MGMR3D, a semi-analytic code for the obtaining the radio footprint from the shower currents

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Motivation:
Use radio emission as tool to learn about shower-currents

Need: Fast and non-MonteCarlo code for radio footprint
(Intensity & polarization).

MGMR3D: Complete pattern for arbitrary current profile in 10 seconds on windows laptop

Approach: Semi-analytic & conveniently parametrized shower structure

This talk:
- Implemented shower parametrization, inspired by CORSIKA
- Compare results with COREAS

formulas

We parametrize the charge-current densities in the shower depending on

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

– height in the atmosphere = z = -c t_s

– lateral distance to the shower axis = $r_s = \sqrt{x_s^2 + y_s^2}$

– distance behind the shower front = h

Lateral distribution function w and pancake function f are normalized

$$\int_0^\infty f(h, r)\, dh = \int w(r)\, dr = 1$$

making $J^0(t_s)$ the net charge and $J^1(t_s)$ and $J^2(t_s)$ the net transverse currents

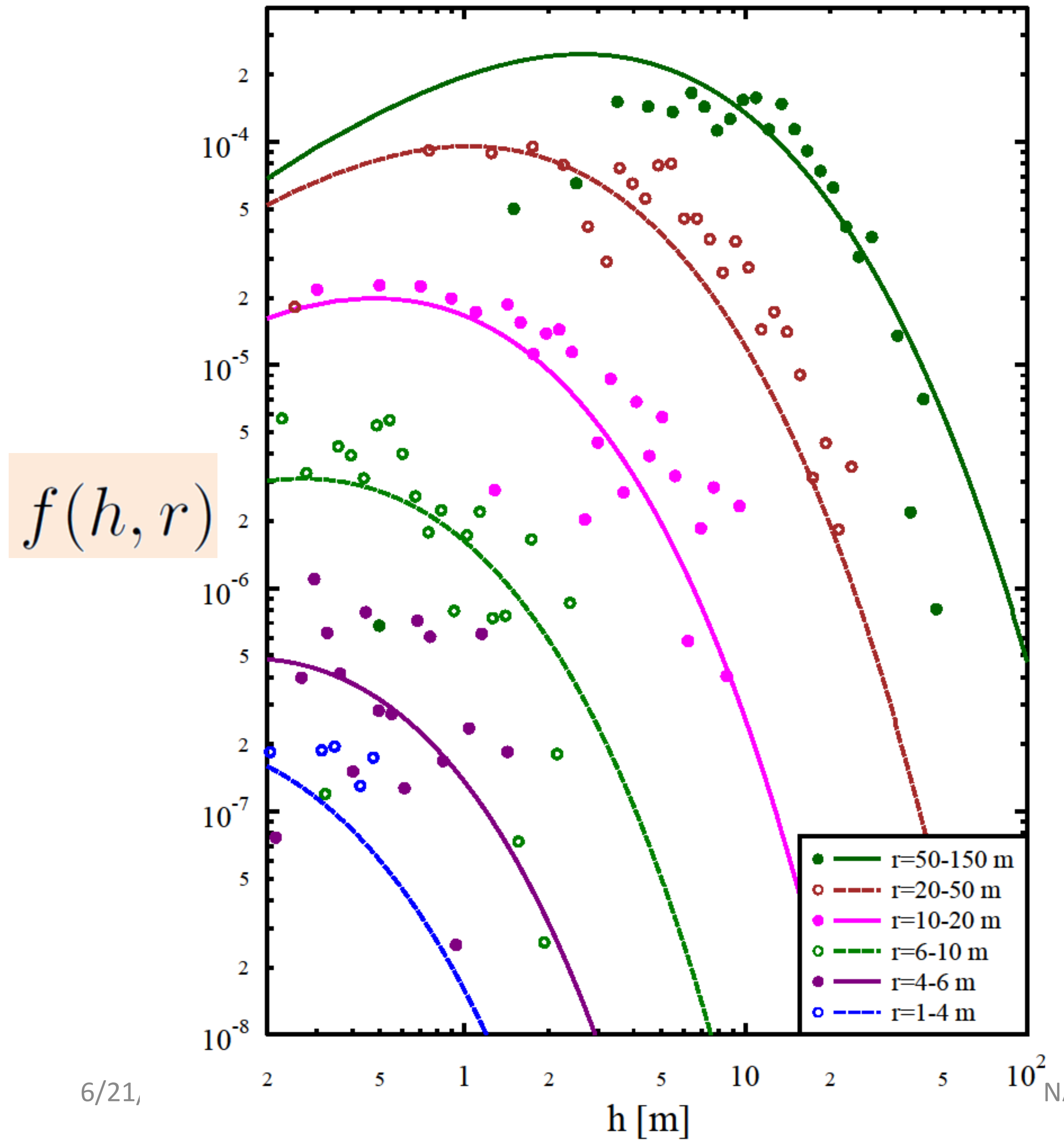
The radiation fields are calculated from the vector potential, including retardation (Cherenkov) effects

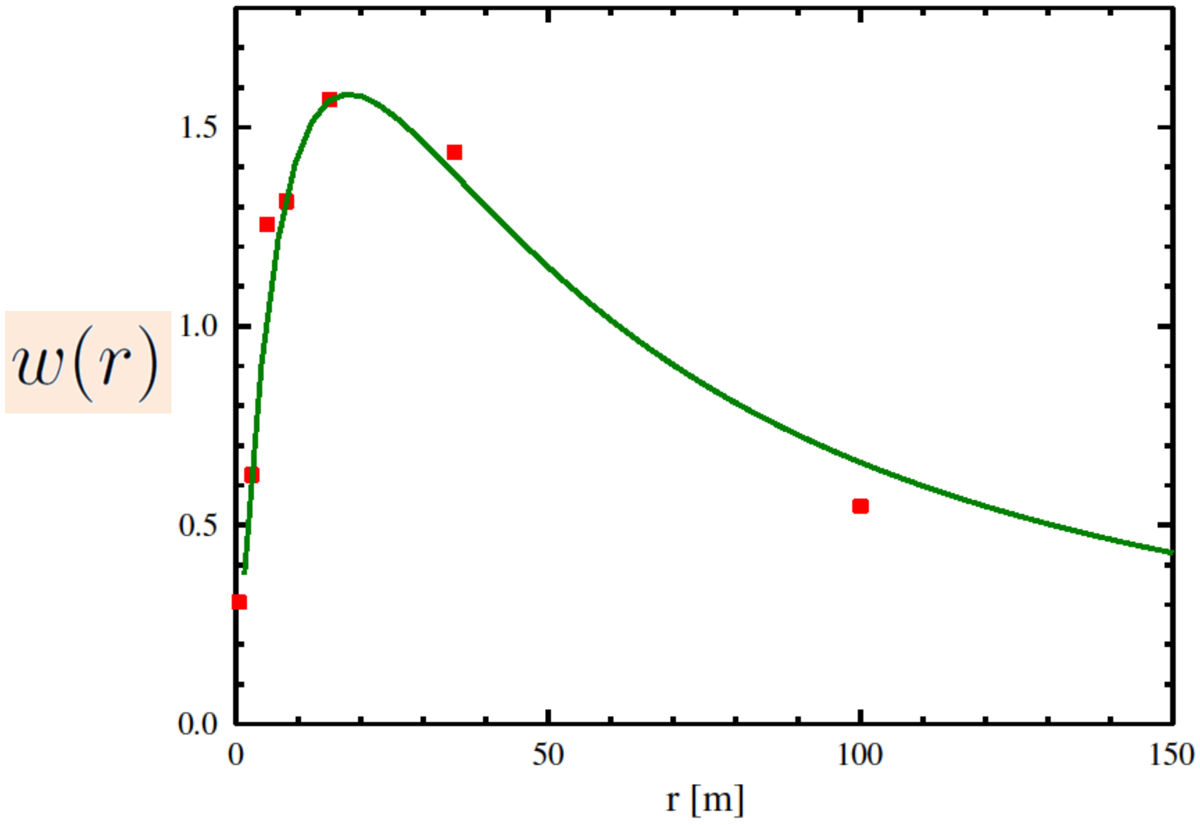
$$A^\mu(t_o, \vec{x}_o) = \int d^3\vec{x}'\, \frac{j^\mu(t_r, \vec{x}')}{\mathcal{D}}$$

