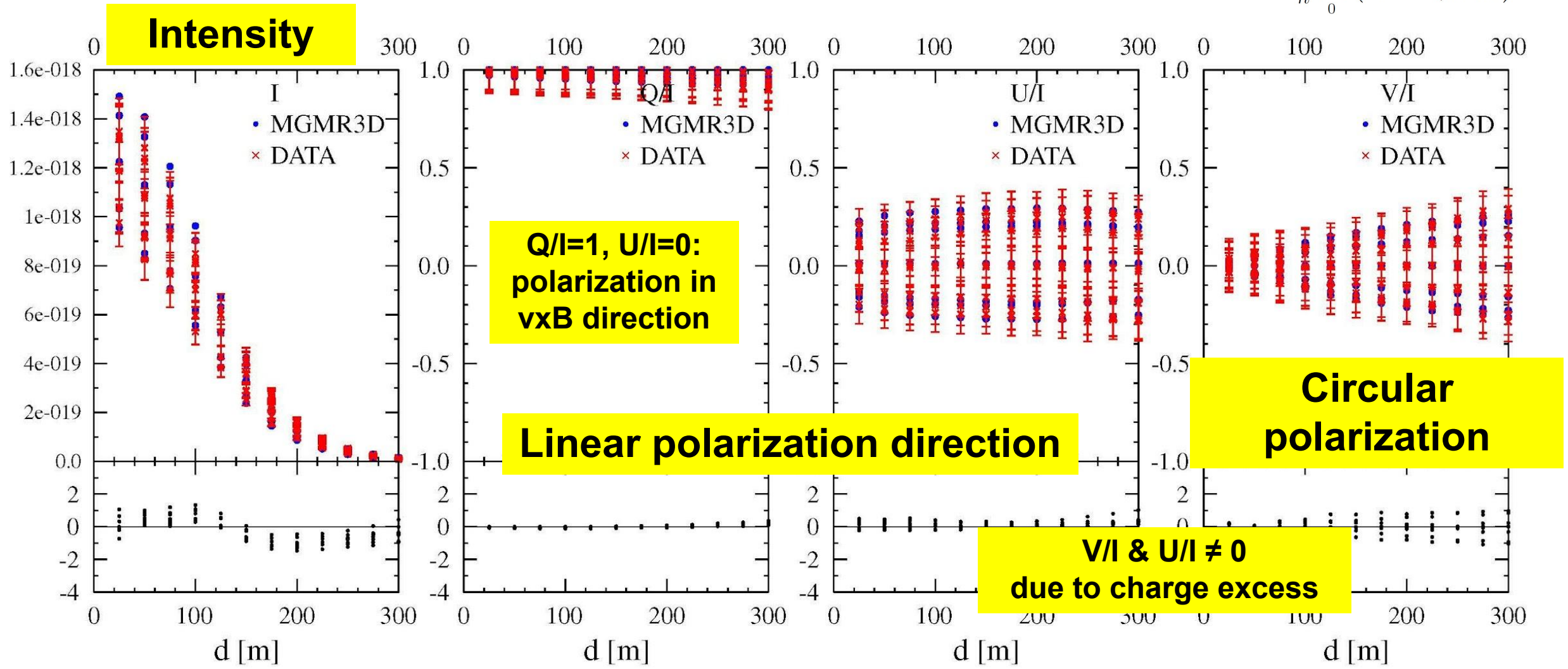
Circular polarization = V/I

Fairweather MGMR3D - CoREAS

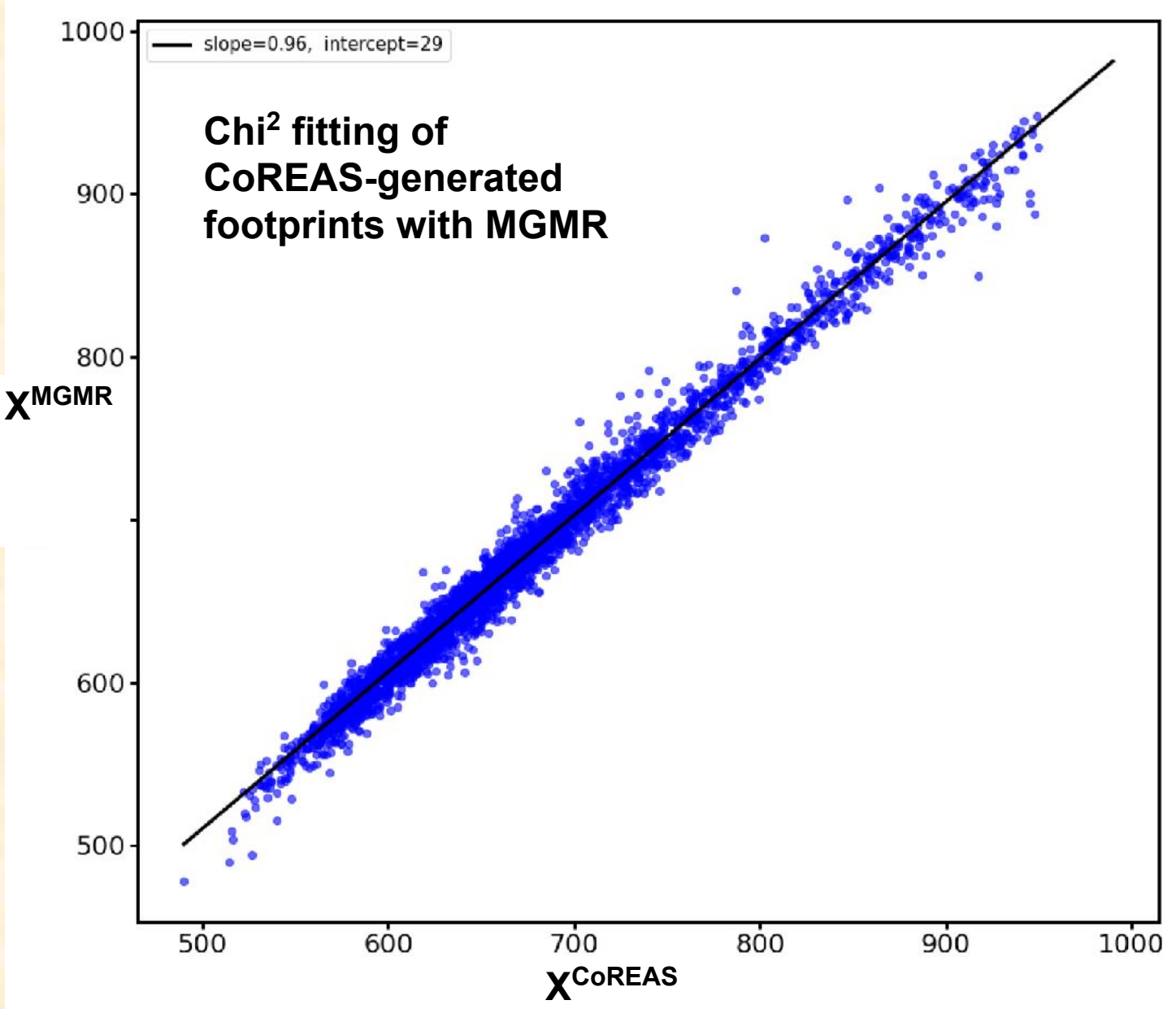
$$I = \frac{1}{n}\sum_{0}^{n-1}\left(|\mathcal{E}|^2_{i,\vec{v}\times\vec{B}} + |\mathcal{E}|^2_{i,\vec{v}\times\vec{v}\times\vec{B}}\right)$$

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

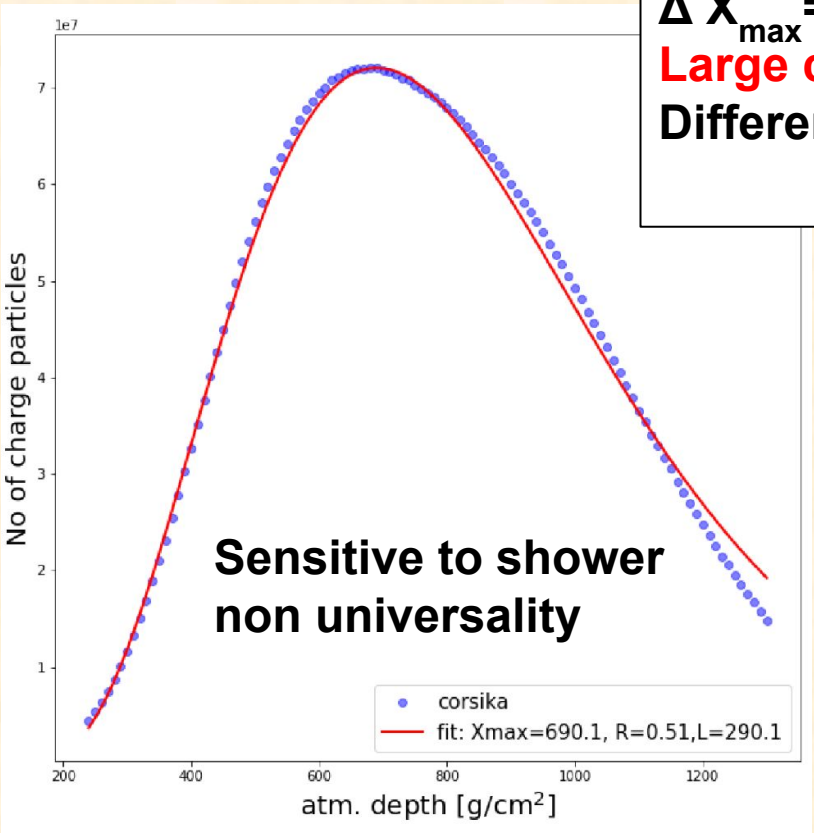
$$U + iV = \frac{2}{n}\sum_{0}^{n-1}\left(\mathcal{E}_{i,\vec{v}\times\vec{B}}\mathcal{E}^*_{i,\vec{v}\times\vec{v}\times\vec{B}}\right) .$$



Comparison for many CoREAS showers



Usually good fit with few exceptions:



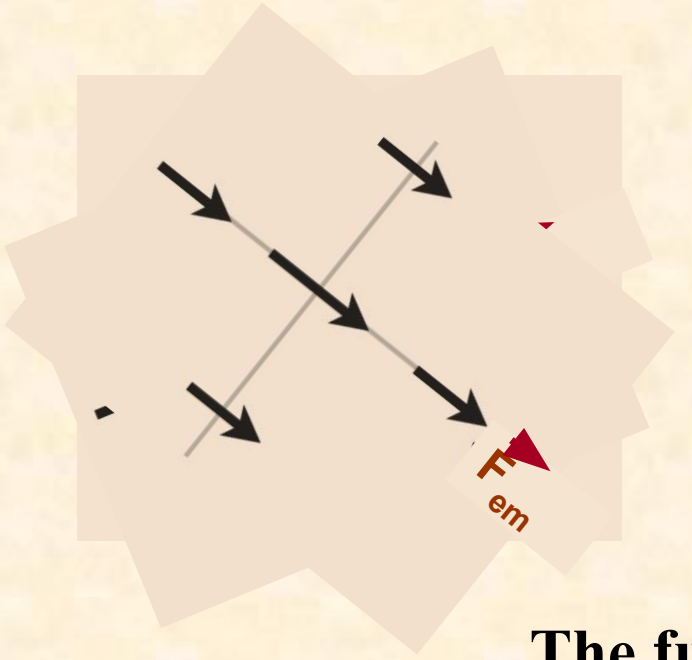
ΔX_{max} = 60 g/cm²
Large chi²
Different profile

- **More shower parameters, beyond X_{max} can be extracted**

Atmospheric electric fields

Transverse current:

- Electrons & positrons have transverse drift, induced by EM force.
- Multi-directional along $F_{em} = v \times B + E(h)$
- Direction and magnitude E depends on height
- Current determined by component perp to shower direction

