High-energy cosmic rays at LOFAR.

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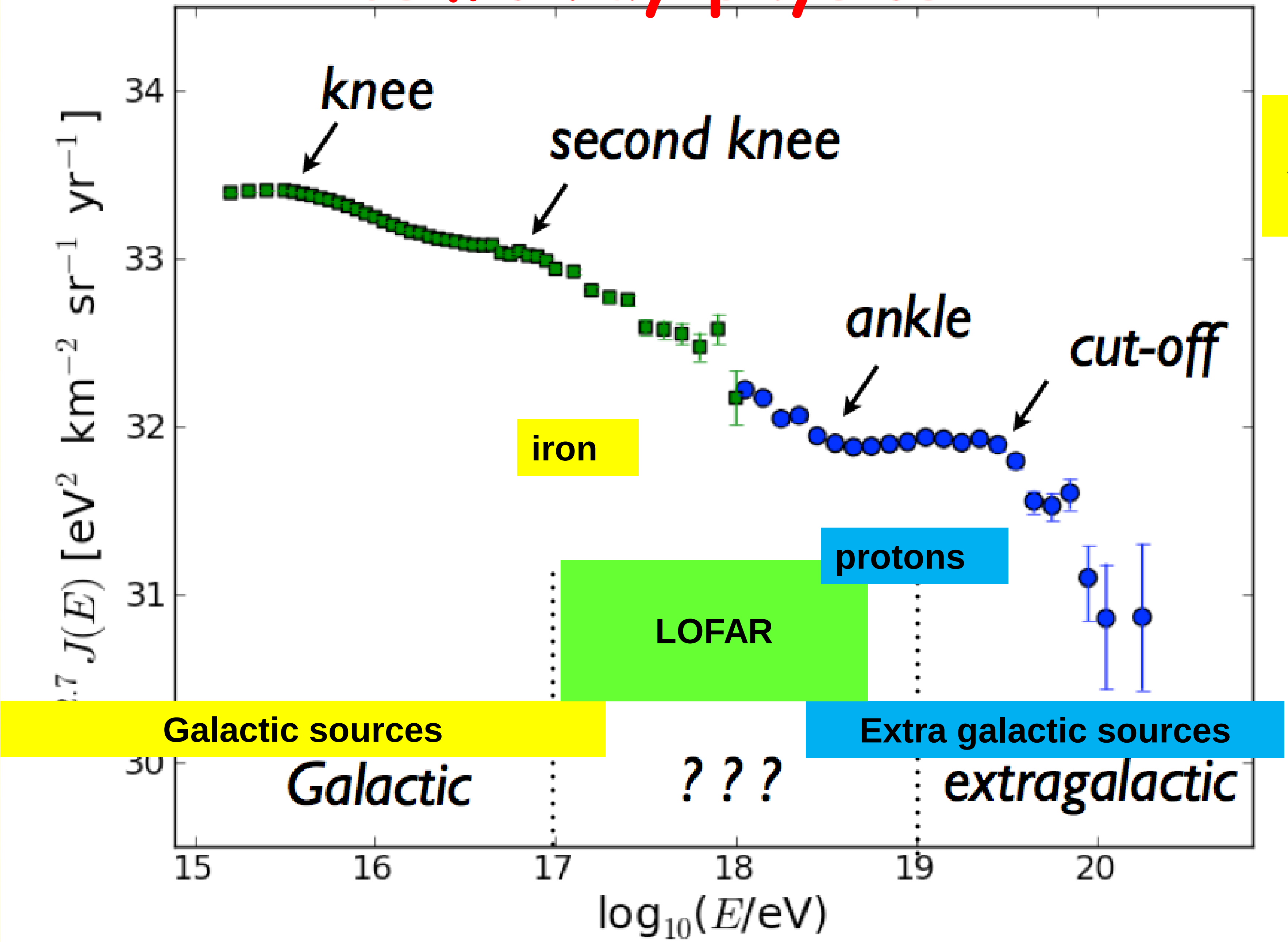
TBB

LOFAR Cosmic Ray KSP & Cosmic Lightning Project

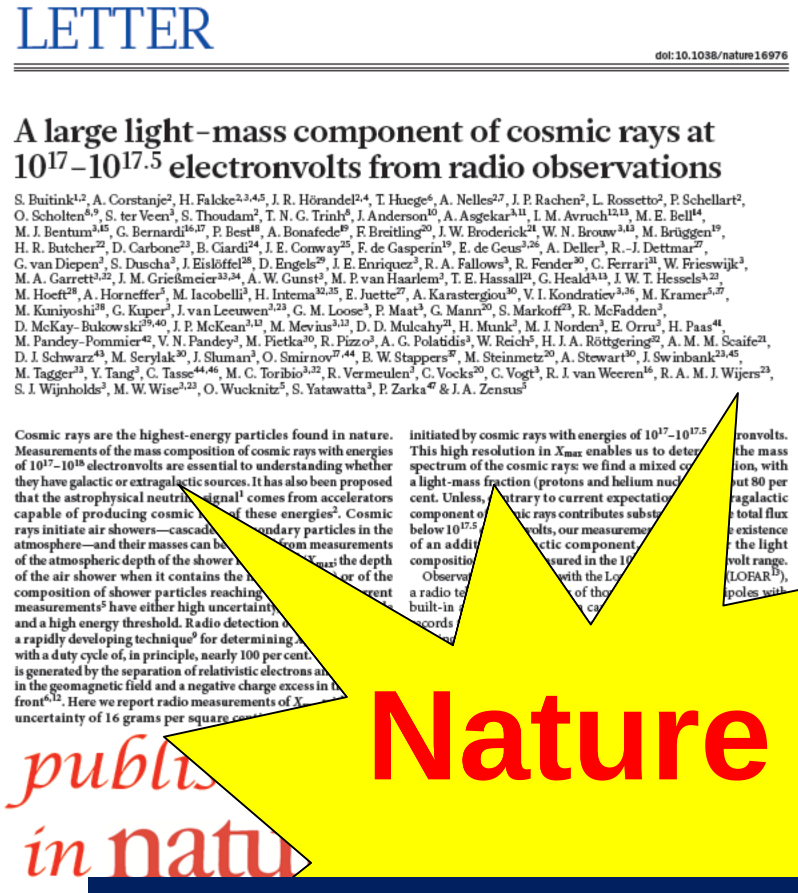
A. Bonardi, S. Buitink, A. Corstanje, J.E. Enriquez, H. Falcke, J.R. Hörandel, T. Karskens, M. Krause, P. Mitra, K. Mulrey, B. A. Nelles, J.P. Rachen, L. Rossetto, P. Schellart, O. Scholten, S. Thoudam, T.N.G. Trinh , S. ter Veen, T. Winchen