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

$$n_{GD} = 1 + n_\rho \rho(z)$$

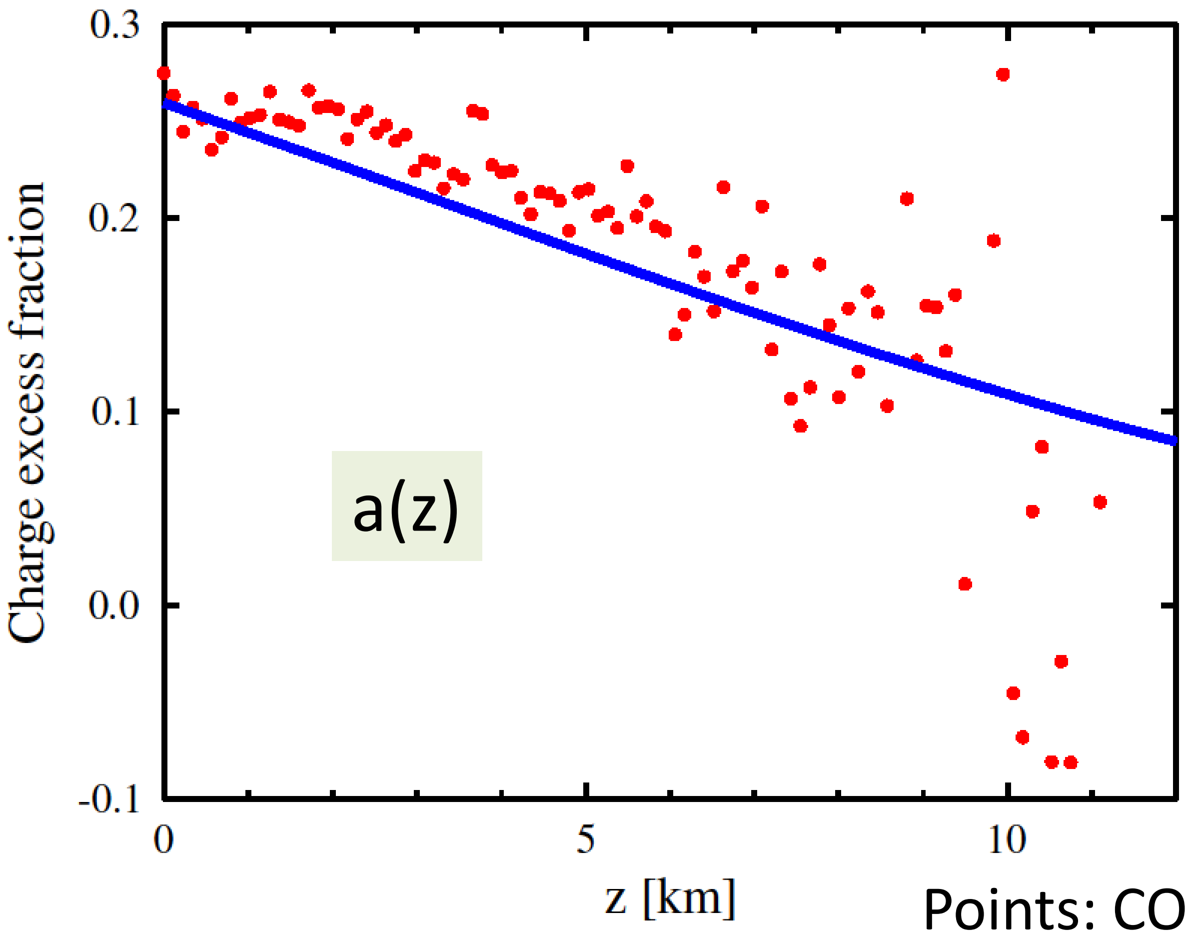
Pancake & Lateral distribution

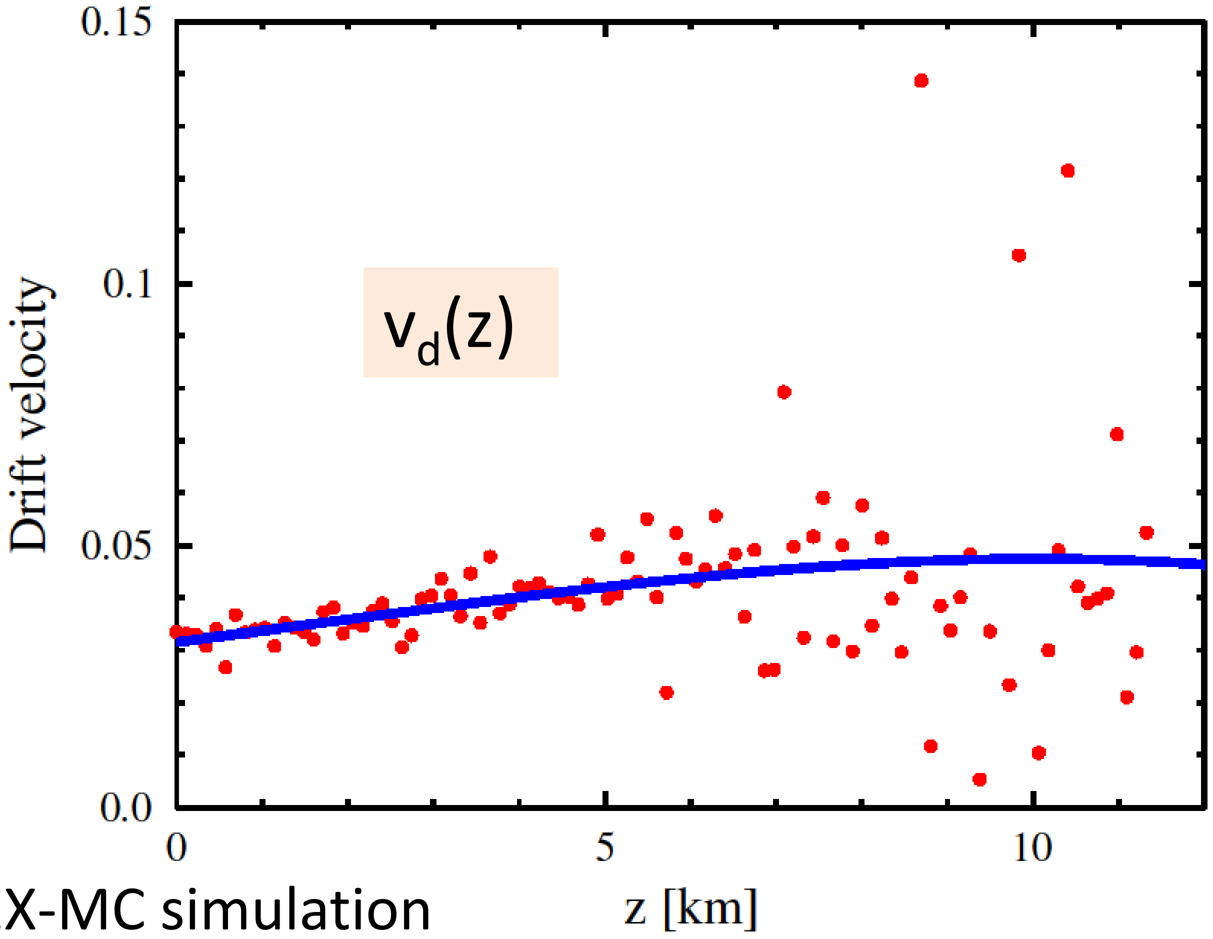




Points: CONEX-MC simulation

Charge excess & drift velocity



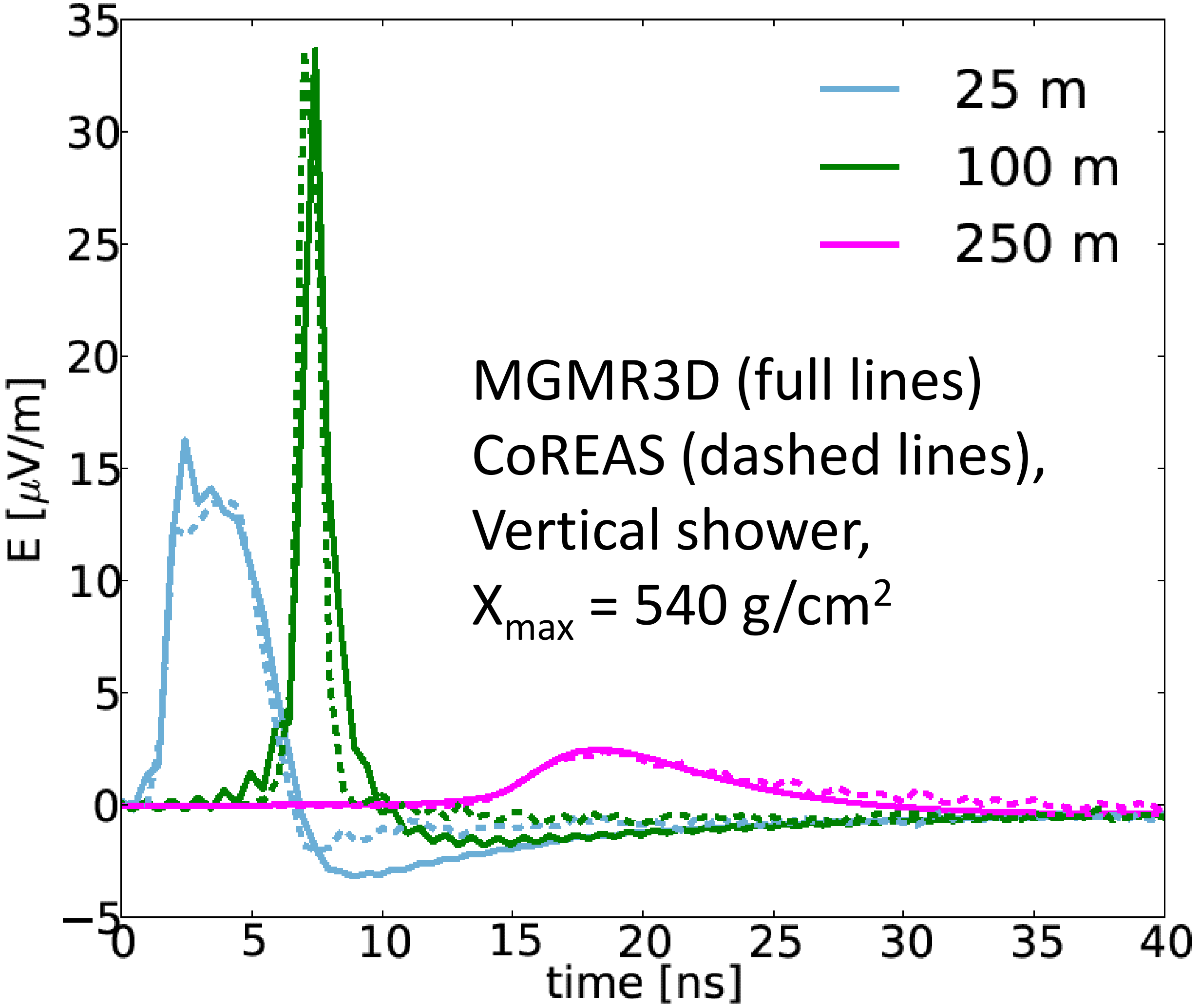


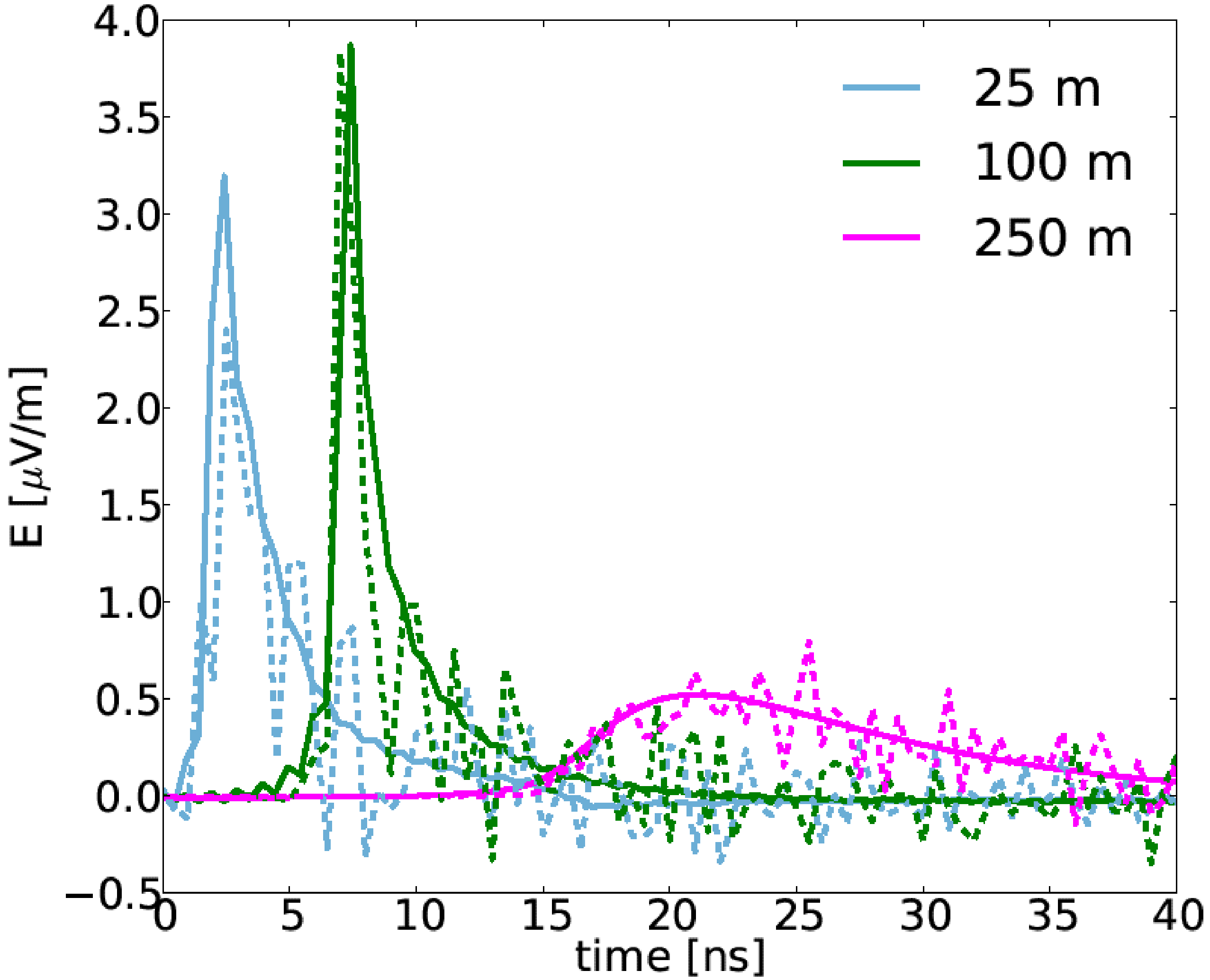
Points: CONEX-MC simulation