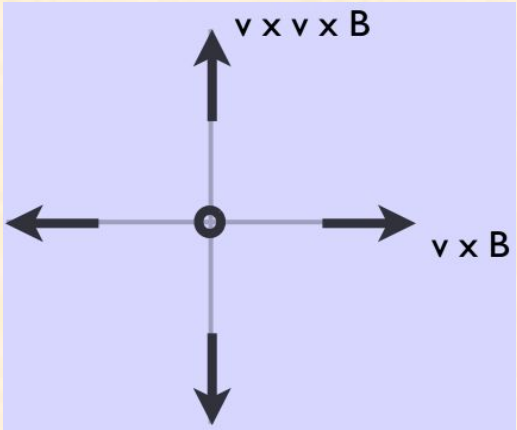


Upper E(h)=0
Middle E(h)≠0
lower height

The full signal: superposition of all

 # Charge excess:

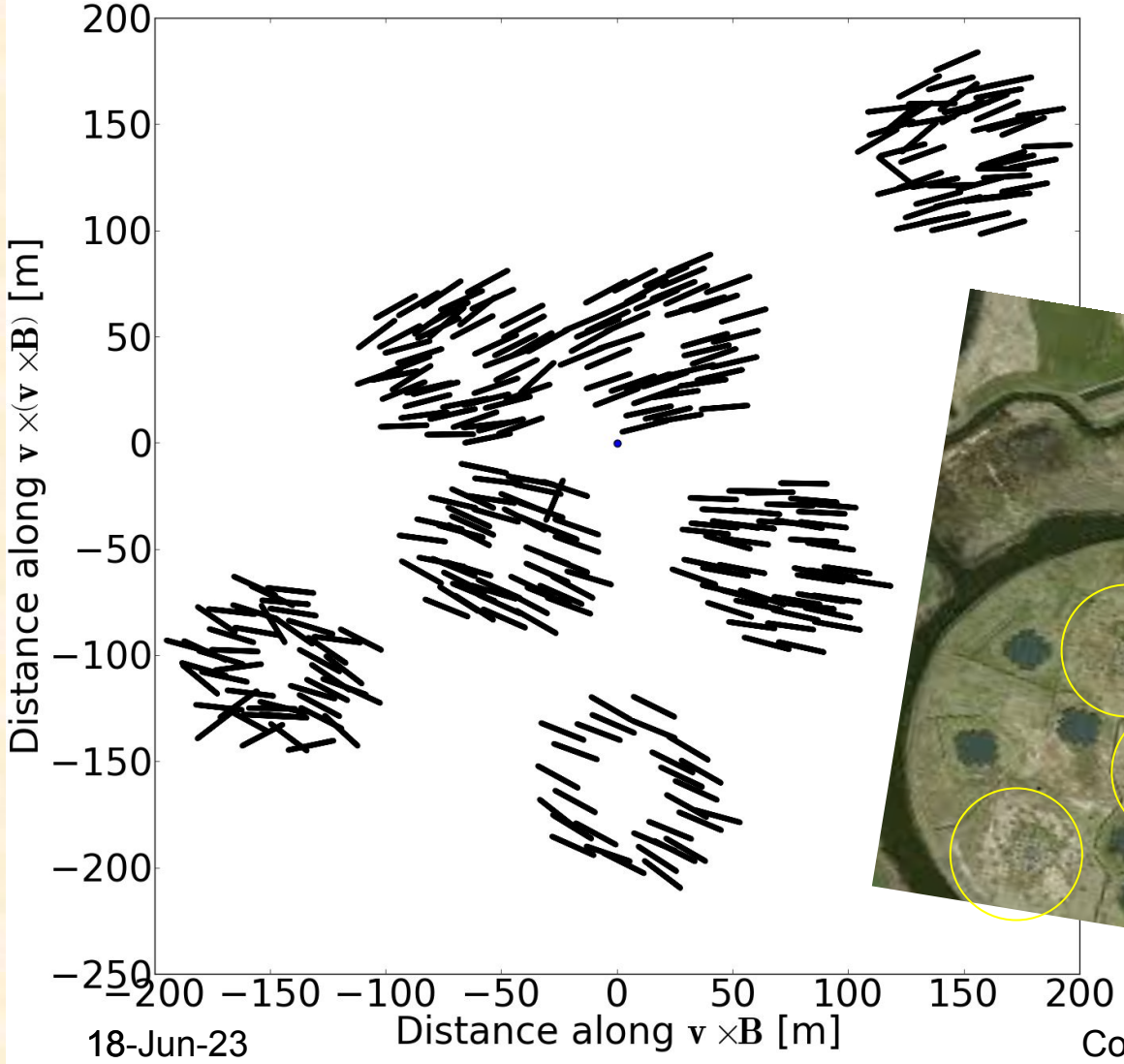
- Linearly polarized, radially from shower axis