Cosmic ray physics:

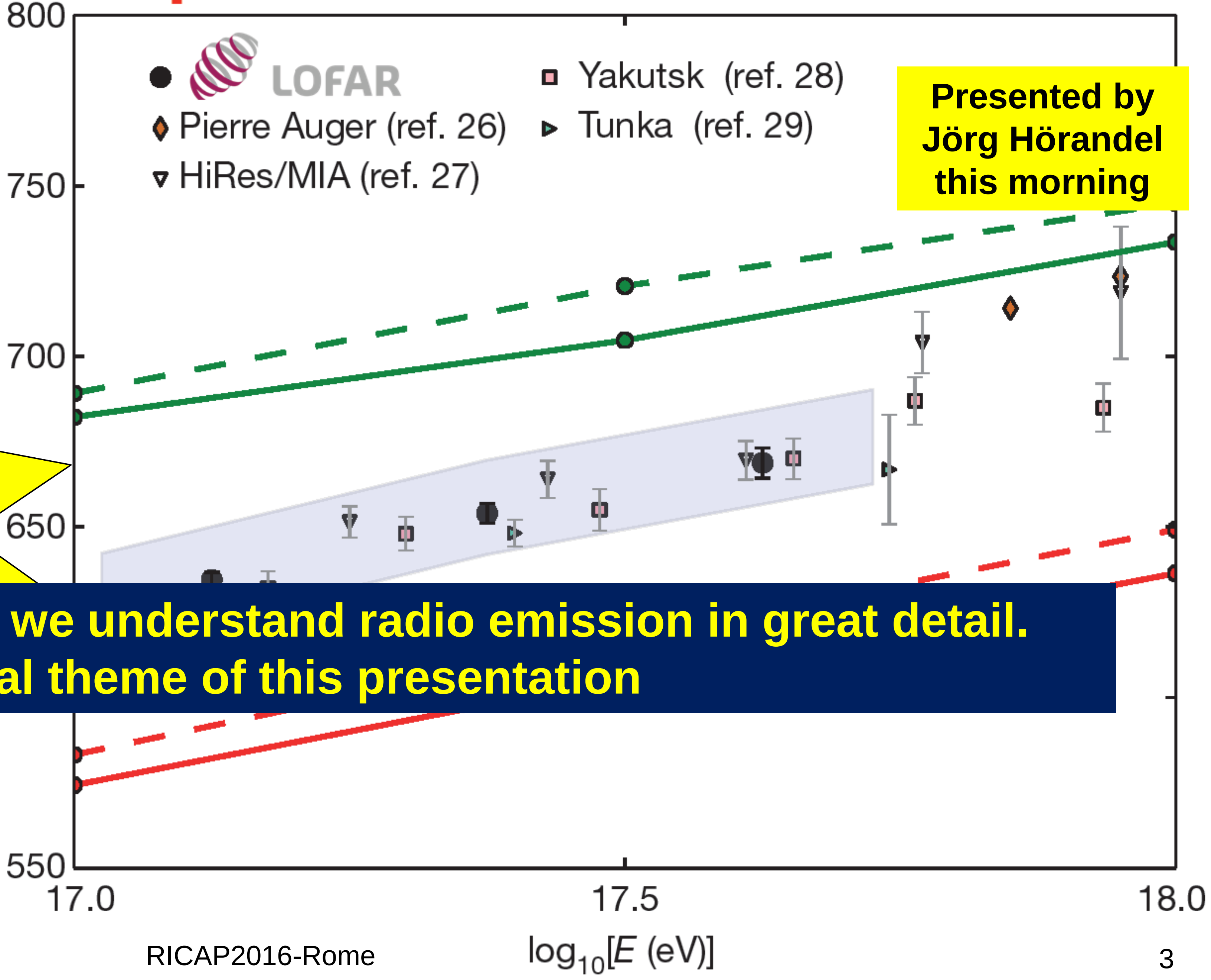


Presented by Jörg Hörandel this morning

Depth of the shower maximum



Nature

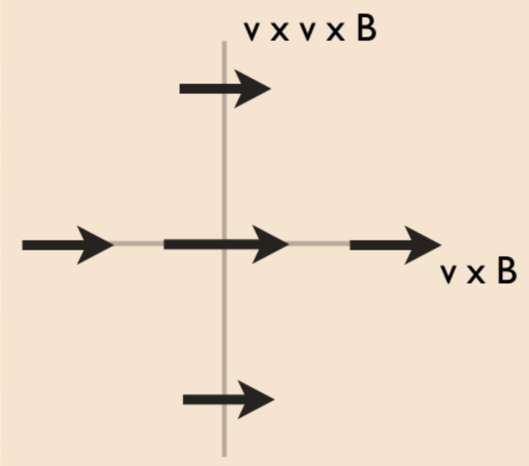


Presented by Jörg Hörandel this morning

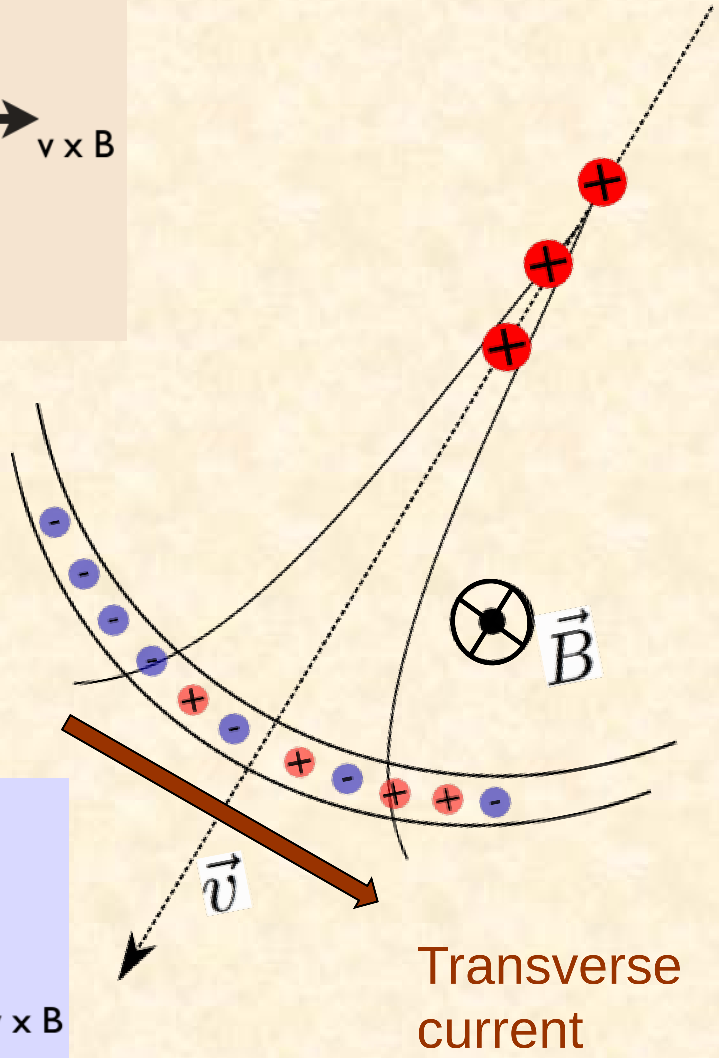
Only possible because we understand radio emission in great detail.