Net charge = $J^0(z) = a(z)\, N(z)$

Net transverse current = $J^i(z) = v_d^i(z)\, N(z)$

Charge excess & transverse current Pulses





Stokes

Stokes parameters:
I, Q, U, V

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

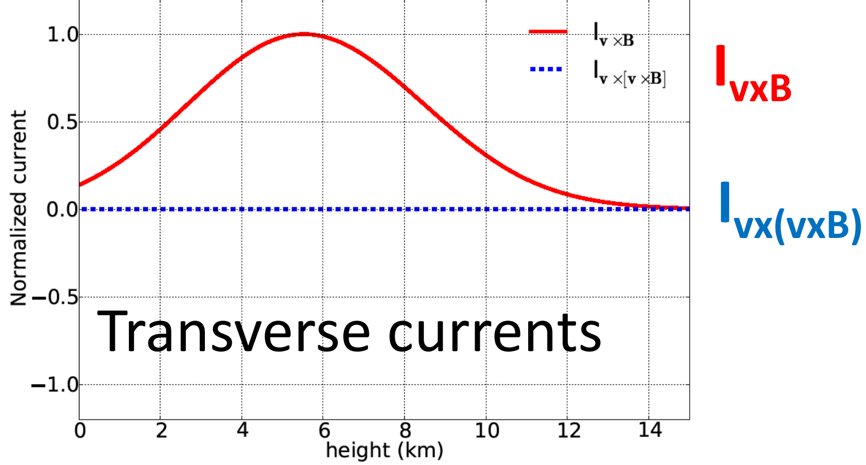
Circular polarization = V/I

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

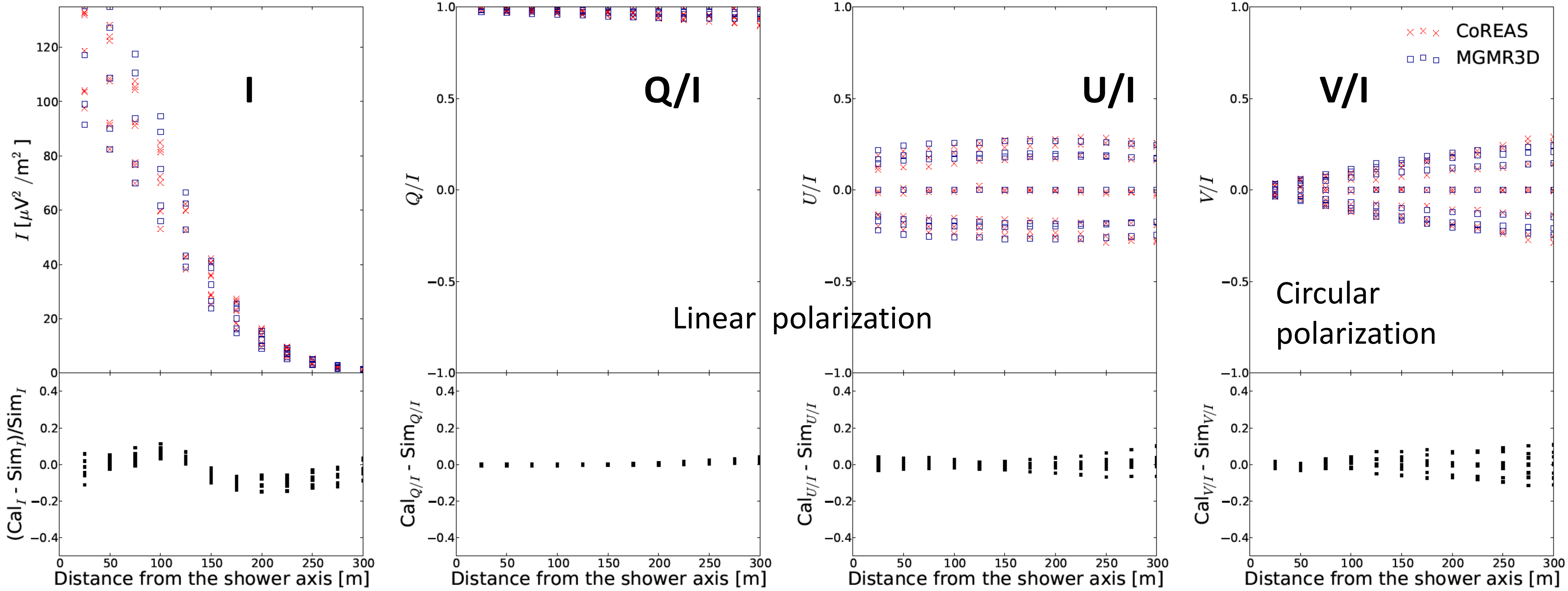