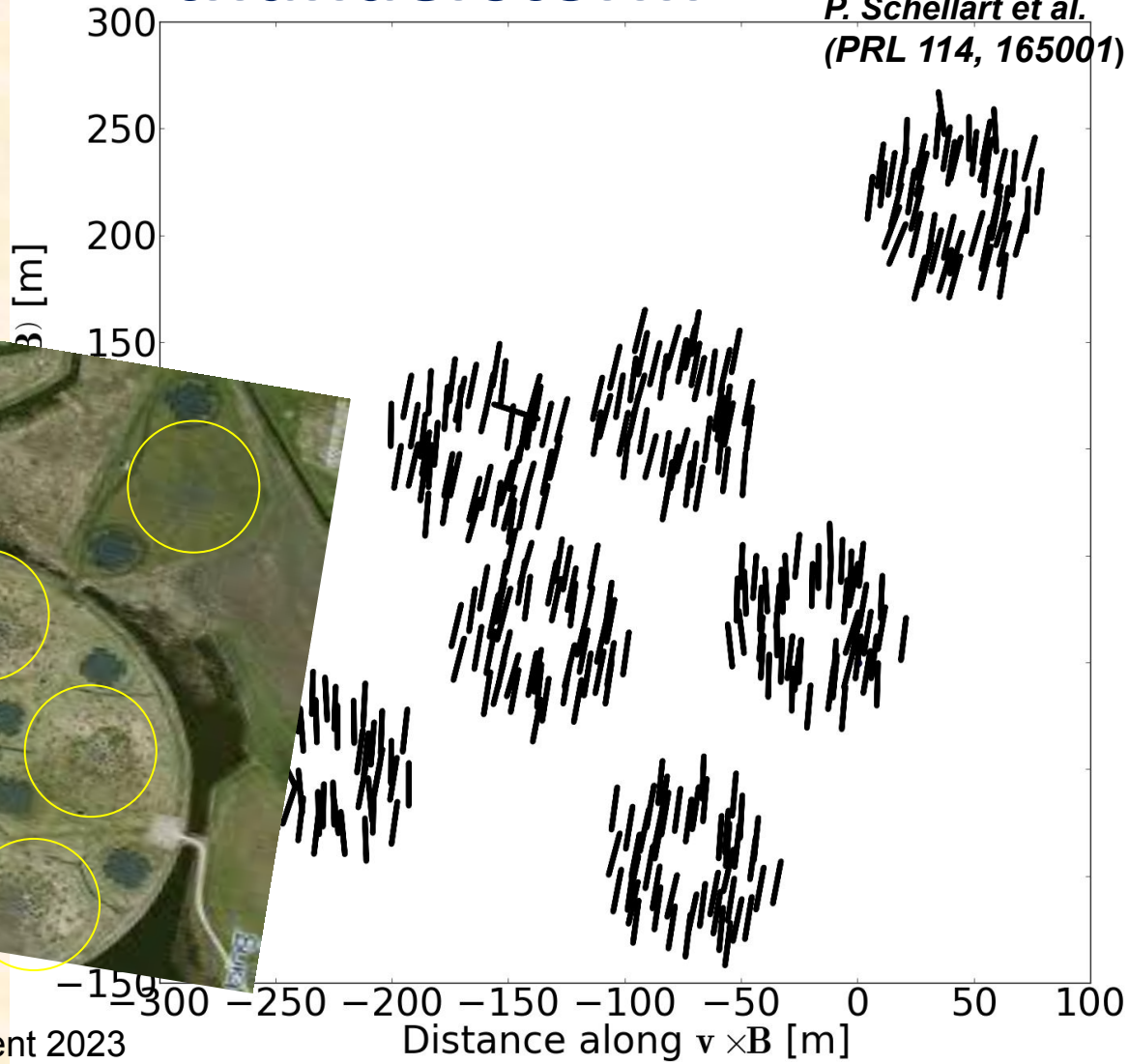


Gia Trinh et al. Phys. Rev. D 93, 023003 (2016); arXiv:1511.03045

Observations; polarization footprint

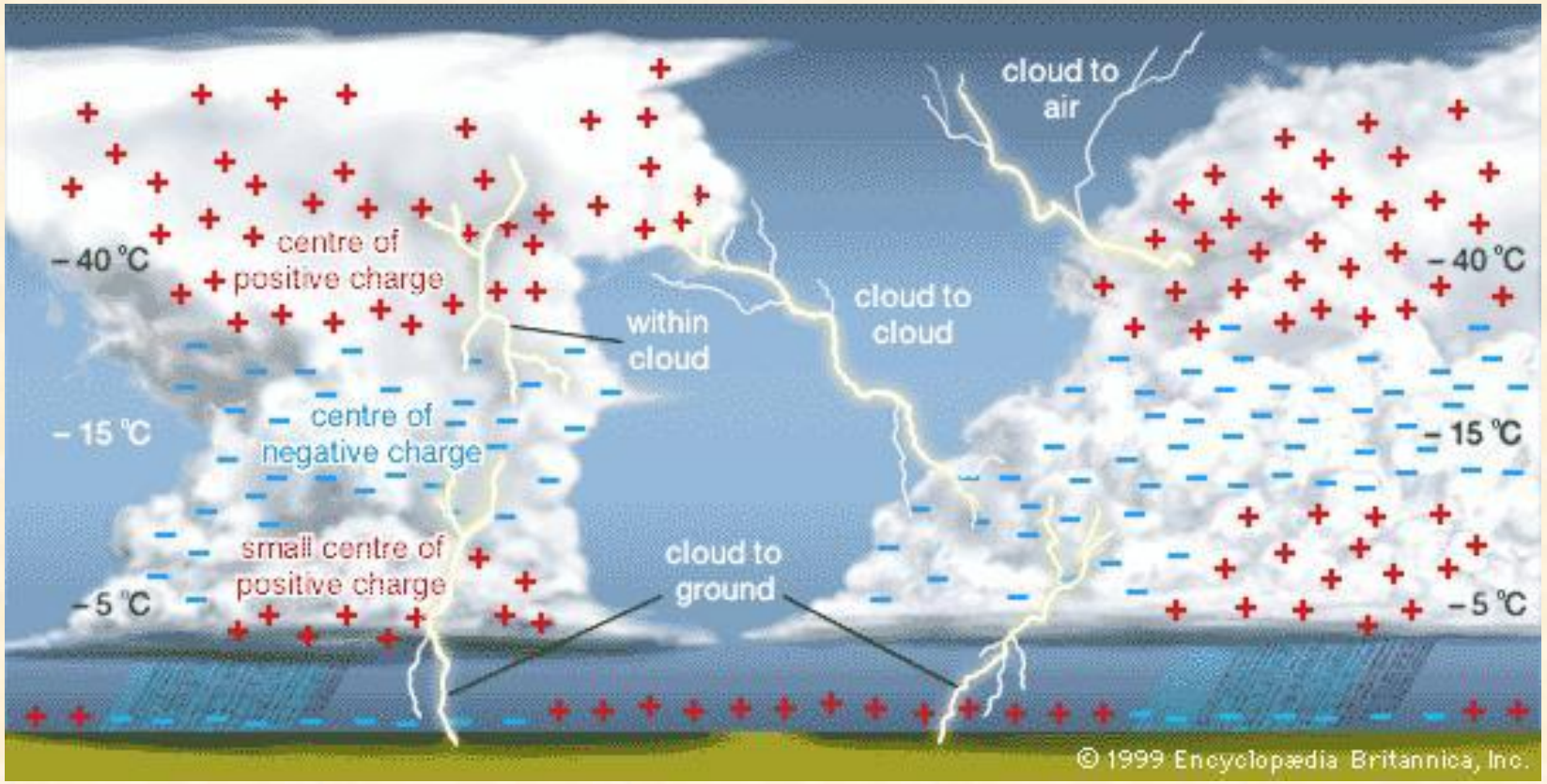
Fair weather vs thunderstorm

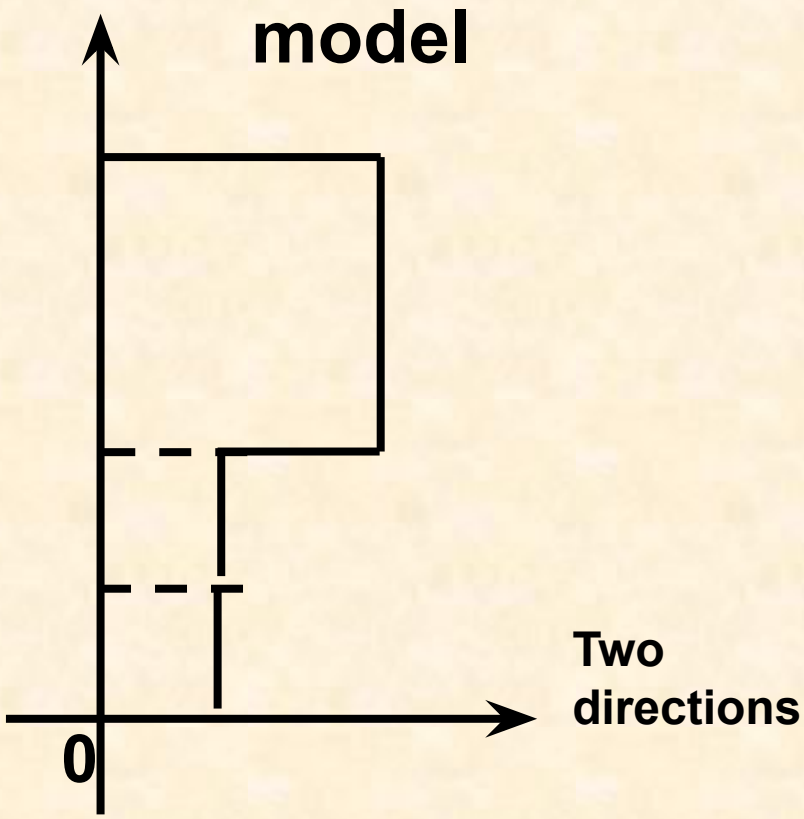




P. Schellart et al. (PRL 114, 165001)

Determining atmospheric electric fields





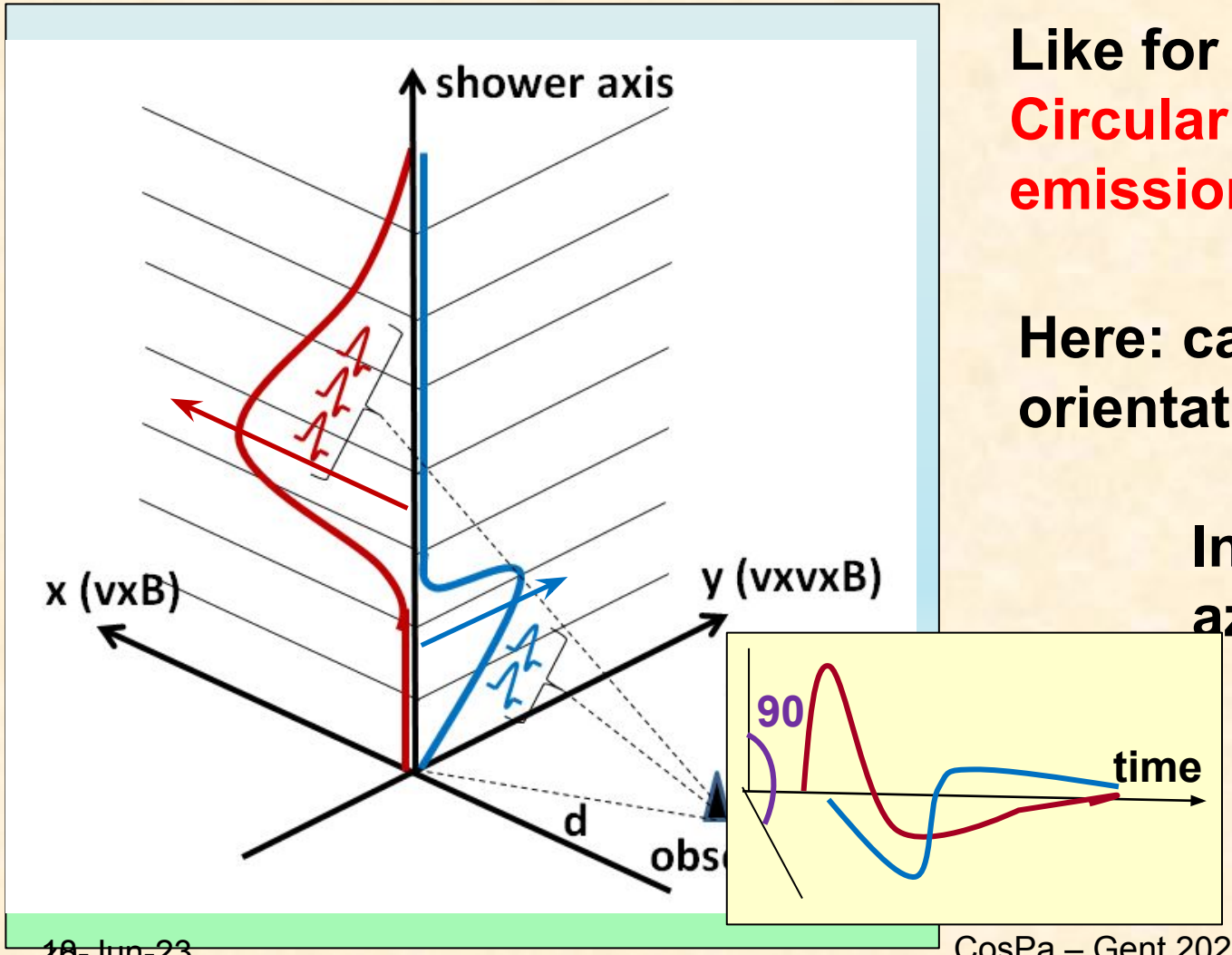
Challenge: **Many parameters □ grid search cumbersome**

Levenberg-Marquardt minimization requires: Fast & Deterministic code

Use MGMR

Physics for thunderstorm events

Atmospheric fields induce electric currents in shower plasma



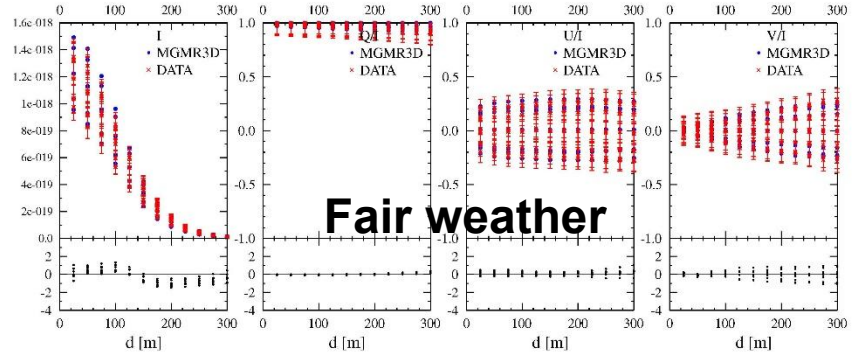
Like for Fair Weather:
Circular polarization due to emission-height differences.

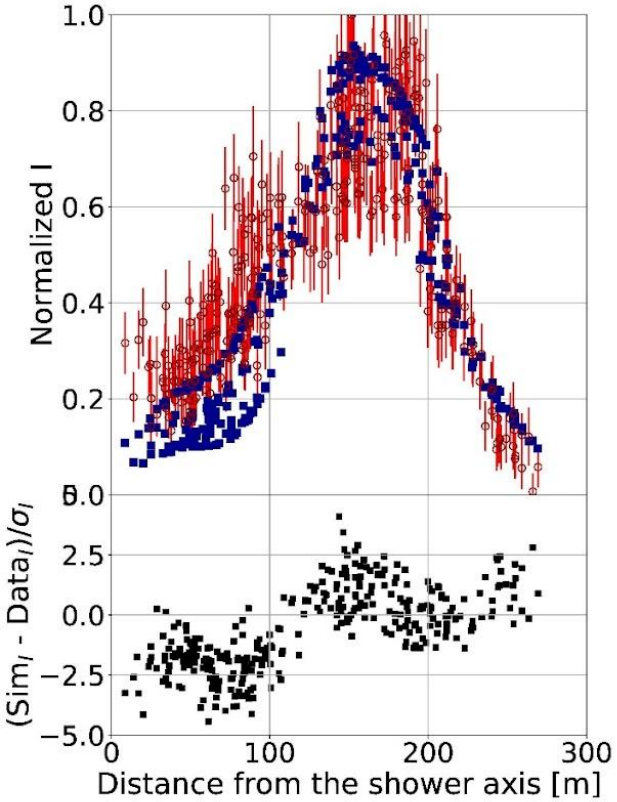
Here: caused by height dependence of orientation of atmospheric fields.

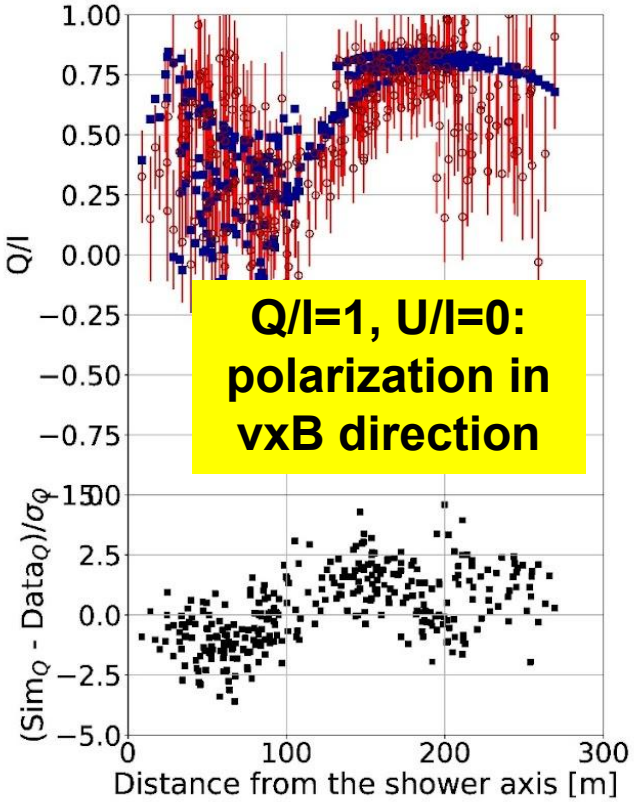
Independent of azimuth position.

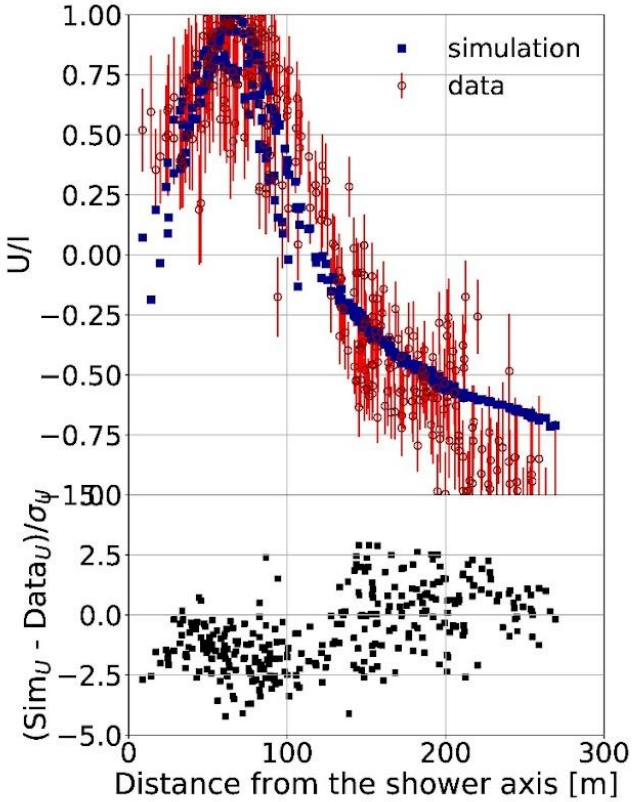
A Thunderstorm event (#7)