Central theme of this presentation

S. Buitink et al., Nature (2016)

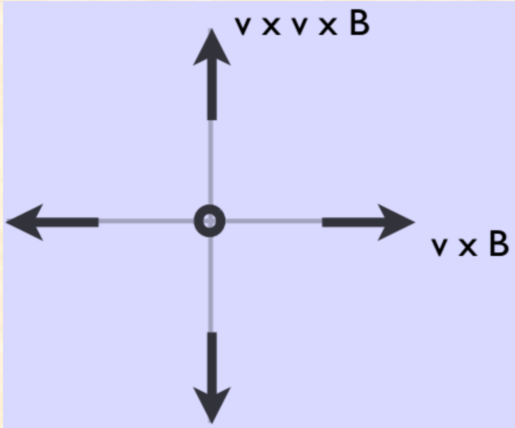
Multiple emission mechanisms



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



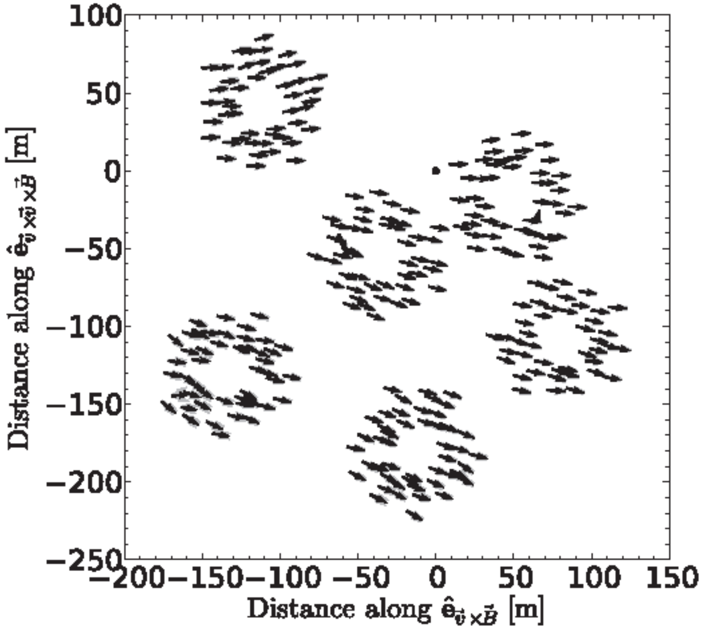
 # Charge excess:
- Negative charge buildup at shower front.
- Linearly polarized, Radially from shower axis