$$Q = \frac{1}{n}\sum_{0}^{n-1}\left(|\mathcal{E}|^2_{i,\mathbf{v}\times\mathbf{B}} - |\mathcal{E}|^2_{i,\mathbf{v}\times(\mathbf{v}\times\mathbf{B})}\right)$$

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

Fair weather,
Vertical, X_{max}=540 g/cm^2

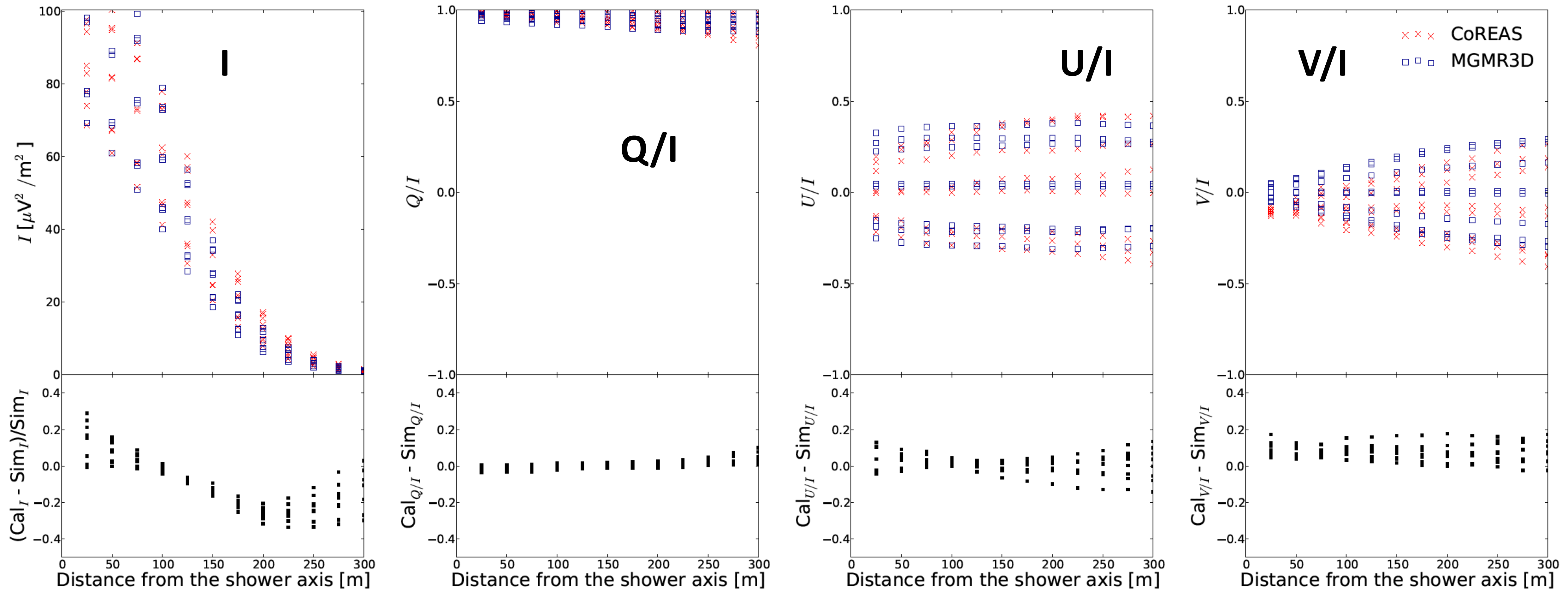


Stokes parameters (30 -- 80 MHz)



Fair weather, 30 deg, X_{max}=693 g/cm^2

Stokes parameters (30 -- 80 MHz)