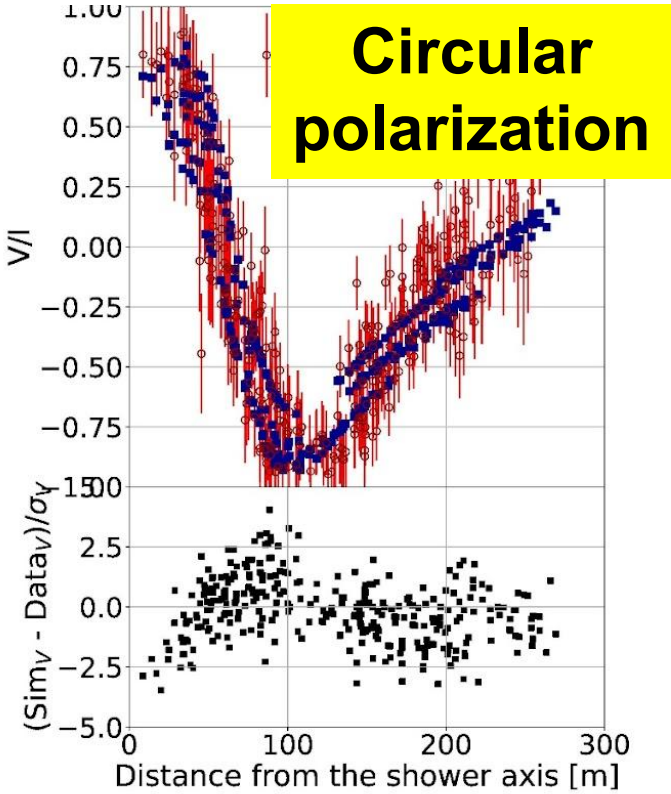
Dots: best fit calculation







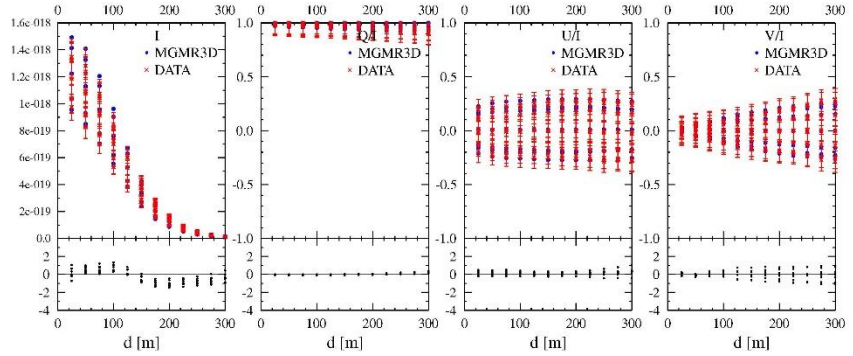


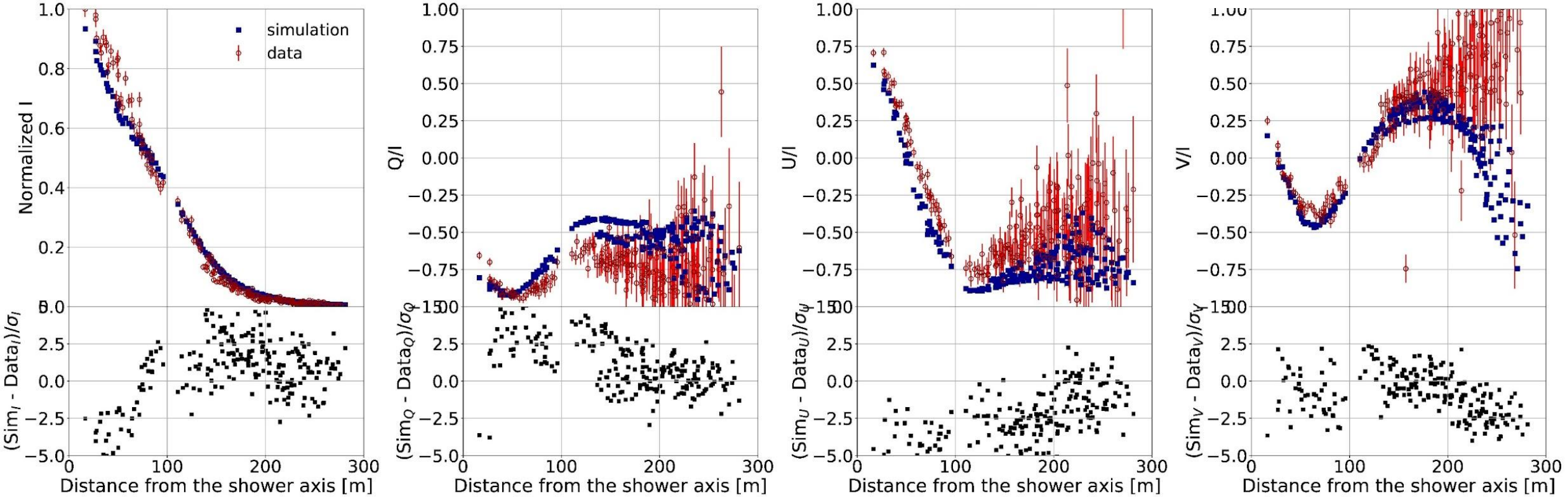


Footprint determined by atmospheric electric fields;
invert problem to find the fields

A Thunderstorm event (#9)

Dots: best fit calculation

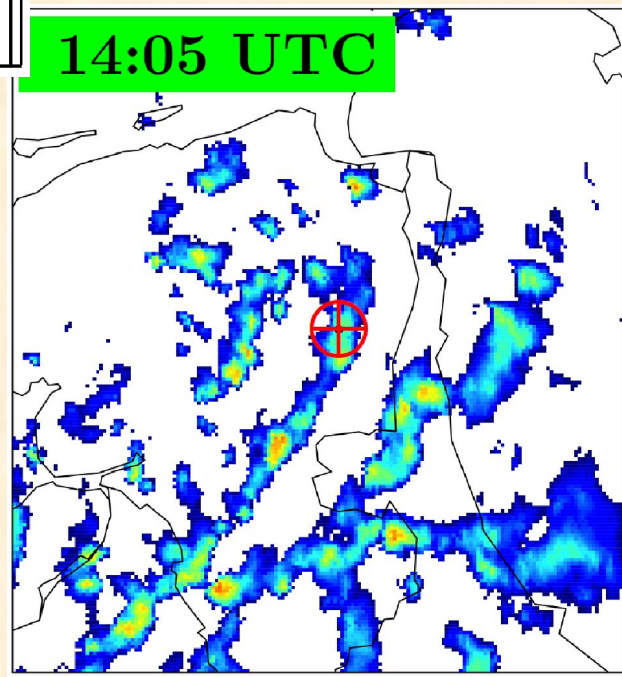




Footprint determined by atmospheric electric fields;
invert problem to find the fields

Analysis - Tomography

event A – event B	$\mathbf{E}_A \cdot (e_{\mathbf{v}_A \times \mathbf{v}_B})$	$\mathbf{E}_B \cdot (e_{\mathbf{v}_A \times \mathbf{v}_B})$	$\mathbf{E}_z$	$\mathbf{E}_z$	height
Top – Top	43	10	-94	-95	≈8 km
Middle – Middle	-2	13	113	114	3.5 km
Bottom – Bottom	4	-9	-15	-15	1.5 km



Radar reflectivity

Relate to atmospheric data and charge structure:

Radar top	8.8 km	Top positive charge	8 km
-10 degree	4.2 km	Main negative charge	3.5 km
Freezing	2.5 km	lower positive charge	1.5 km

Summary

- Field is very young, developed fast
- Modern (digital) radio detection started in 2003
- Understanding in terms of geomagnetic (transverse current) & charge excess radiation (with Cherenkov effects) from 2008
- Precise detection & interpretation of radio footprint (with LOFAR) in 2014
- Complementary Microscopic and Macroscopic approaches

- Present: major roll-out of radio detection GRAND, Pierre Auger Observatory, IceCube & RNO-G, SKA

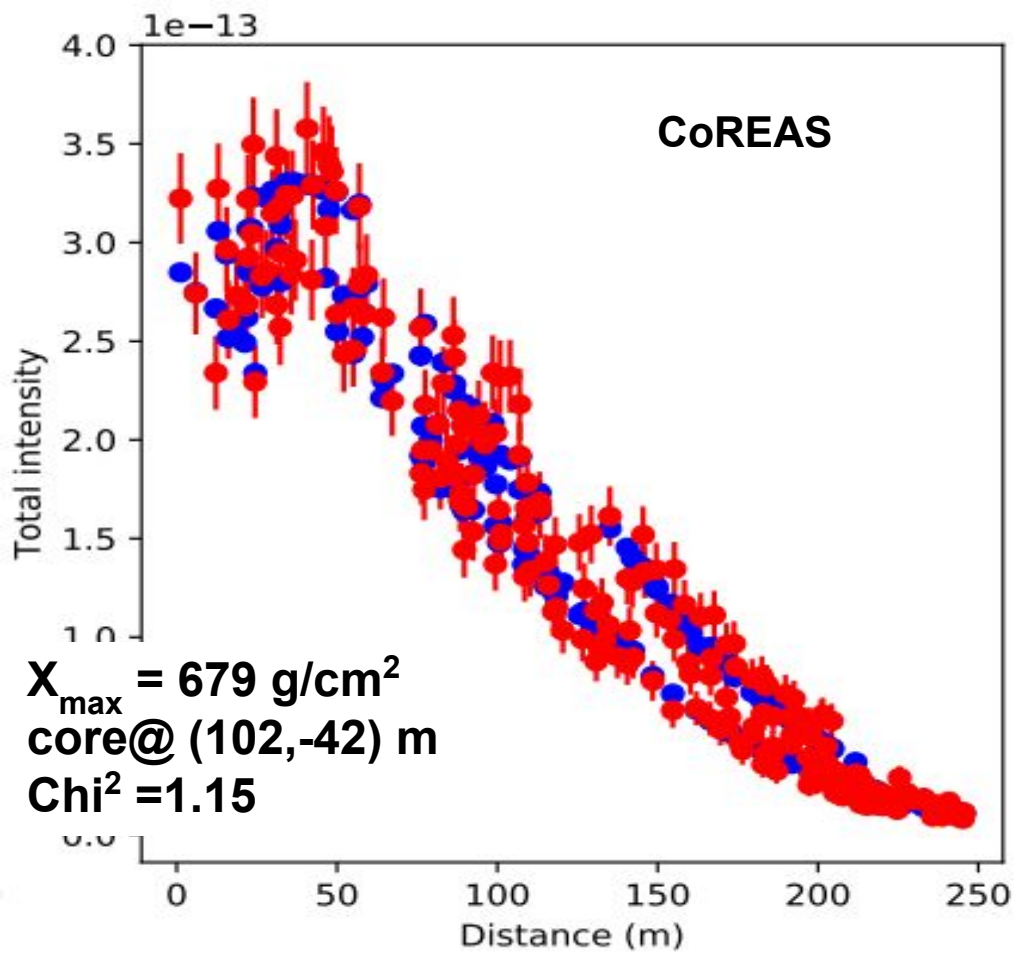
LOFAR lightning physics:

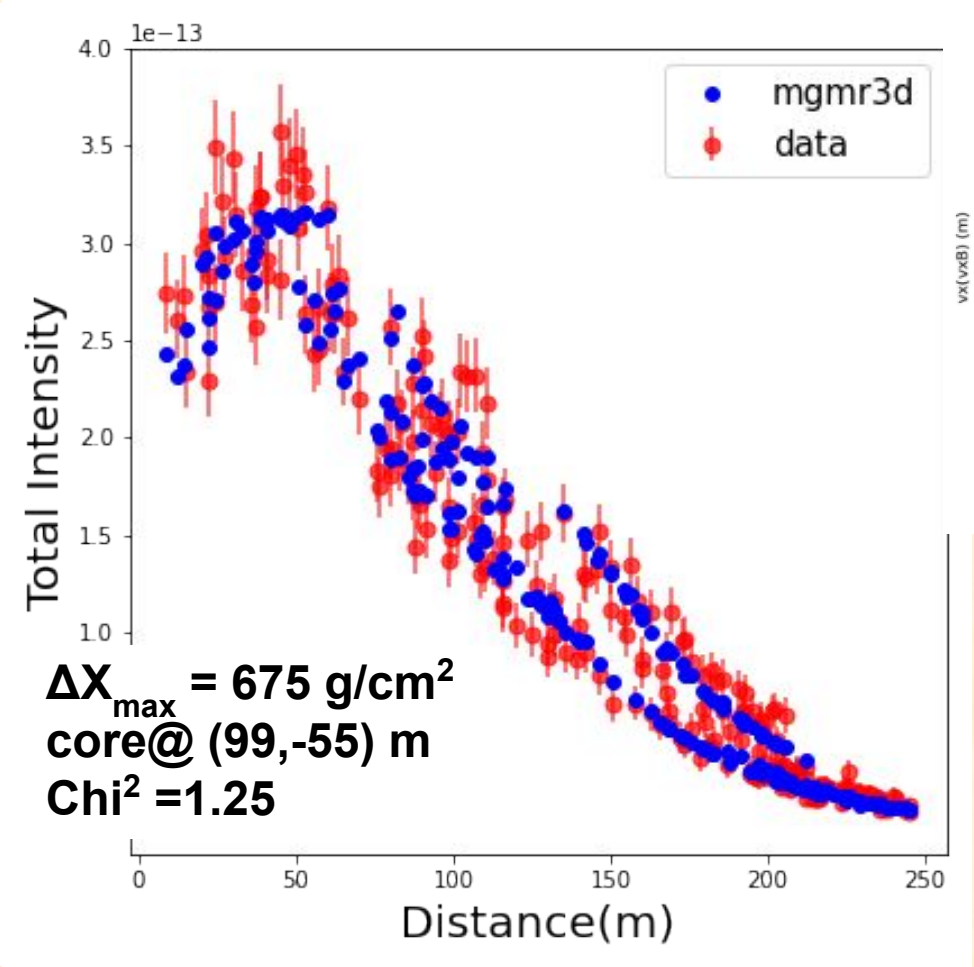
1) Non-intrusive E-field determination
2) Nano-second LMA