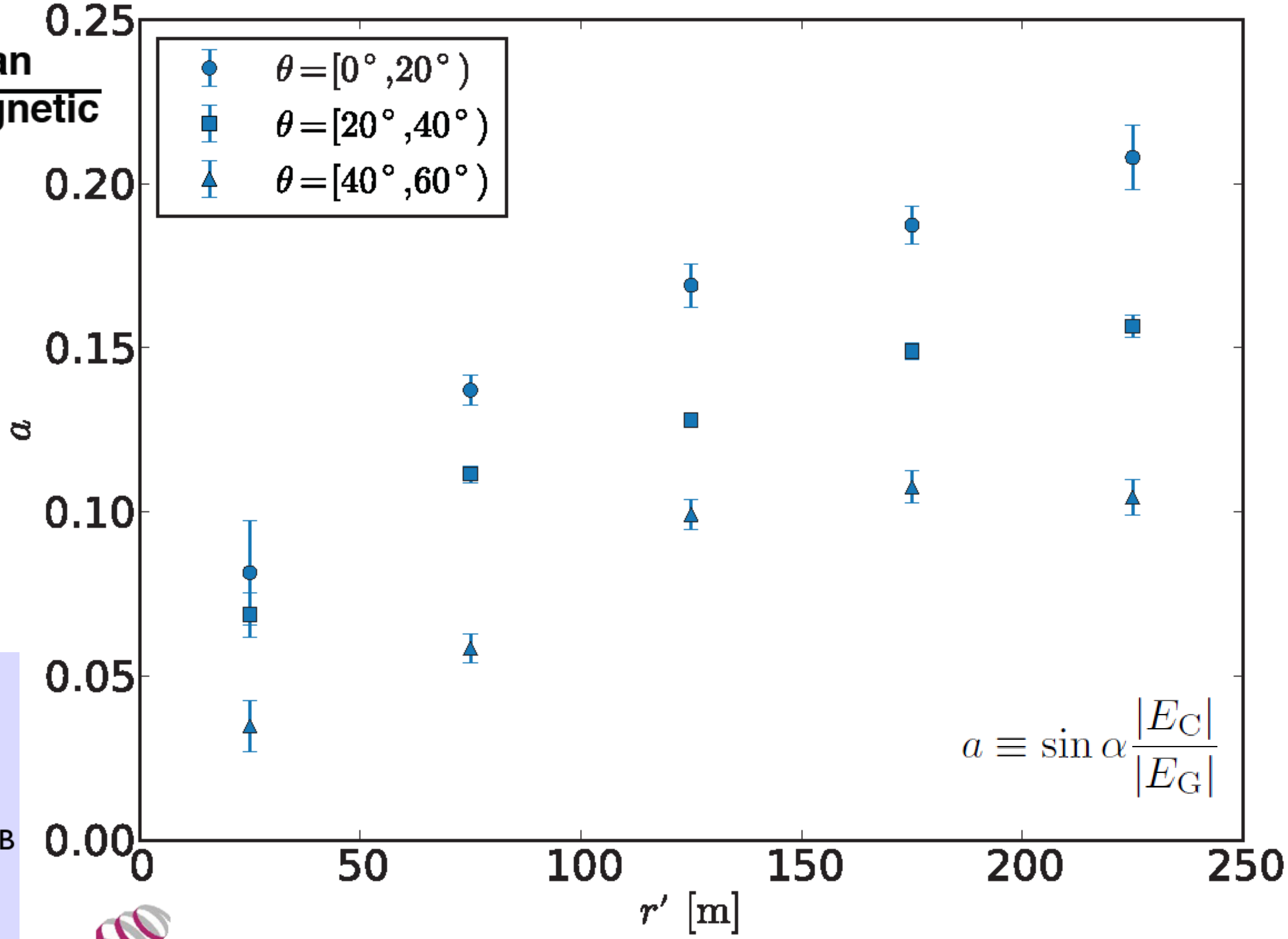
K. Werner et al., ApP 29 (2008) 393

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

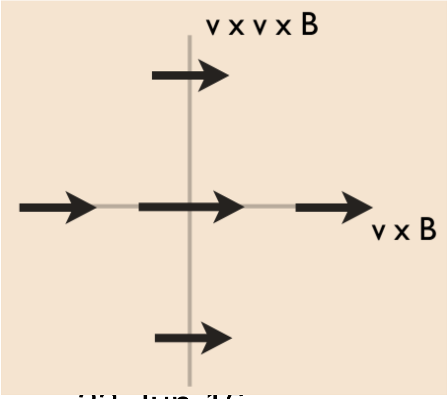
Charge excess fraction



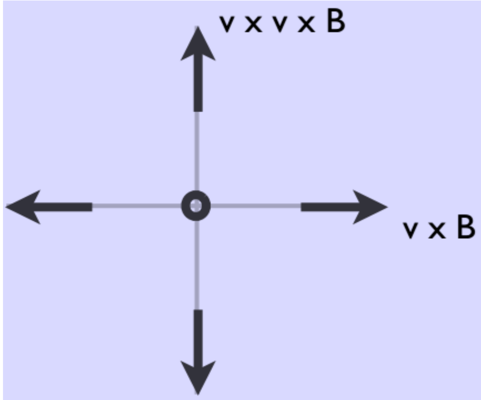
$$\frac{\textbf{Askaryan}}{\textbf{geomagnetic}}$$



geomagnetic



Askaryan



P. Schellart et al., JCAP 10 (2014) 014

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)

NEW: Circular polarization = V/I

Interpretation circ-pol for fair weather

Transverse current: constant near core,

Charge excess: vanishes at core, thus:

→ Proportional to sin(viewing angle) = d/h

→ Emission at lower heights enhanced (with the same current profile)