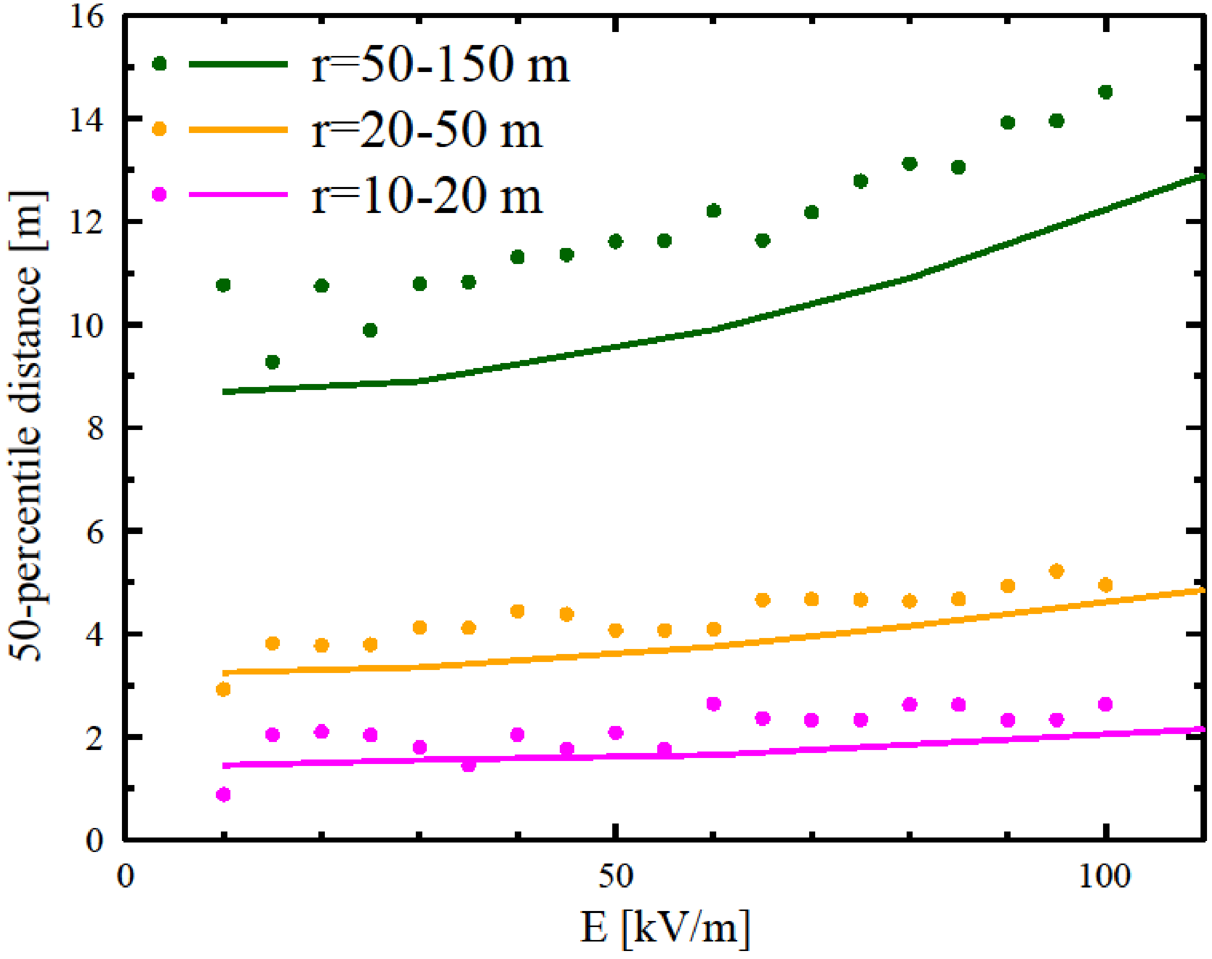


Shower parameters depend on atmospheric electric field

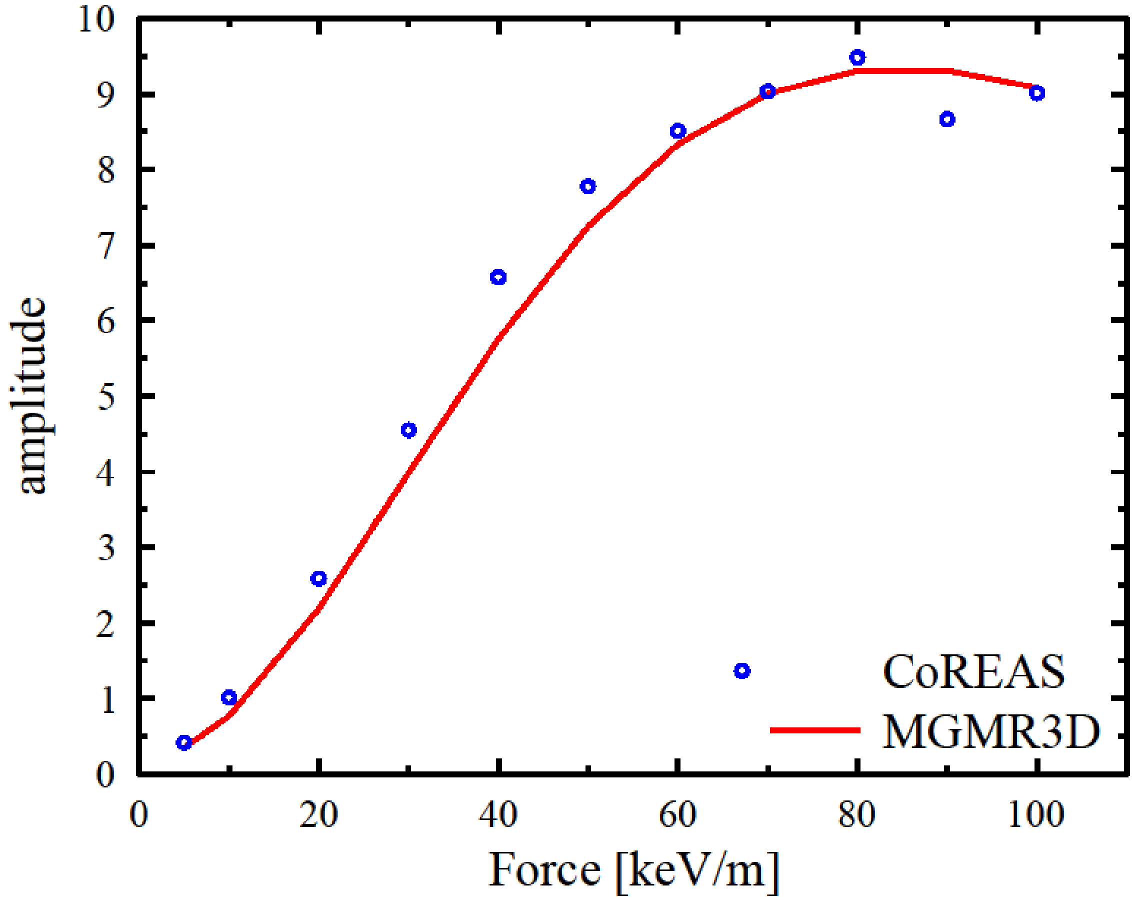
PRD93(2016)023003

Important for analysis of thunderstorm events

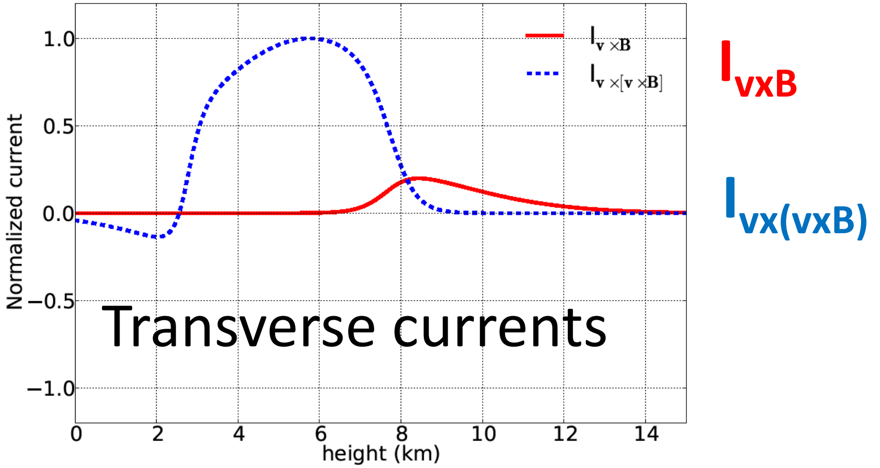
Pancake distribution



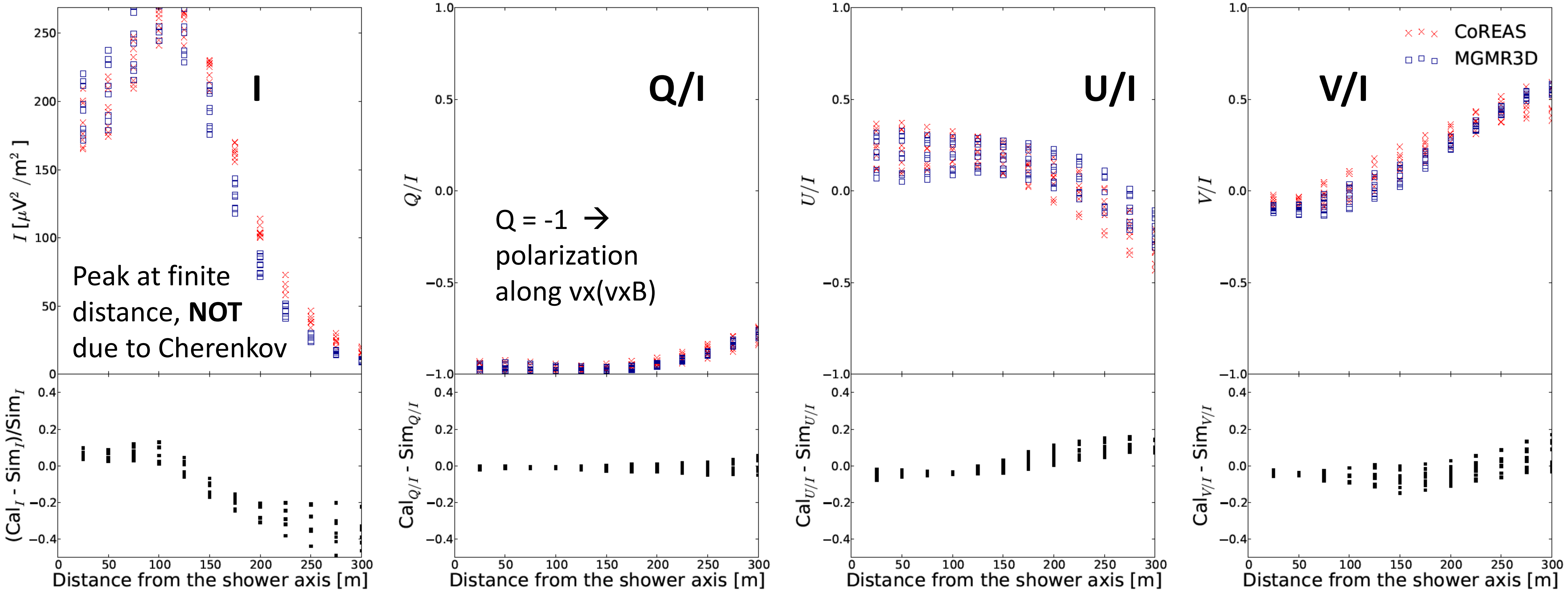