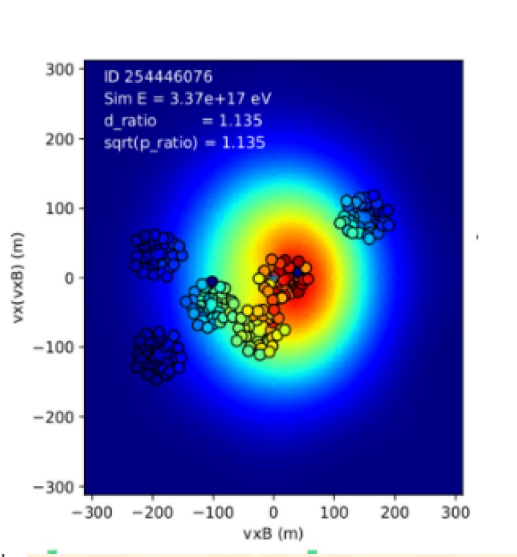
B. Hare et al., Nature 568, 360–363 (2019)

Applying to LOFAR data

Compare results CoREAS and MGMR based analyses of LOFAR data.
Fit: Energy, X_{max}, & Core position. Compare extracted parameters for all 270 quality events.

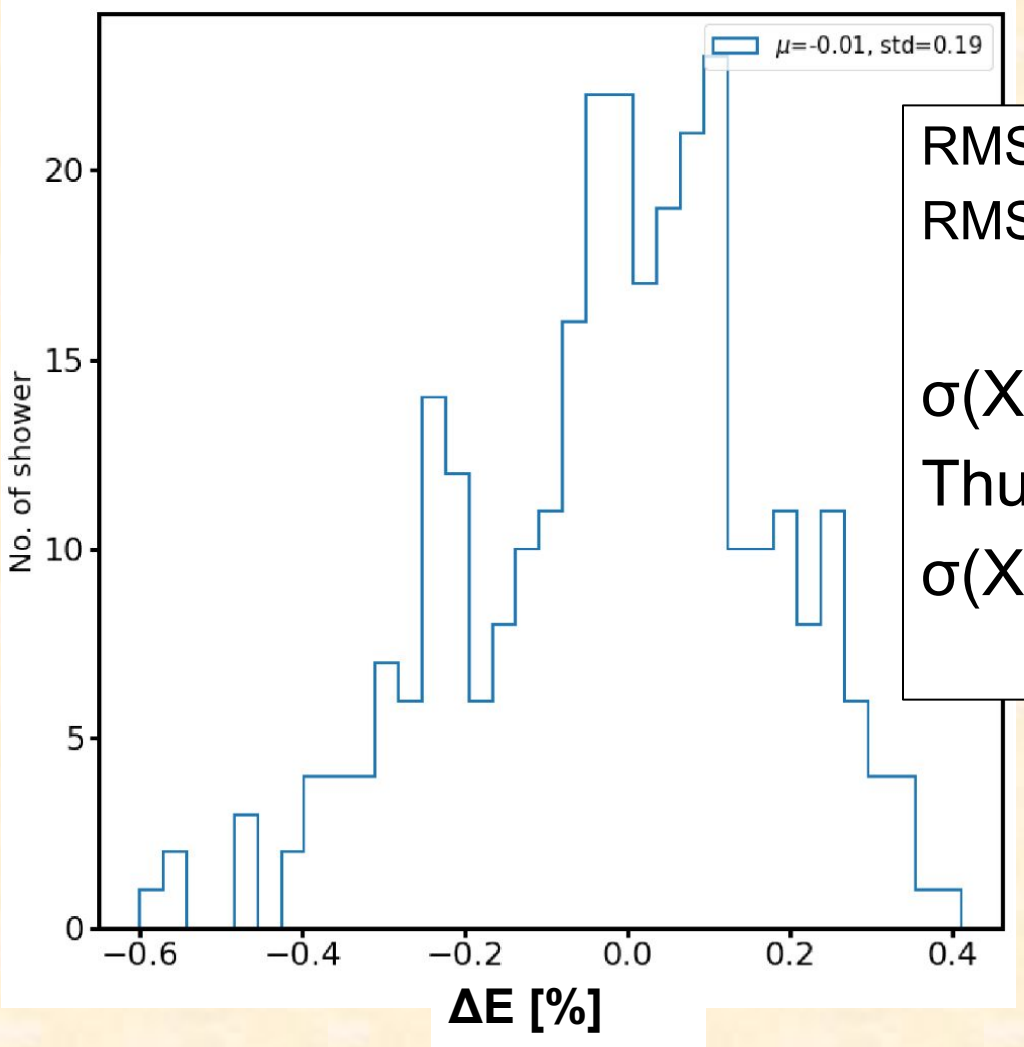






Applying to LOFAR data

Compare results CoREAS and MGMR based analyses of LOFAR data.
Fit: Energy, X_{max}, & Core position. Compare extracted parameters for all 270 quality events.



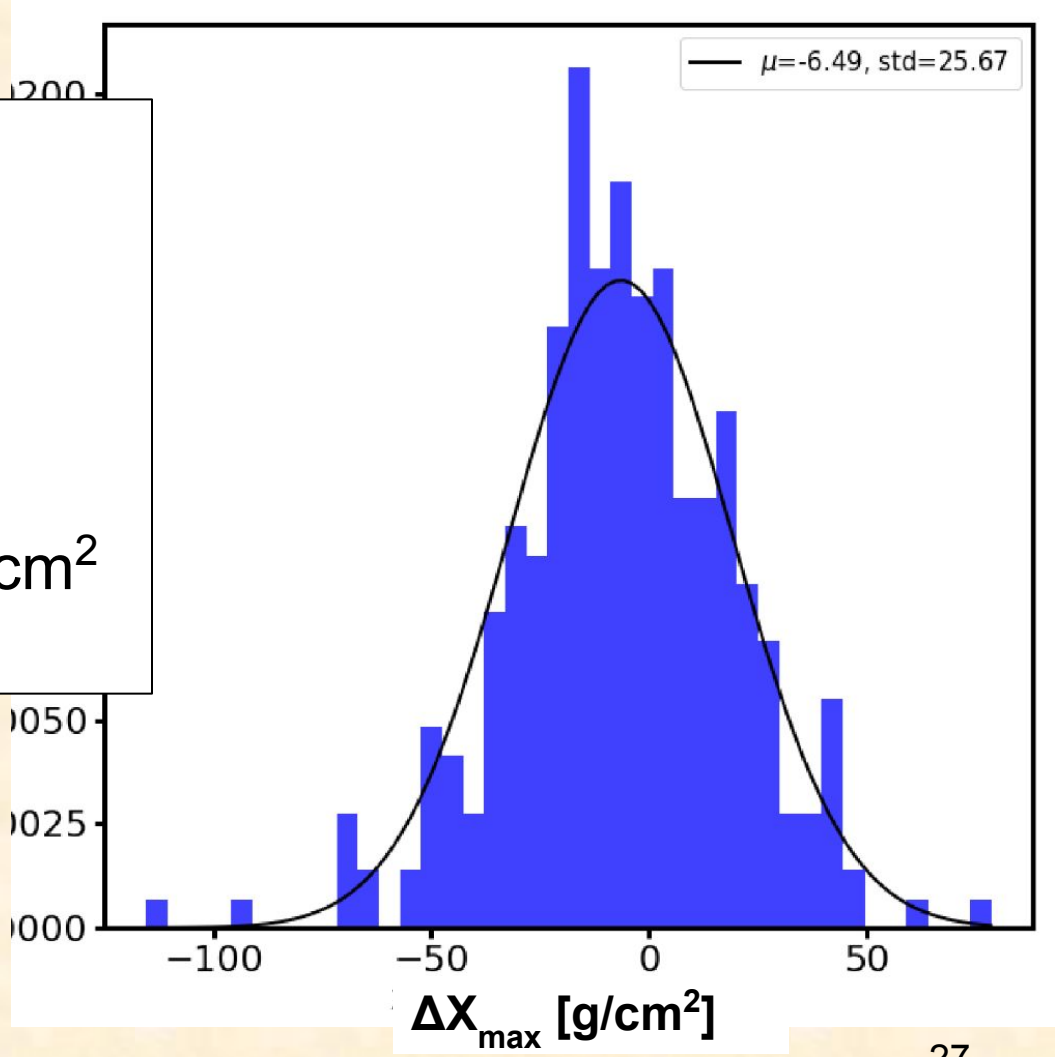
RMS(ΔE)=19%

RMS(ΔX_{max})=26 g/cm^2

$\sigma(X_{max}^{CoREAS})$=14.5

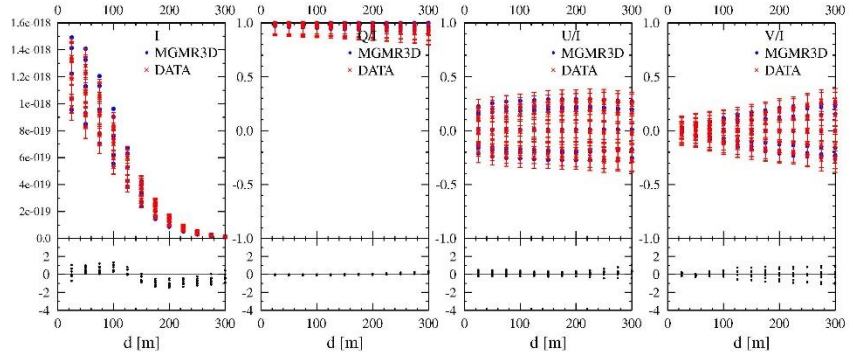
Thus

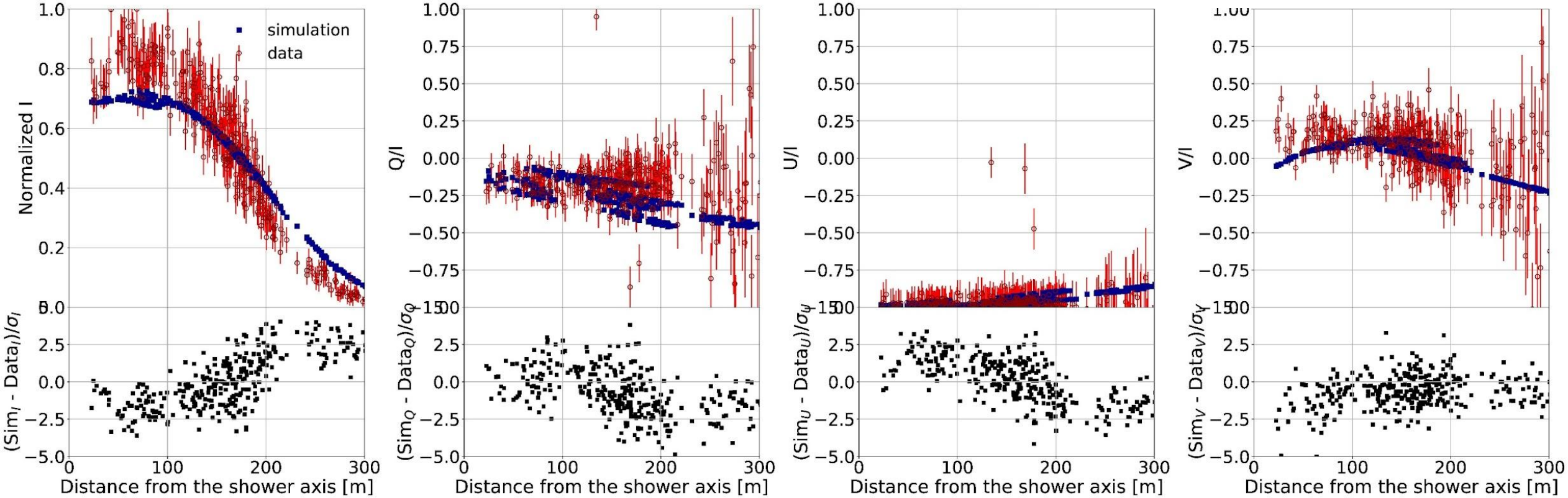
$\sigma(X_{max}^{MGMR})$=22.5 g/cm^2



A Thunderstorm event (#6)