→ Pulse maximum arrives slightly later

→ V/U=tan(phase diff) is measure of time shift

Delay is frequency and distance dependent

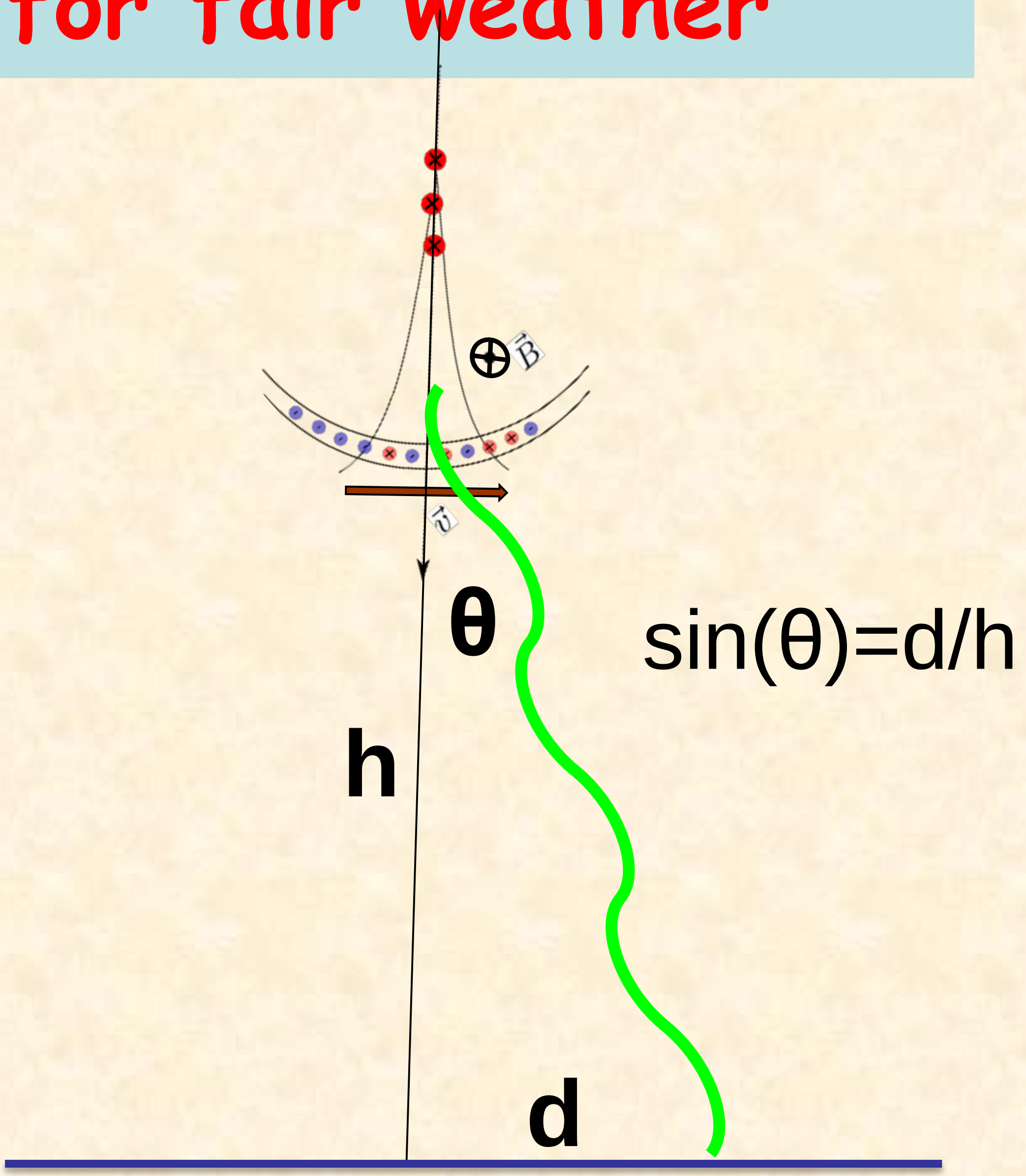
At 100 m, 30-80 MHz, delay = 1 ns

$E_{ch}(t) = (d/h)\, E_{tc}(t)$

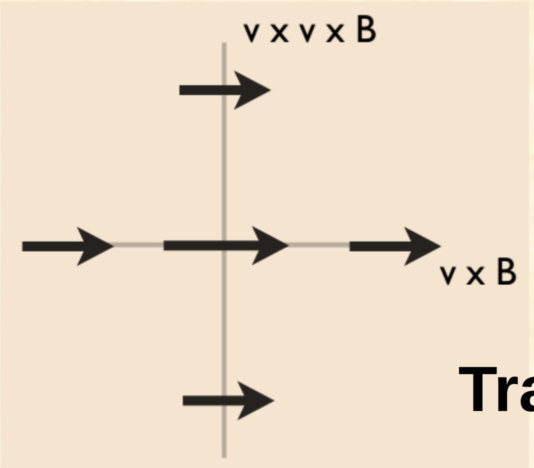
$t = d^2/(2hc)$ → $h = d^2/(2tc)$

→ $E_{ch}(t) = t\,(2c/d)\, E_{tc}(t)$

N.B. formula does not apply when d=0=t

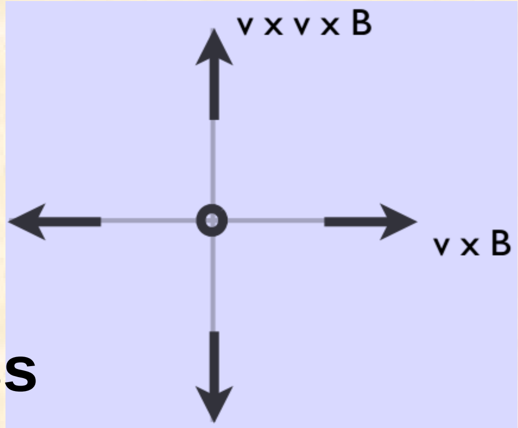


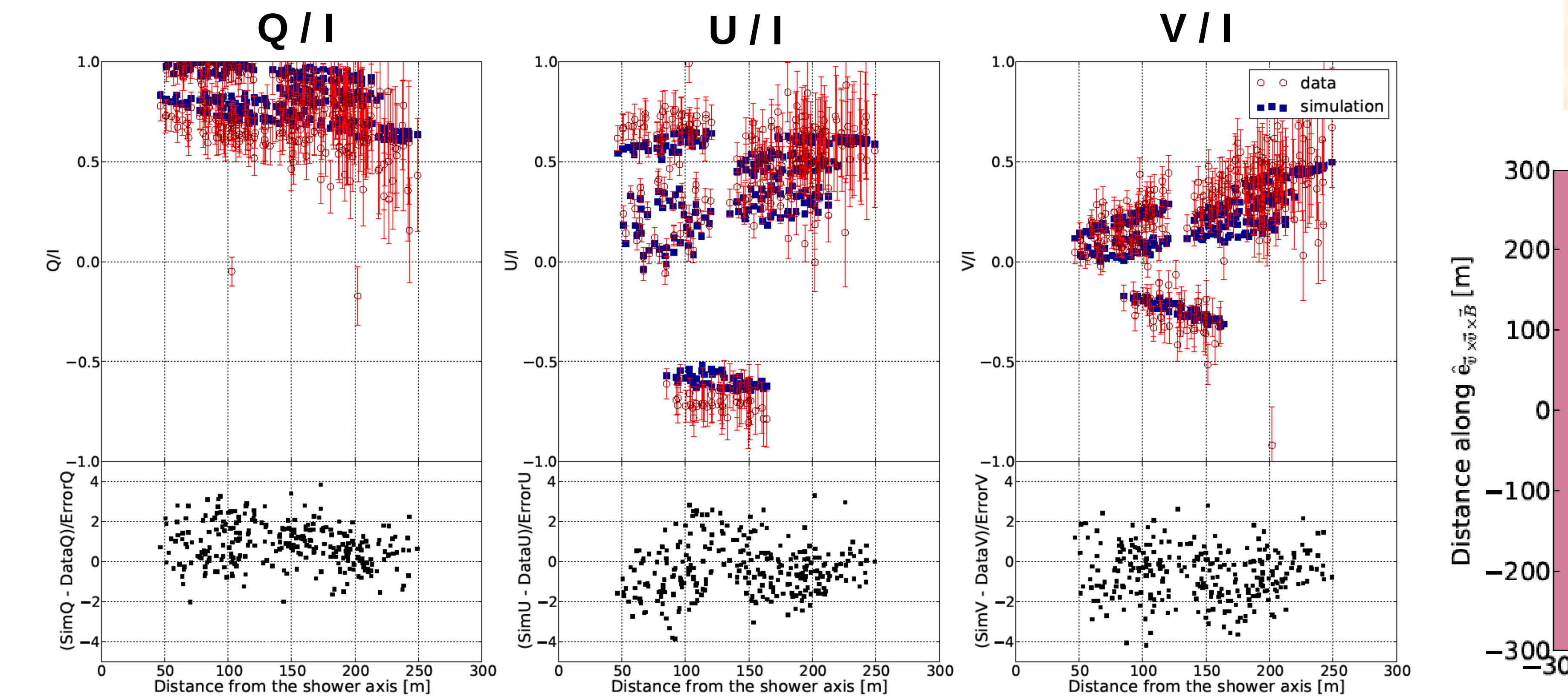