Peak radio power (30-80 MHz)



2-layered electric field, Vertical, X_{max}=510 g/cm^2

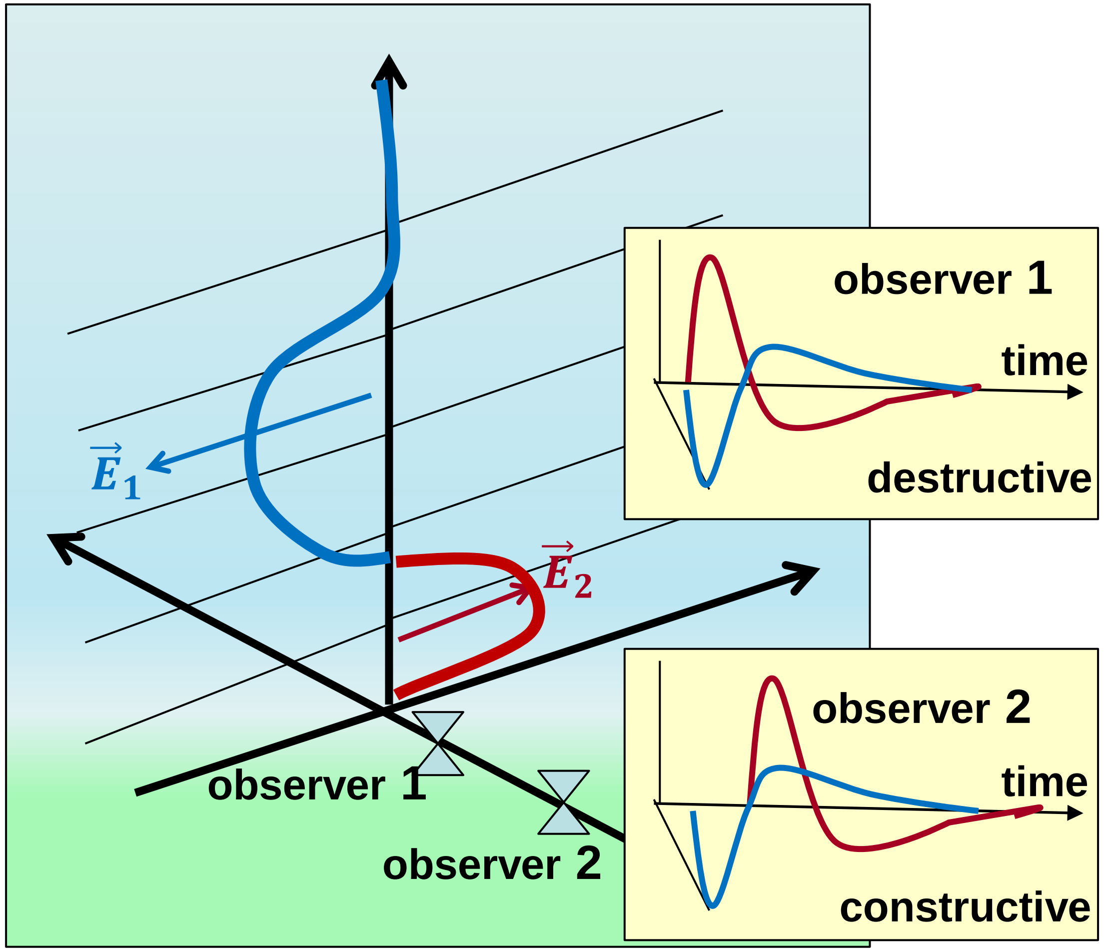


Stokes parameters (30 -- 80 MHz)



Interference of emission from different heights

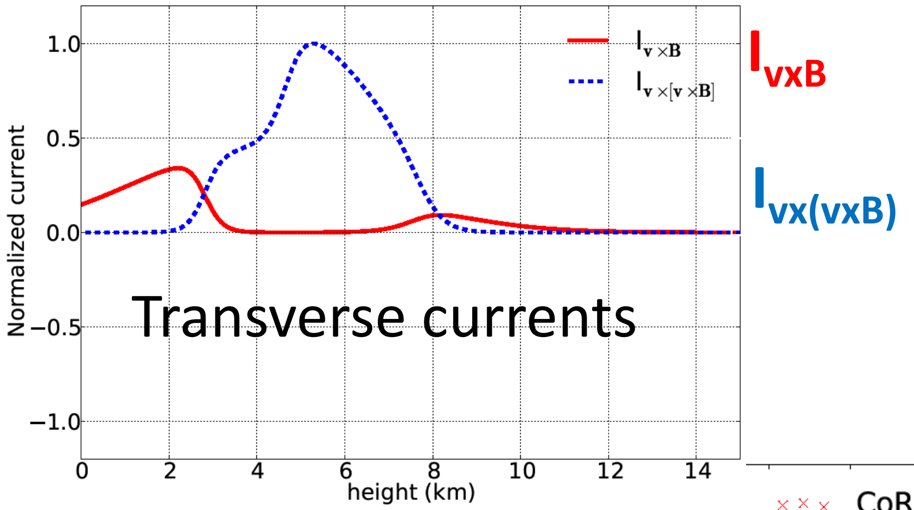
Electric fields in different layers are in opposite directions