Dots: best fit calculation

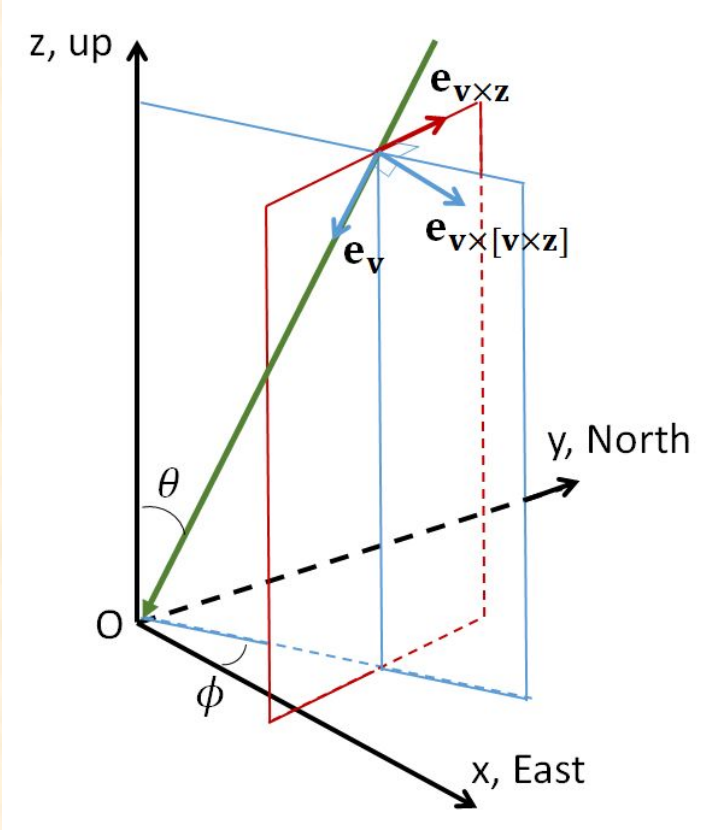




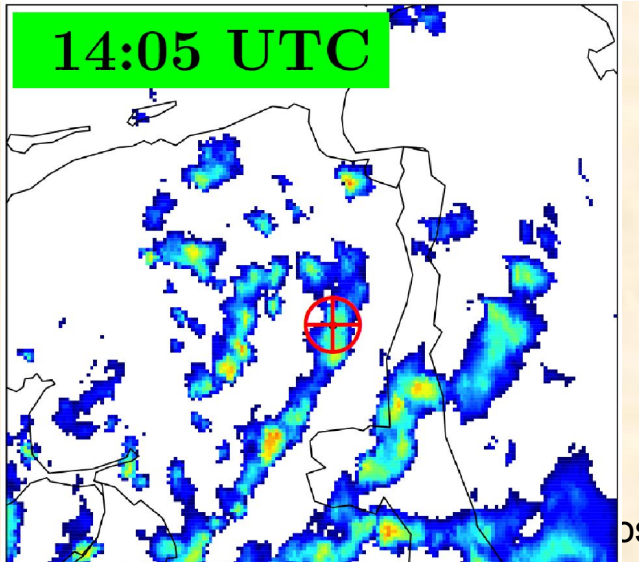
Footprint determined by atmospheric electric fields;
invert problem to find the fields

Analysis of two events (#6, #7)

Event	A			B		
Time 26/08/2012	13:52:23 UTC			14:02:56 UTC		
(θ, ϕ)	$(23°, 144°)$			$(18°, 310°)$		
Energy [eV]	4.4×10^{16}			3.9×10^{16}		
Layer	h [km]	$E_{\mathbf{v}\times\mathbf{z}}$ [kV/m]	$E_{\mathbf{v}\times(\mathbf{v}\times\mathbf{z})}$ [kV/m]	h [km]	$E_{\mathbf{v}\times\mathbf{z}}$ [kV/m]	$E_{\mathbf{v}\times(\mathbf{v}\times\mathbf{z})}$ [kV/m]
1	9.1	-47.3	32.3	5.8	14.1	26.2
2	4.0	1.9	2.7	3.4	1.0	-82.5
3	1.2	-4.3	-0.6	1.7	-6.9	11.6



radar reflectivity



Two events in 10 minutes, through same cloud

Conclusions

- MGMR offers an fast alternative for analyzing shower radio footprints for
  - Fair weather events to extract air shower profile
  - Thunderstorm events to extract atmospheric electric fields

Some relevant Publications:

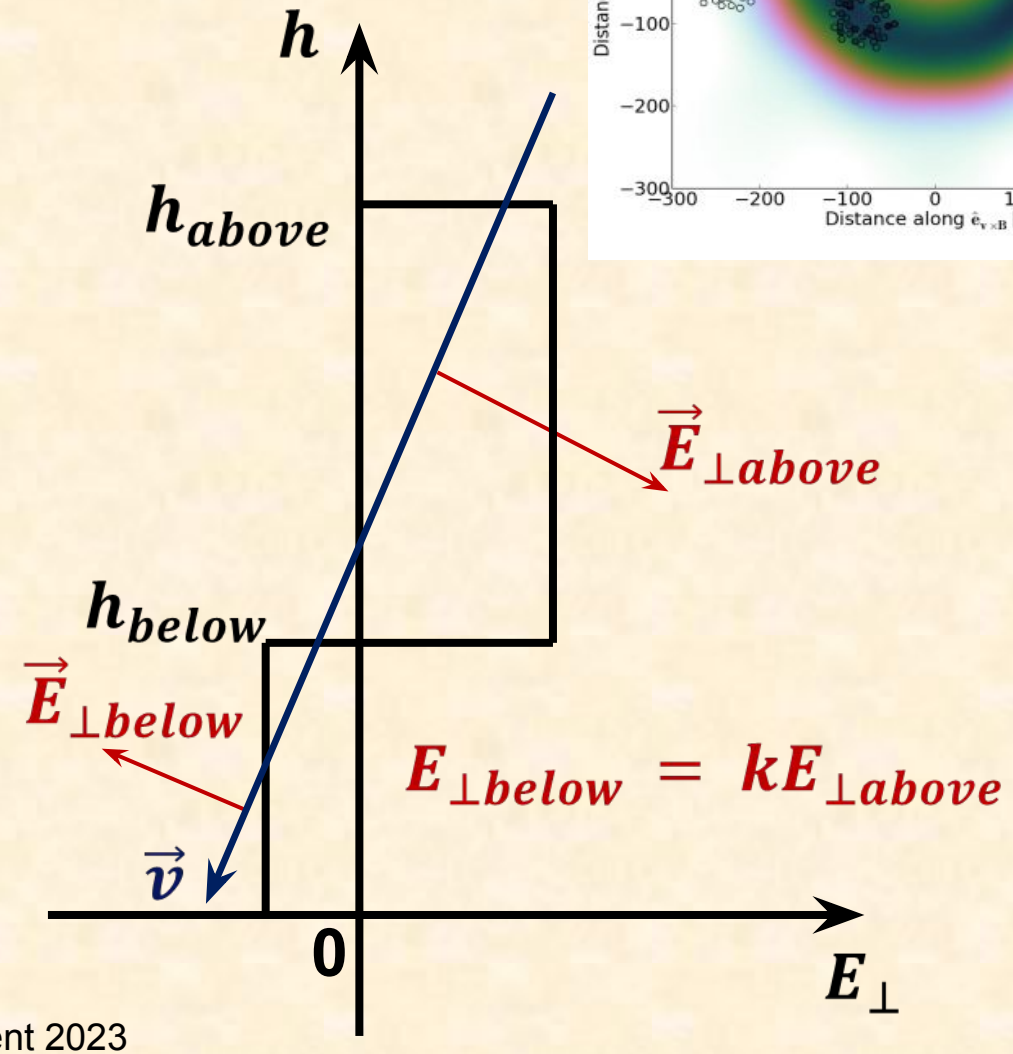
- **Gia Trinh** et al., *Influence of Atmospheric Electric Fields on the Radio Emission from Extensive Air Showers*., Phys. Rev. D 93, 023003 (2016); arXiv:1511.03045.
- **Gia Trinh** et al., Thunderstorm electric fields probed by extensive air showers through their polarized radio emission. Phys. Rev. D, 95 (2017) 083004
- Olaf Scholten et al,, Analytic calculation of radio emission from parametrized extensive air showers: A tool to extract shower parameters. Phys. Rev. D, 97 (2018) 023005
- **Gia Trinh** et al., *Determining electric fields in thunderclouds with the radiotelescope LOFAR*, JGR 125, e2019JD031433 (2020).
- **Gia Trinh** et al., *Determining atmospheric electric fields using MGMR3D*. Phys. Rev. D105, 063027 (2022)
- **Pragati Mitra**, *High precision reconstruction of air shower properties with dense radio arrays*, PhD thesis VUB 2021 and in preparation.

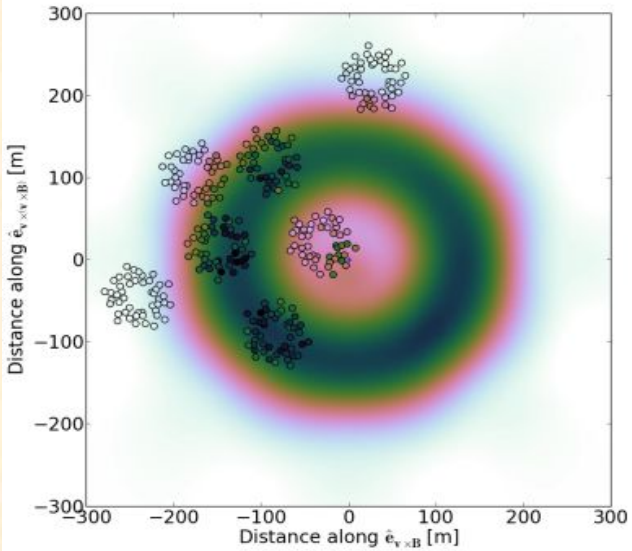
P. Schellart , T.N.G. Trinh et al.
(PRL 114, 165001)