LOFAR data v.s. CoREAS

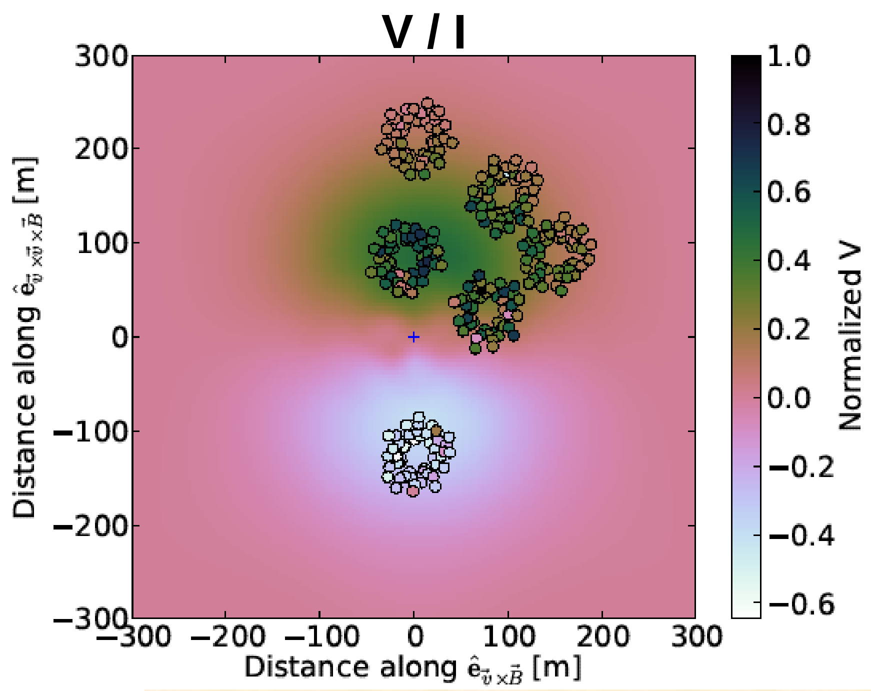


Reason for fair-weather circular polarization:

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





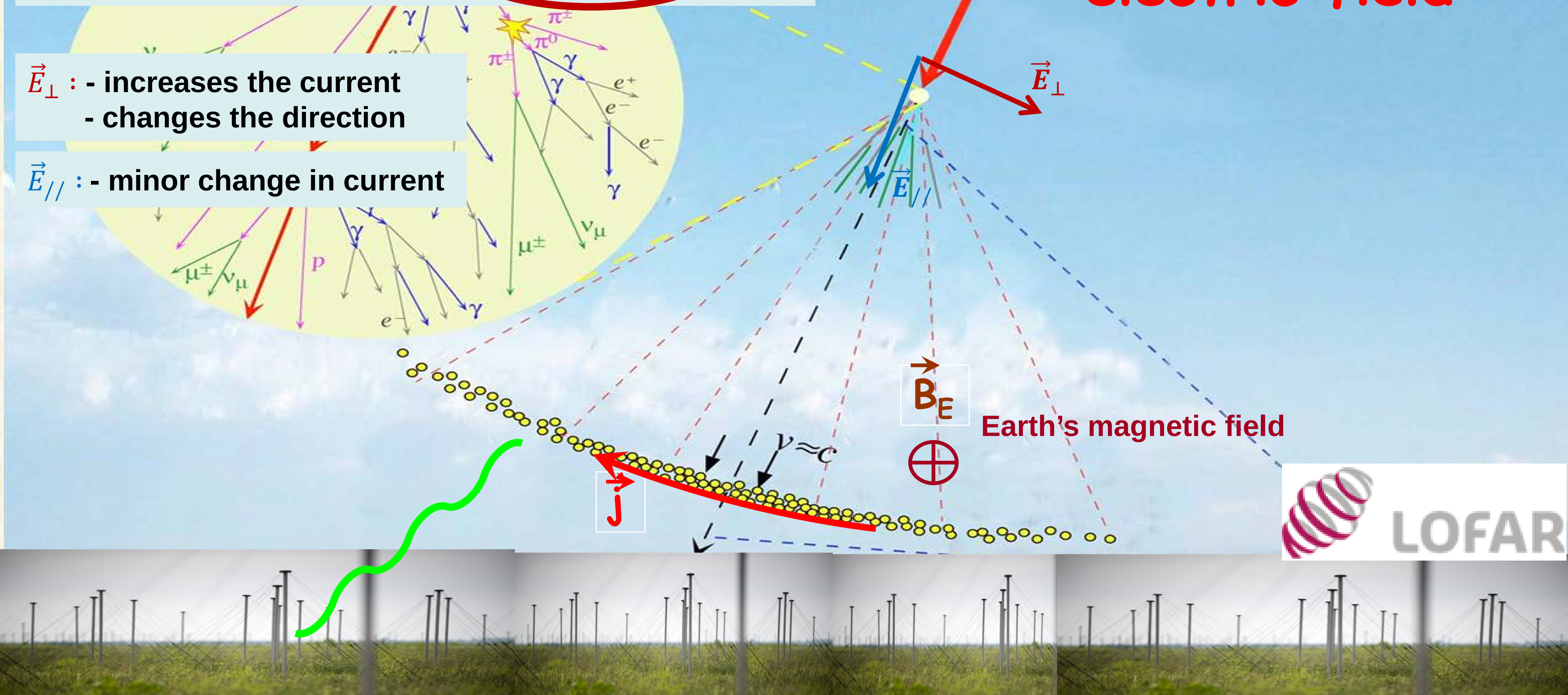


Radio emission in presence of an electric field

The Earth magnetic field in combination with the electric field induces an electric current $\vec{j}$ in the air-shower pancake in the direction $F = v \times B + E_{\perp}$