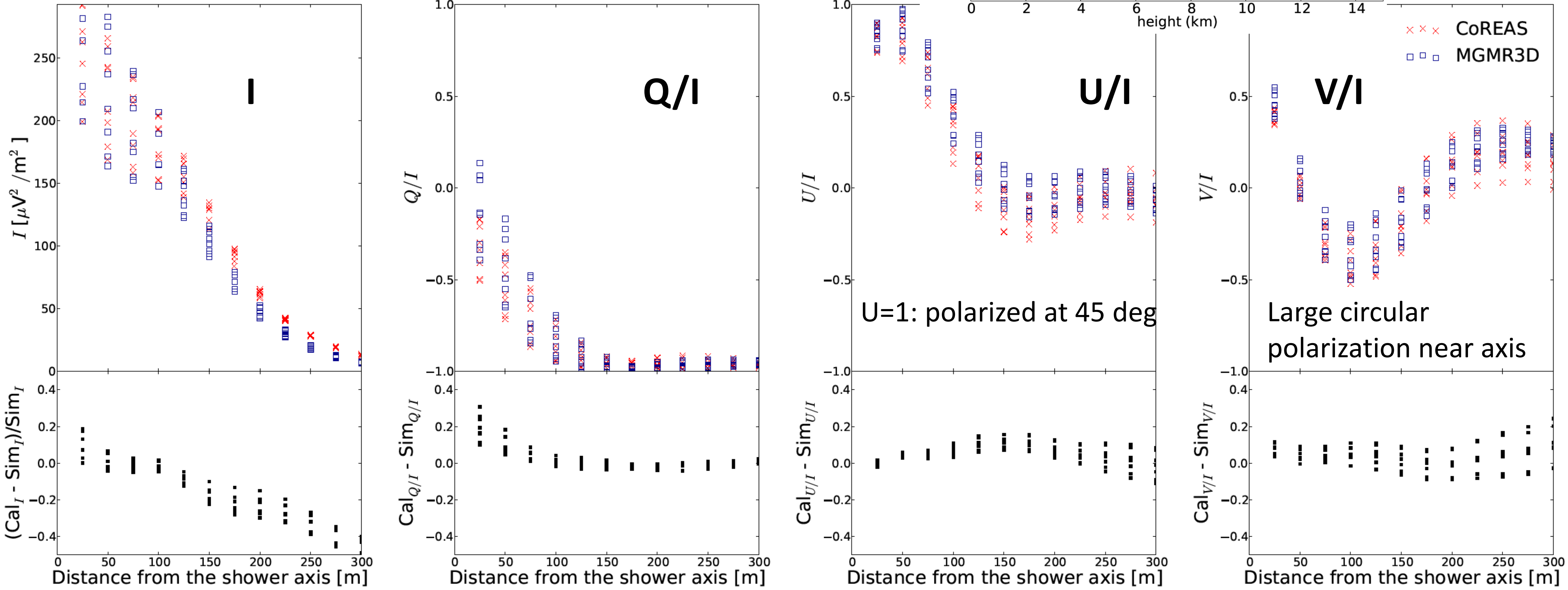
Destructive interference depends on relative arrival times, or distance to shower axis.
Intensity pattern will have a ring-like structure.

Signal is linearly polarized along direction of atmospheric electric field

Triple layered field, Vertical, X_{max}=660 g/cm^2

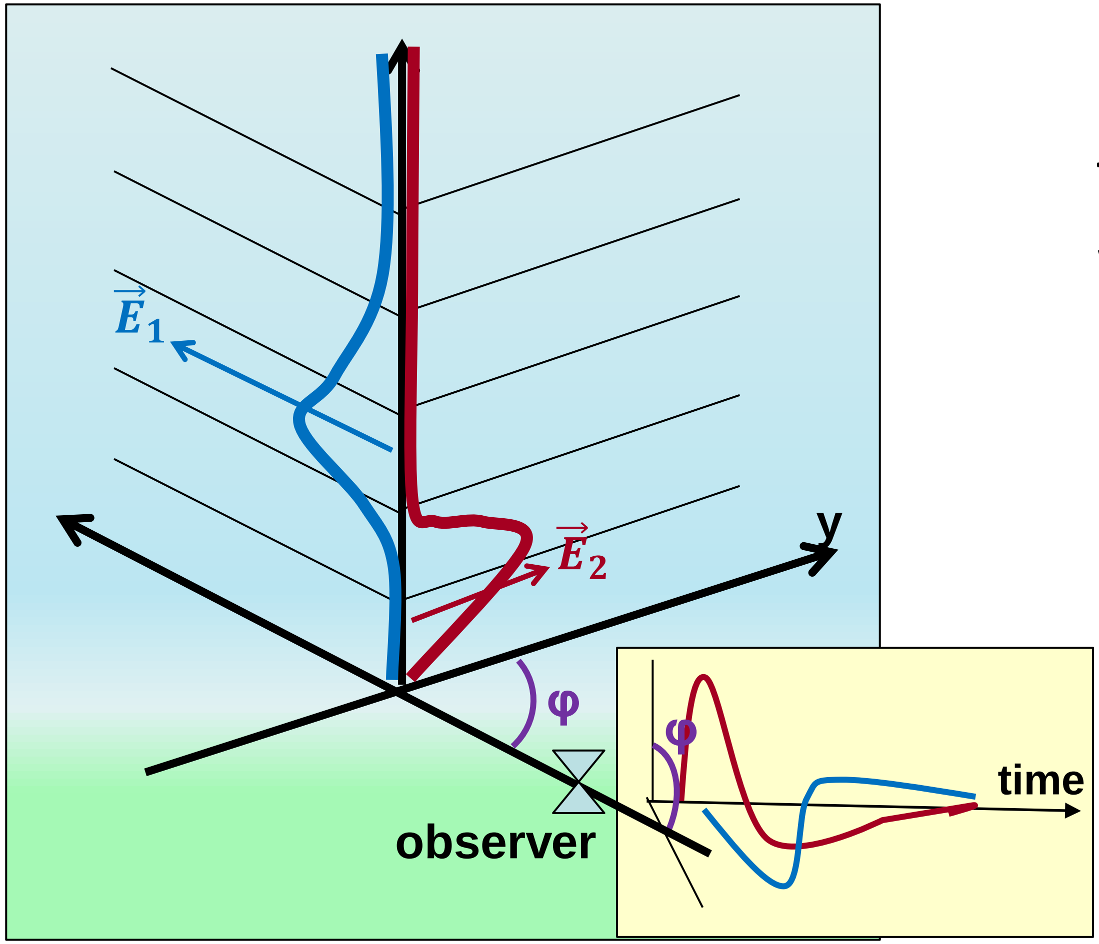


Stokes parameters (30 -- 80 MHz)



Circular polarization in thunderstorm events

Electric fields in different layers are at an angle



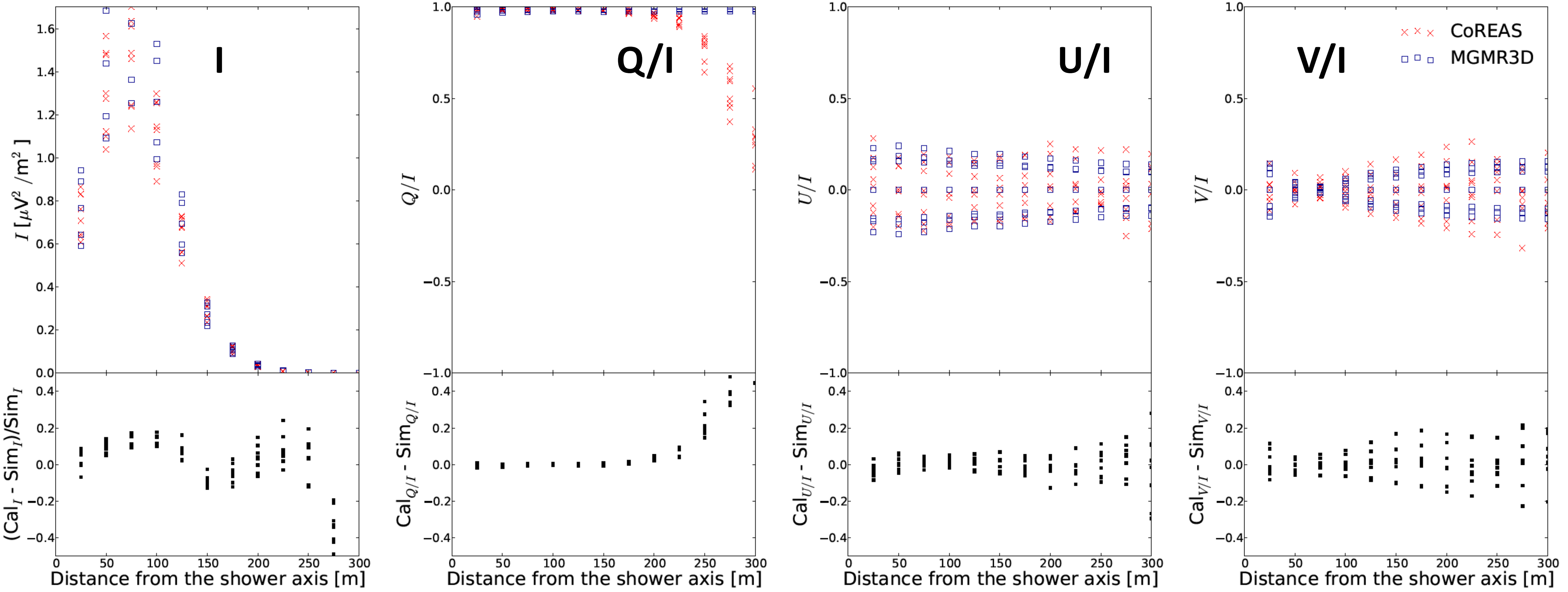
The pulses from the upper layer arrive with a delay with respect to the pulses from the lower layer resulting in a change of the polarization angle over the duration of the pulse, seen as circular polarization.