Fitting the intensity

E_a

E_b



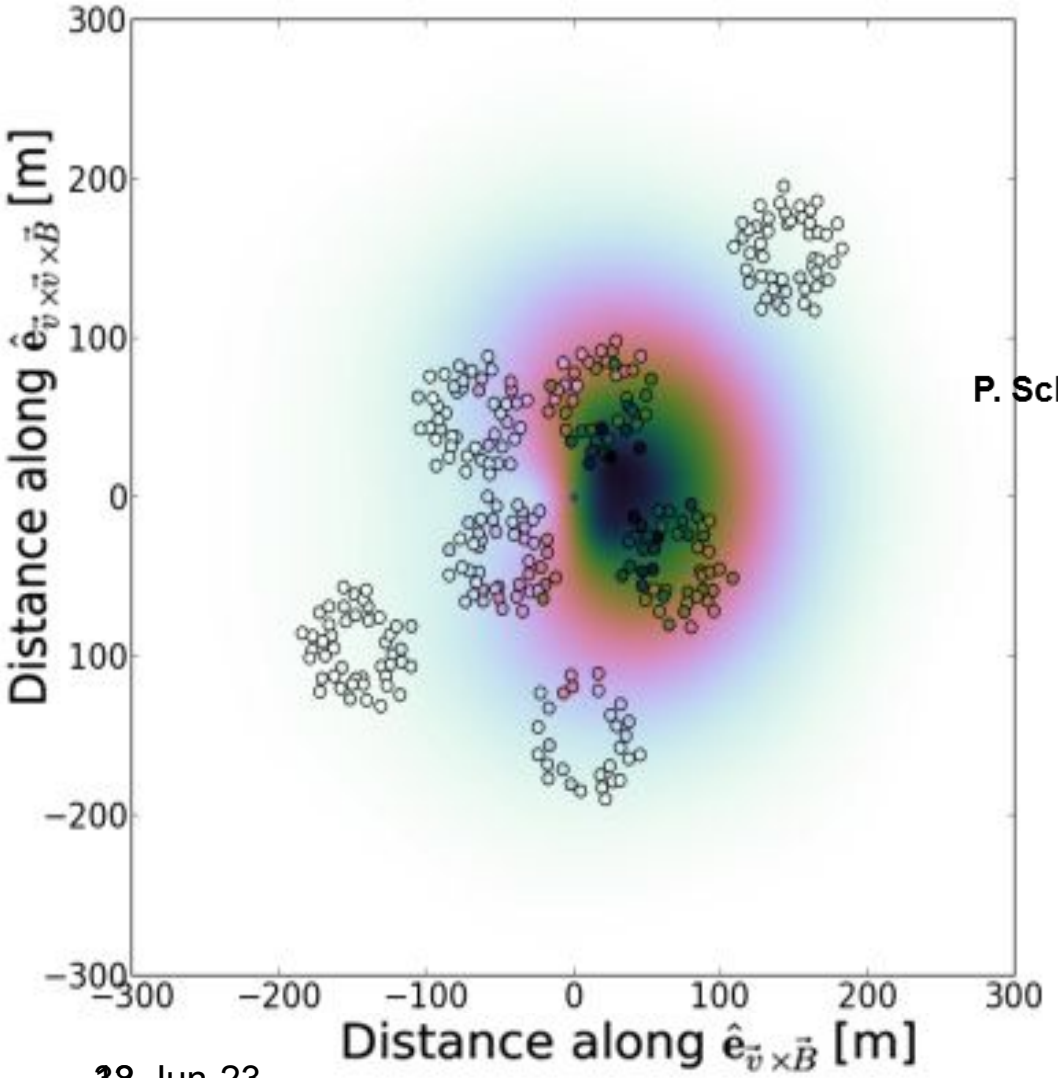


Observations; intensity footprint

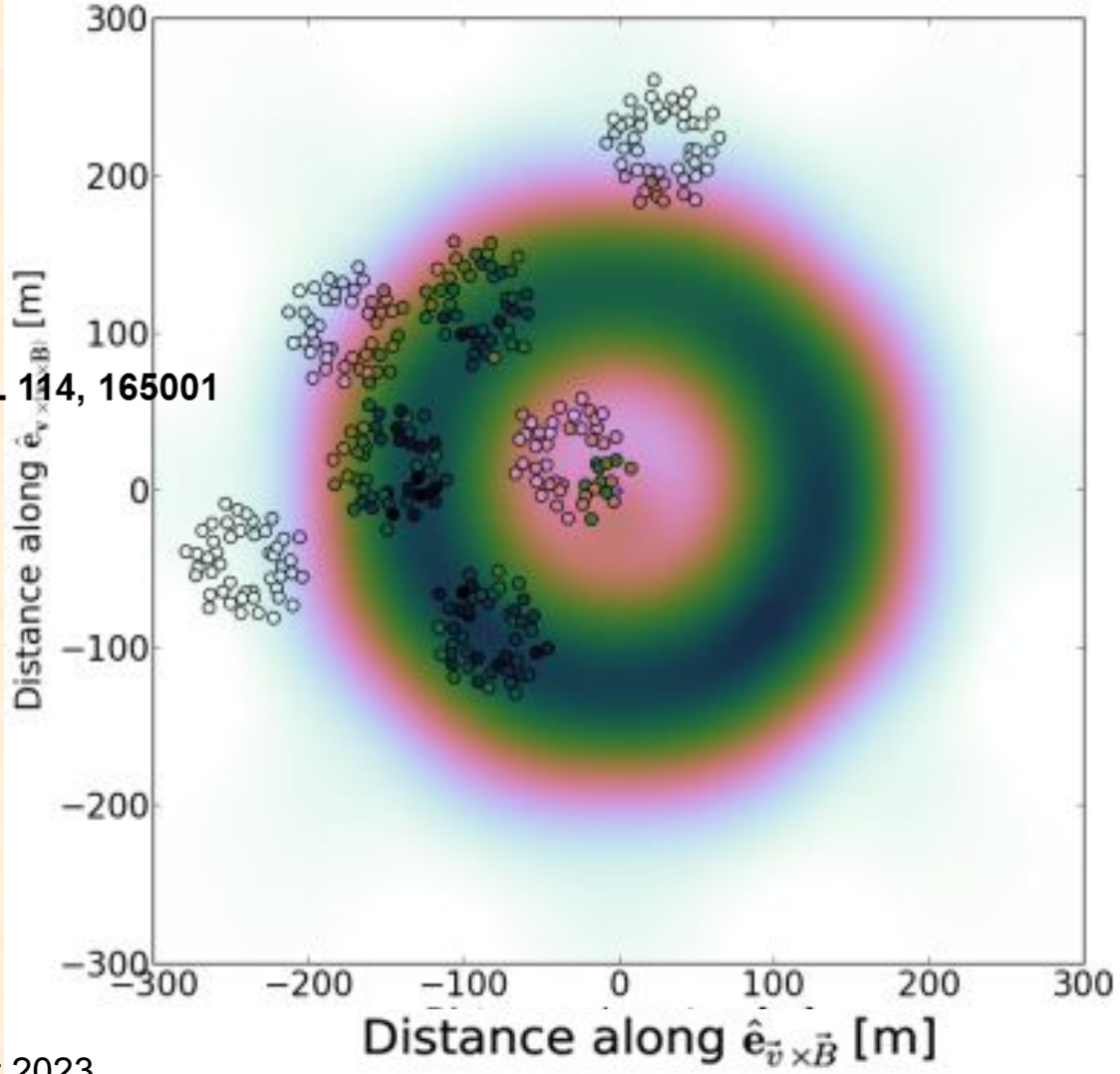
S. Buitink et al.
PRD 90, 082003 (2014)