$\vec{E}_{\perp}$: - increases the current
- changes the direction

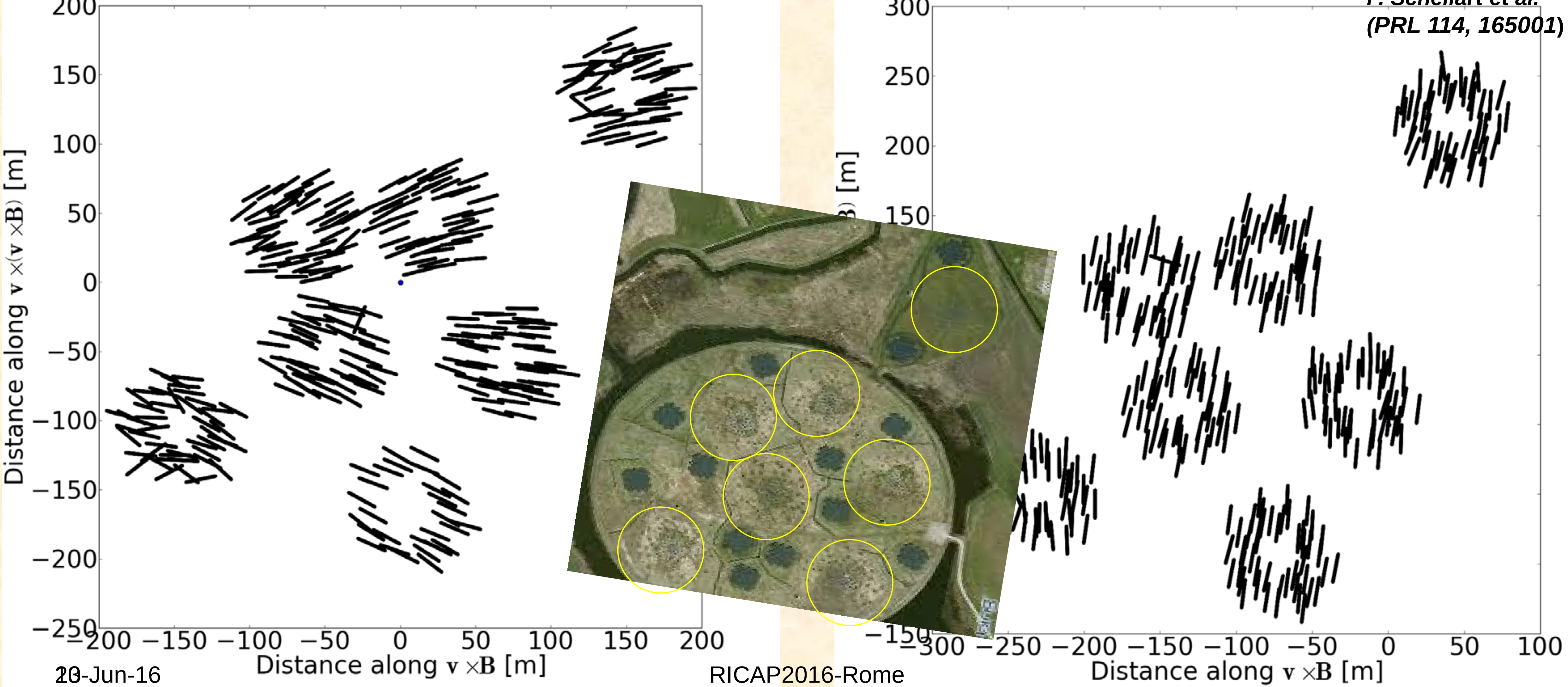
$\vec{E}_{//}$: - minor change in current