Measured signal has strong circular polarization (Stokes V/I ≠ 0)

See: Trinh et. al. (2016) *Physical Rev. D* 95, 083004

Fair weather, Vertical, X_{max}=540 g/cm^2

Stokes parameters (100 -- 200 MHz)



Summary & Conclusions:

MGMR3D Gives a realistic physics-based estimate of the radio footprint

- intensity
- polarization
- time structure & frequency content
- handles complicated current profile

Code is fast and can be used in chi-square search

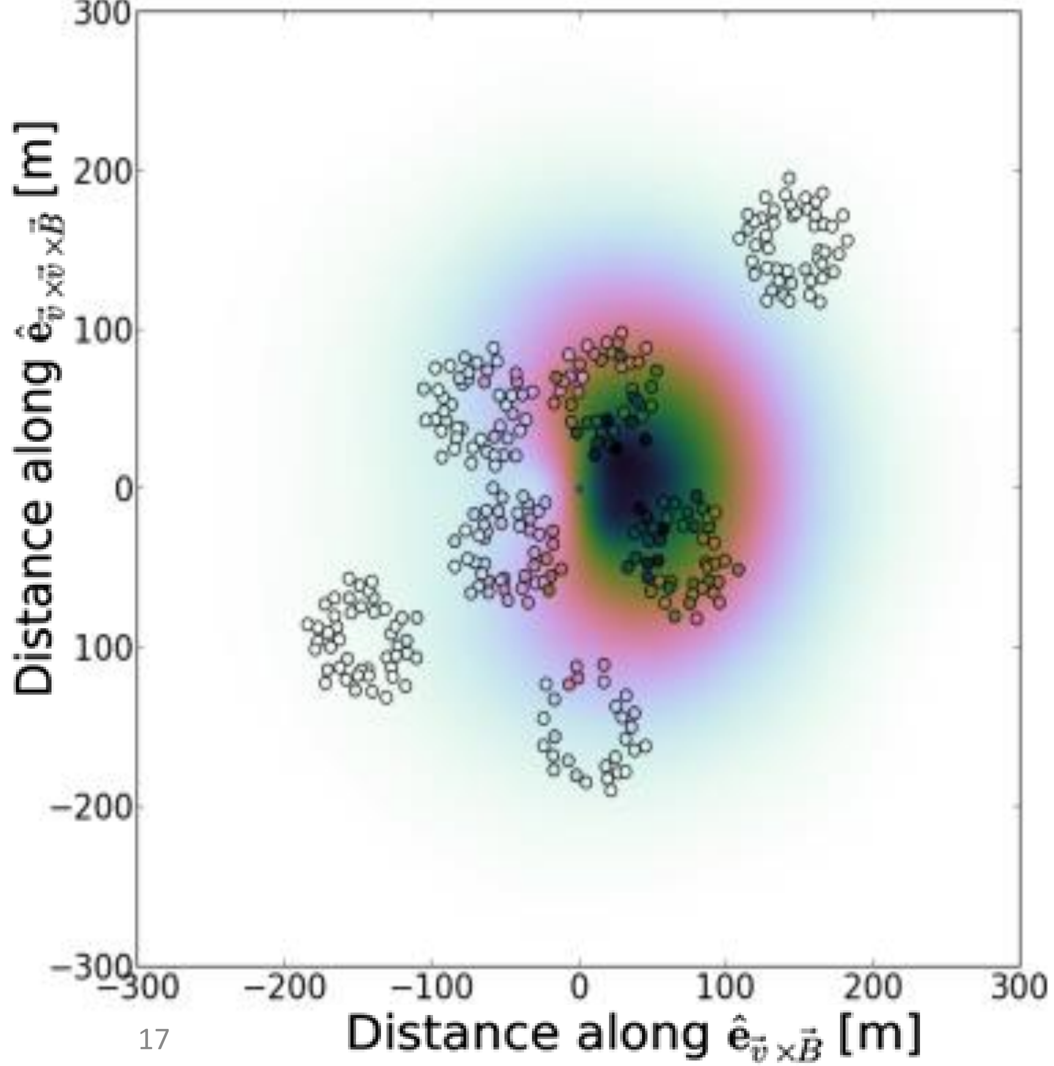
Ref: PRD97(2017)0230005; code available upon request

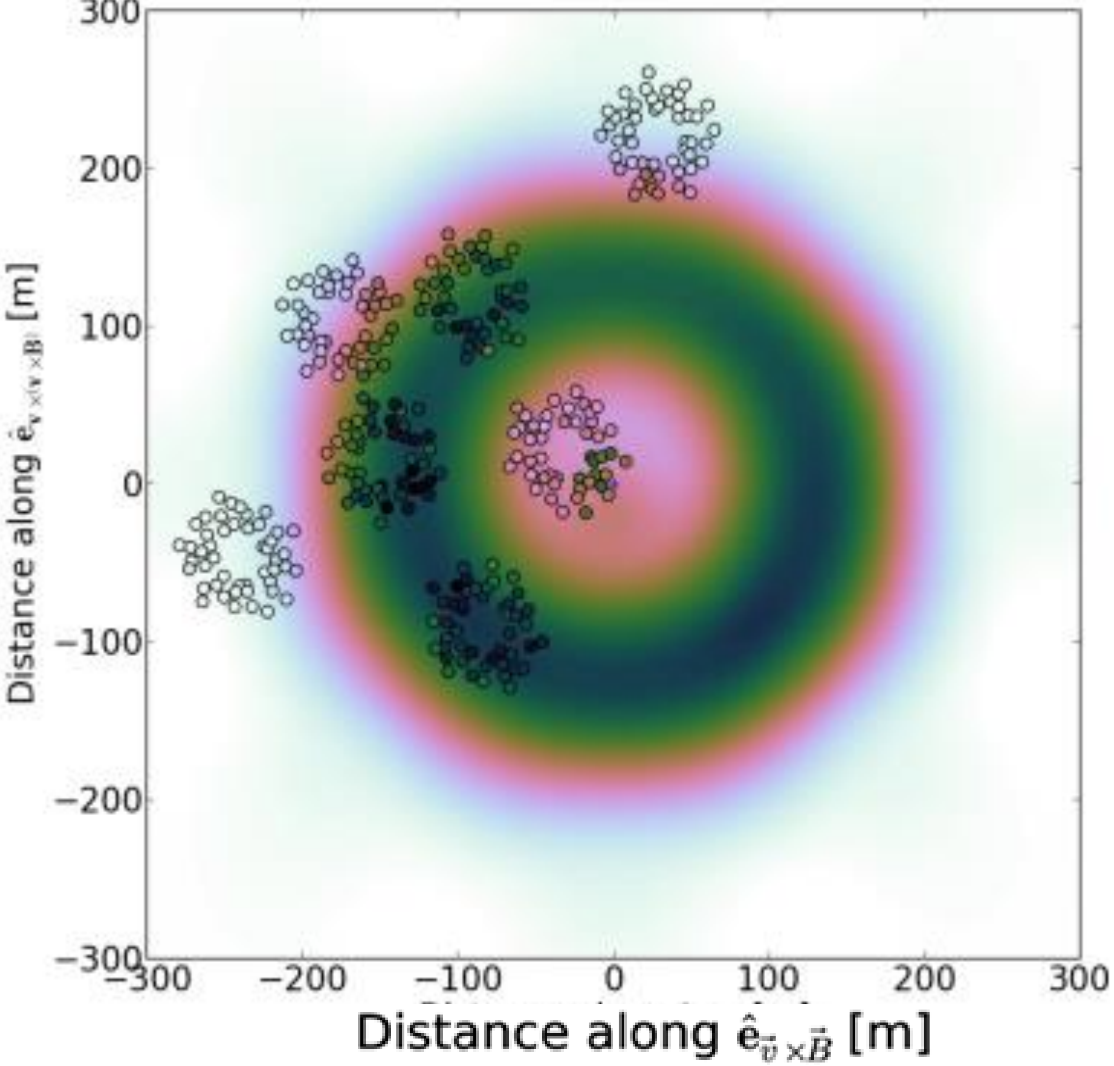
Observations; intensity footprint

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

Fair weather vs thunderstorm

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





A reconstructed thunderstorm event