Fair weather vs thunderstorm

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

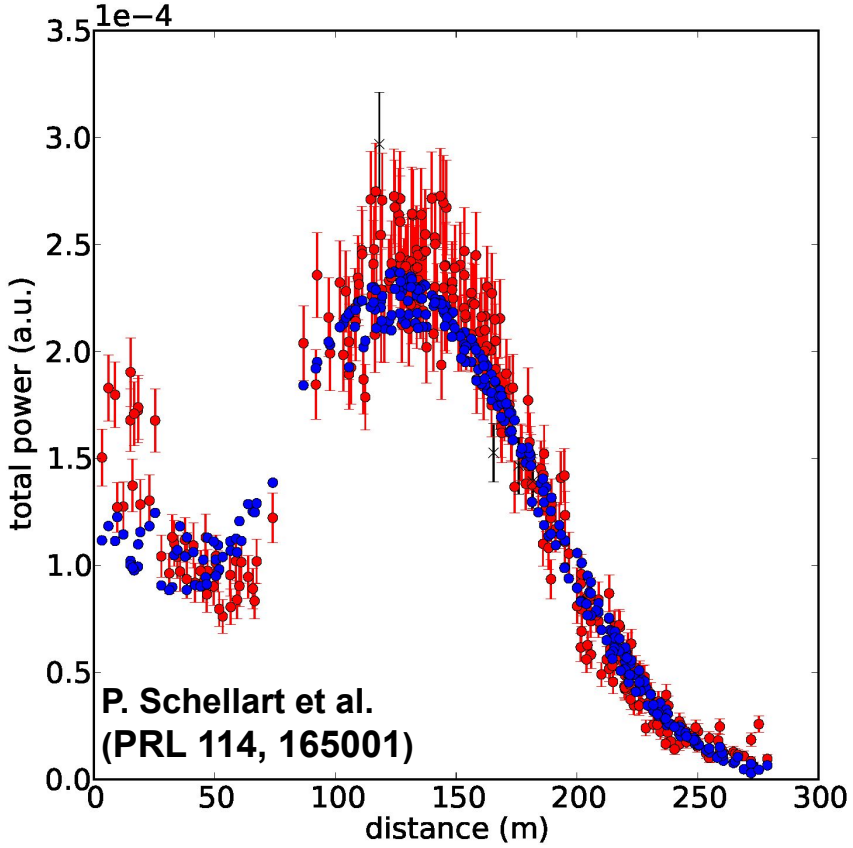


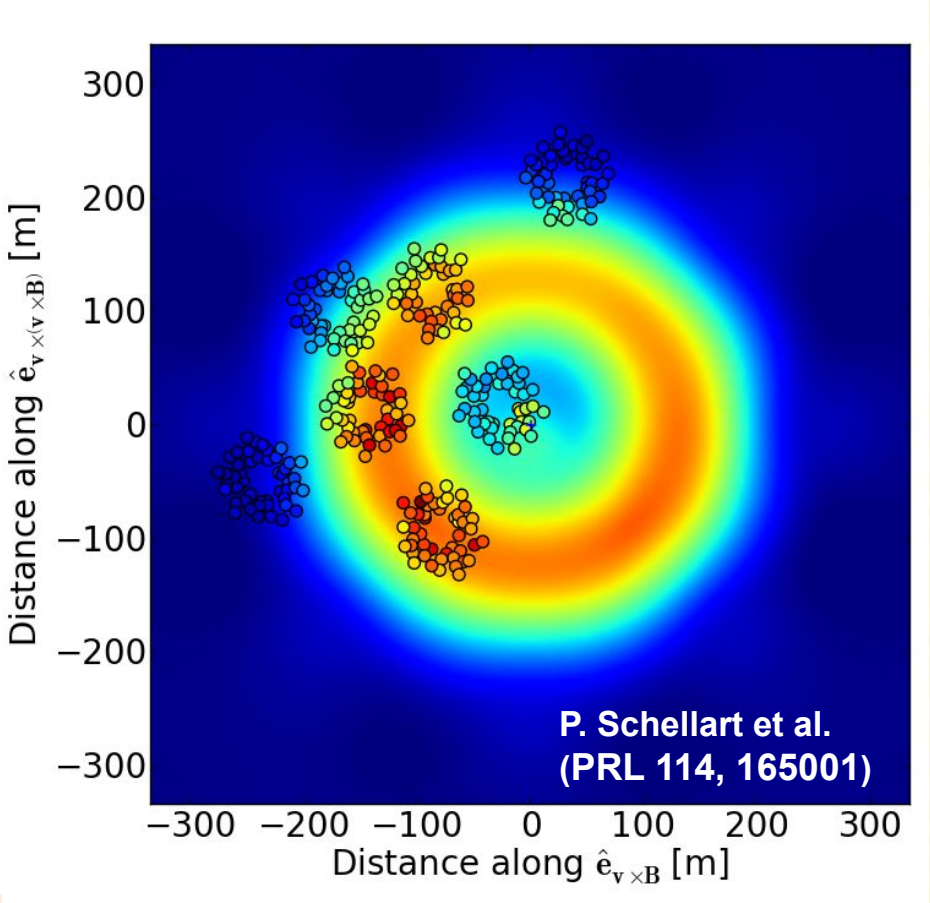
P. Schellart et al., PRL 114, 165001



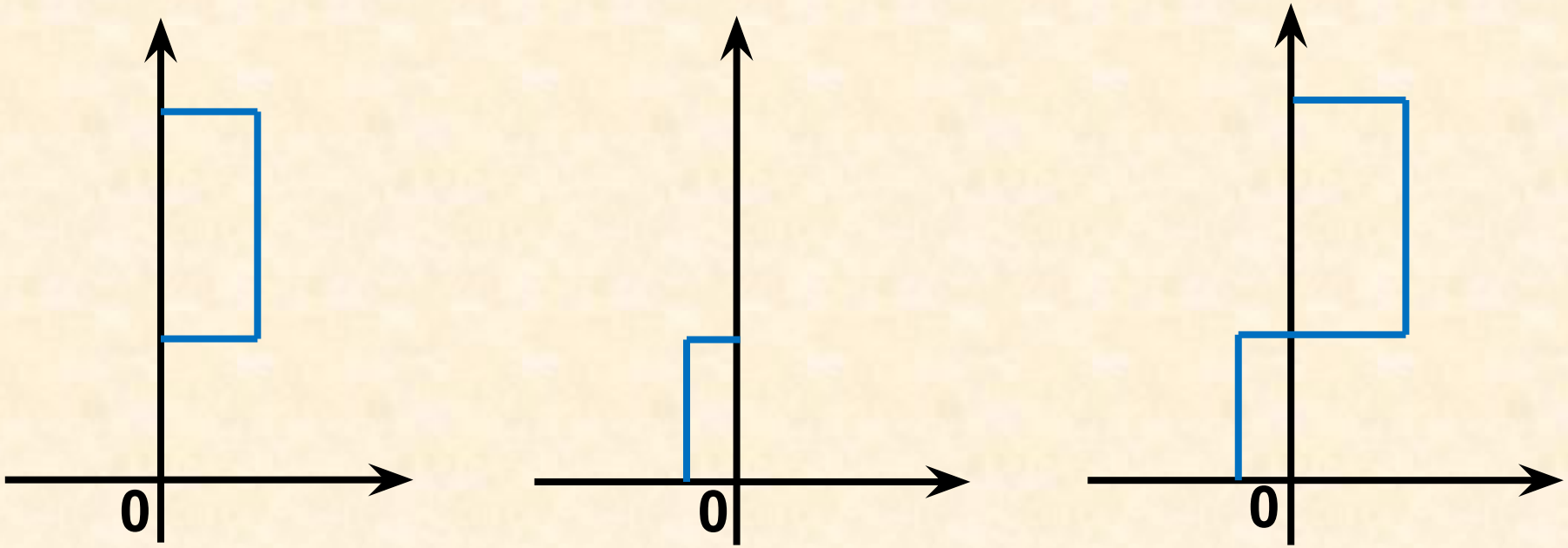
Structure of the field

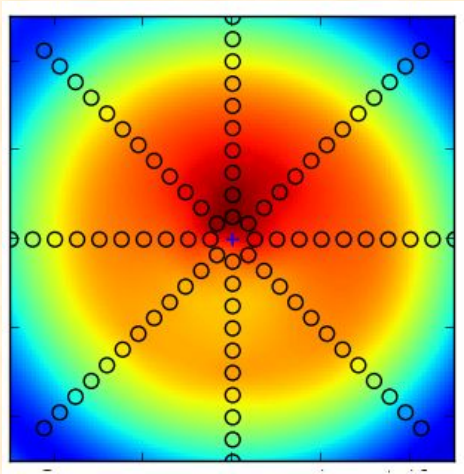
A reconstructed thunderstorm event





Ring vorming door intergerentie





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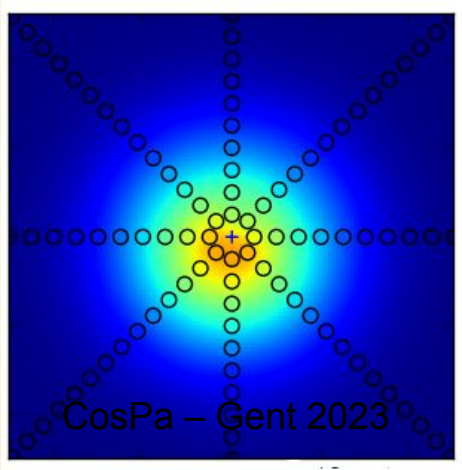

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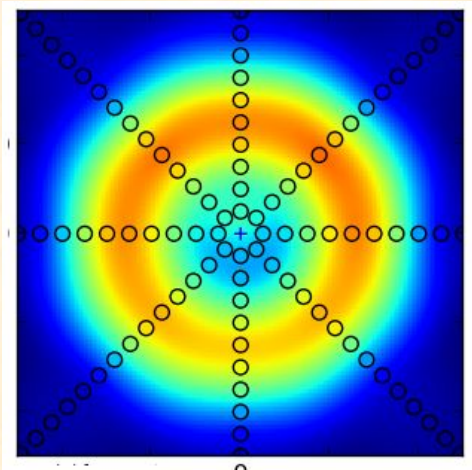
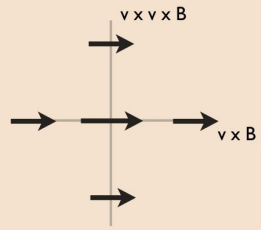
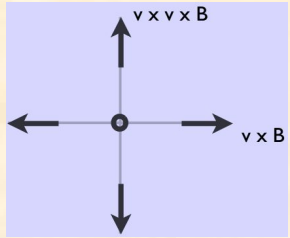


Interpretation circular-polarization for fair weather

GeoMagnetic:



Charge eXcess:



ChX Peaks lower in atmosphere than GM (physics)

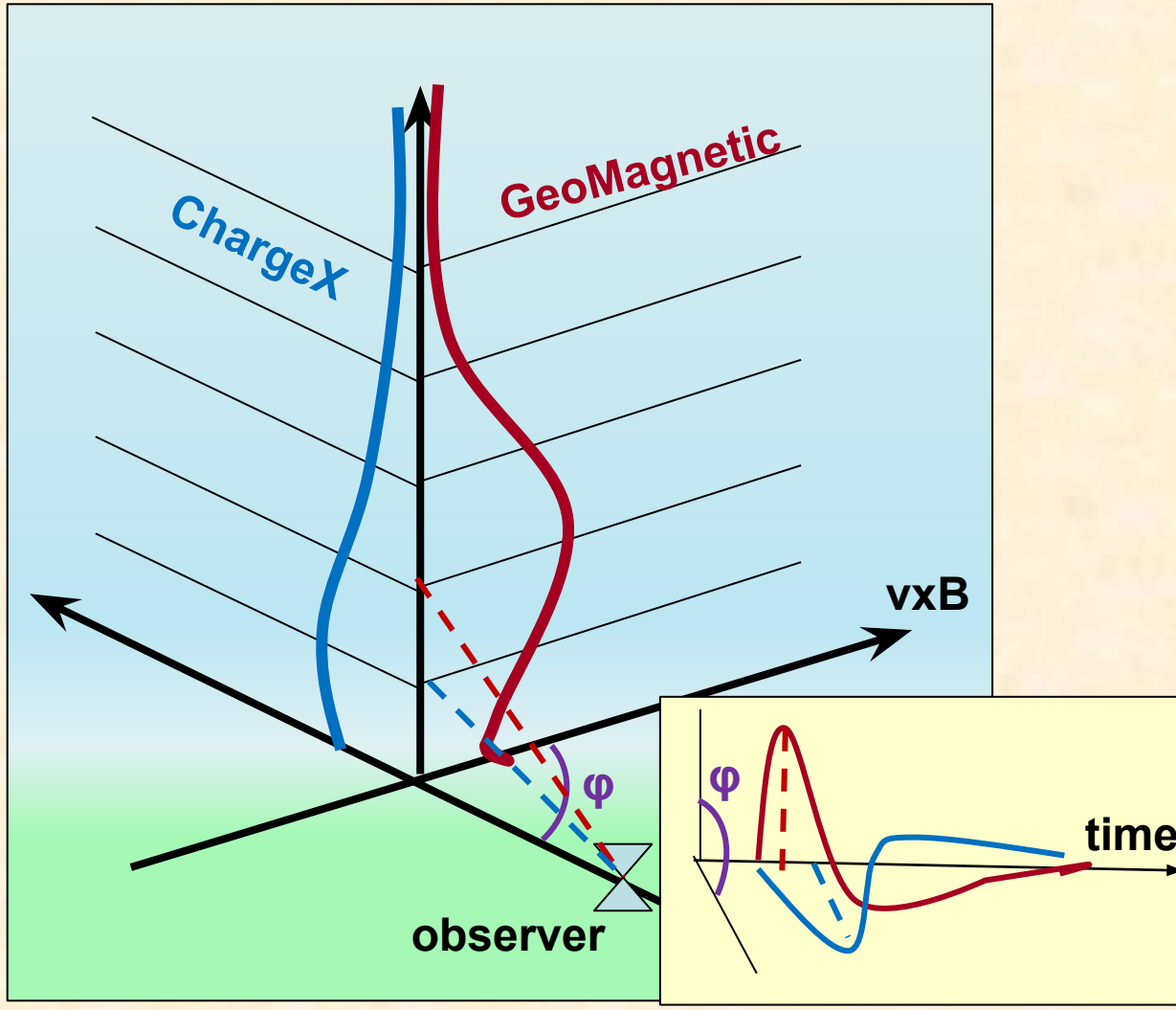
At 100 m, 30-80 MHz, delay = 1 ns

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

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

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

Stokes parameter V is measure of circular polarization



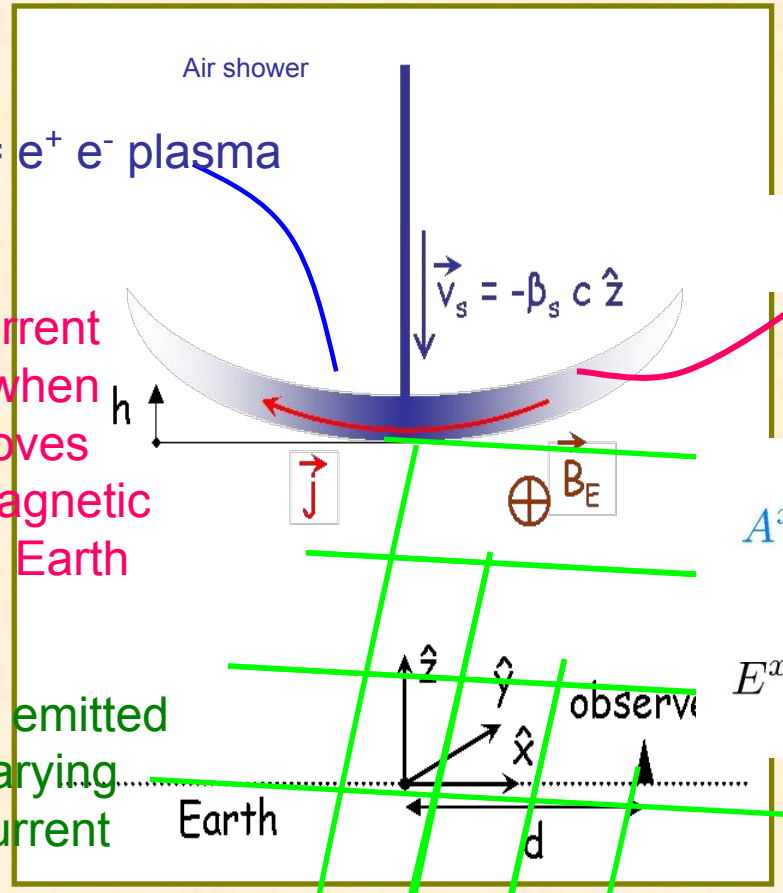
Slight delay between GM &ChX causes rotation in polarization

Macroscopic GeoMagnetic Radiation
> The Basic picture <

Pancake = $e^+ e^-$ plasma

Electric current develops when plasma moves through magnetic field of the Earth

Radiation emitted by time varying electric current

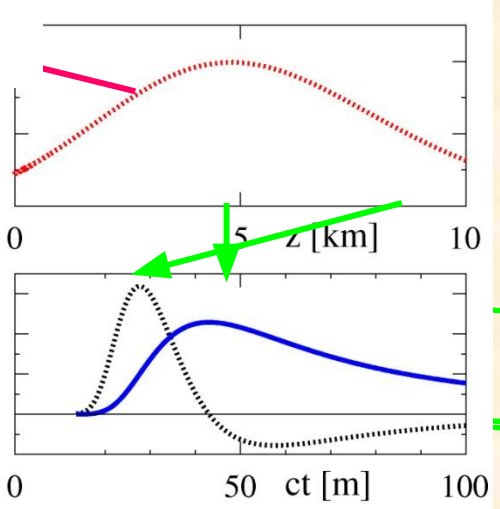


Horizontal drift velocity of electrons creates current

$$j_x(z) = J_0 \rho_e(z)$$

$$A^x(t,d) = \frac{j_x(z)}{\mathcal{D}}\bigg|_{\text{ret}}$$

$$E^x(t,d) = \frac{d}{dt} A^x(t,d)$$



Parametrized:

$$j^\mu(t_s, x_s, y_s, h) = \frac{w(r_s)}{r_s} f(h, r_s)\, J^\mu(t_s)$$

$$A^\mu(t_o, \vec{x}_o) = \int d^3\vec{x}' \, \frac{j^\mu(t_r, \vec{x}')}{\mathcal{D}}$$

$$\mathcal{D} \stackrel{1}{=} nR \left| \frac{dt_o}{dt_r} \right| \stackrel{2}{=} nR\,(1 - n\vec{\beta}\cdot\hat{n})\Big|_{\text{ret}}$$

- LOFAR
- Radio emission mechanisms
- Include AtmElField, e-par, e perp, circ pol
- Footprint, stokes, fair-weather values & plot
- Thunderstorm values & plots
- Inverse problem, fitting
- Full field, tomography
- Conclusions –also E in non th-clouds – non intrusive tomography