Observations; polarization footprint

Fair weather vs thunderstorm

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

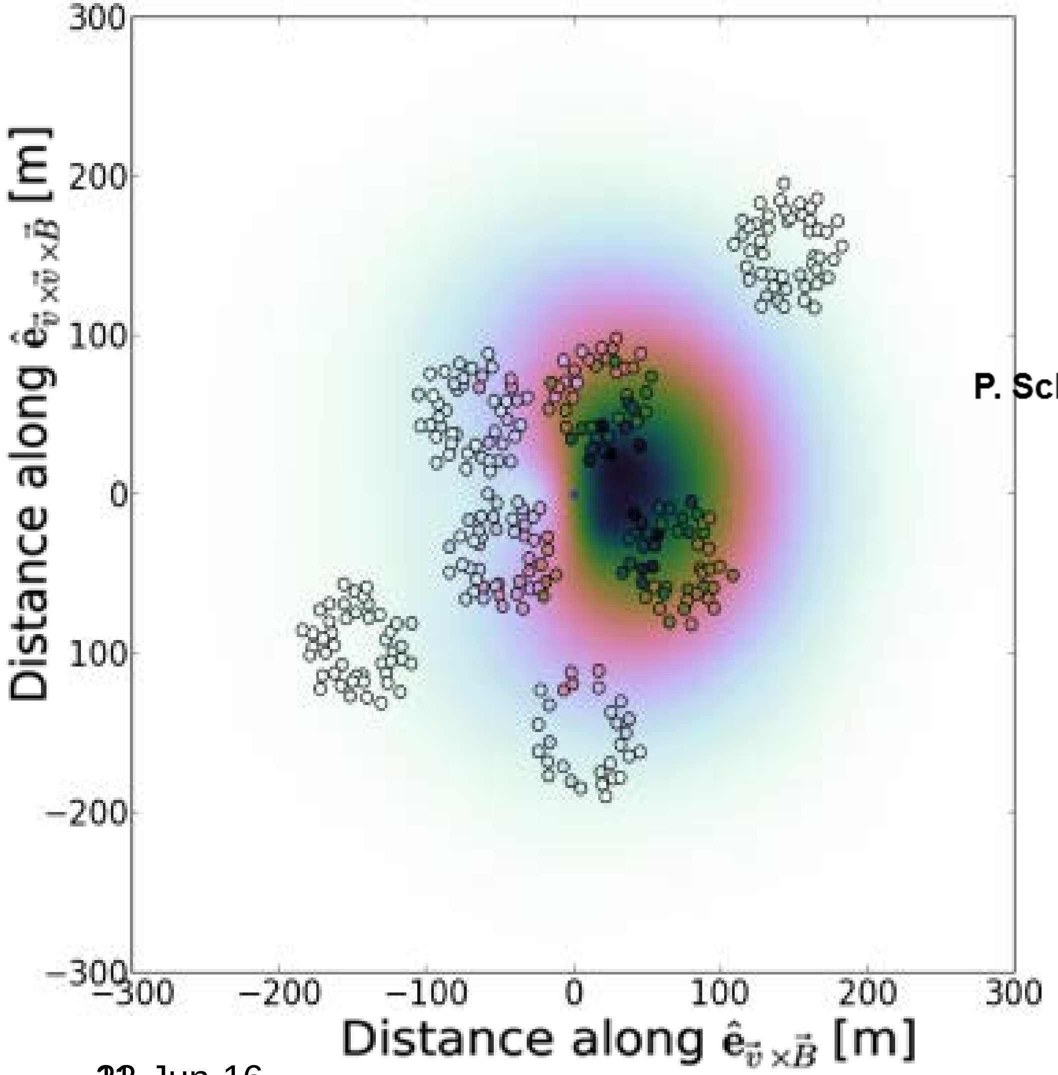


Observations; intensity footprint

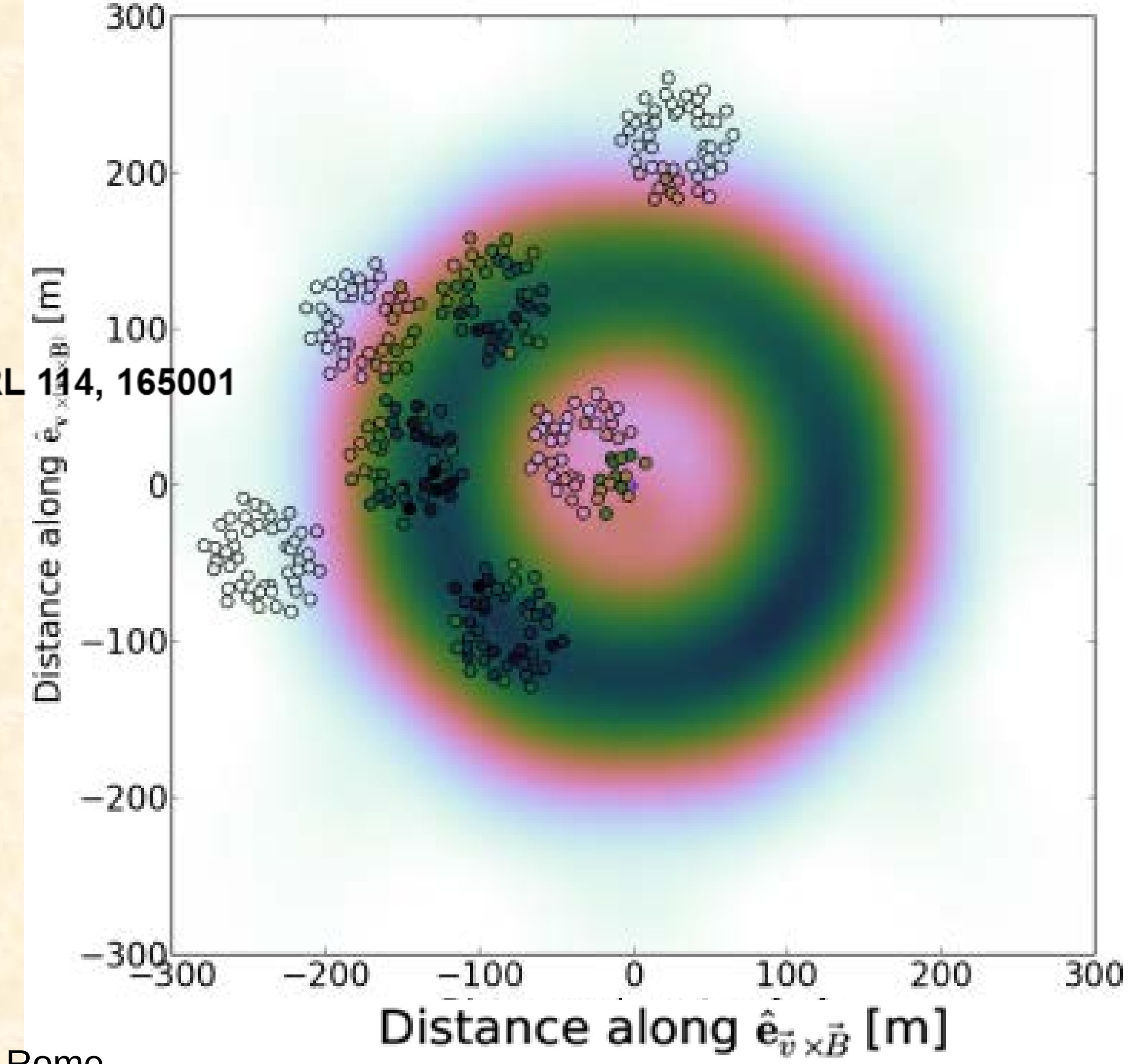
S. Buitink et al.
PRD 90, 082003 (2014)

Fair weather vs thunderstorm

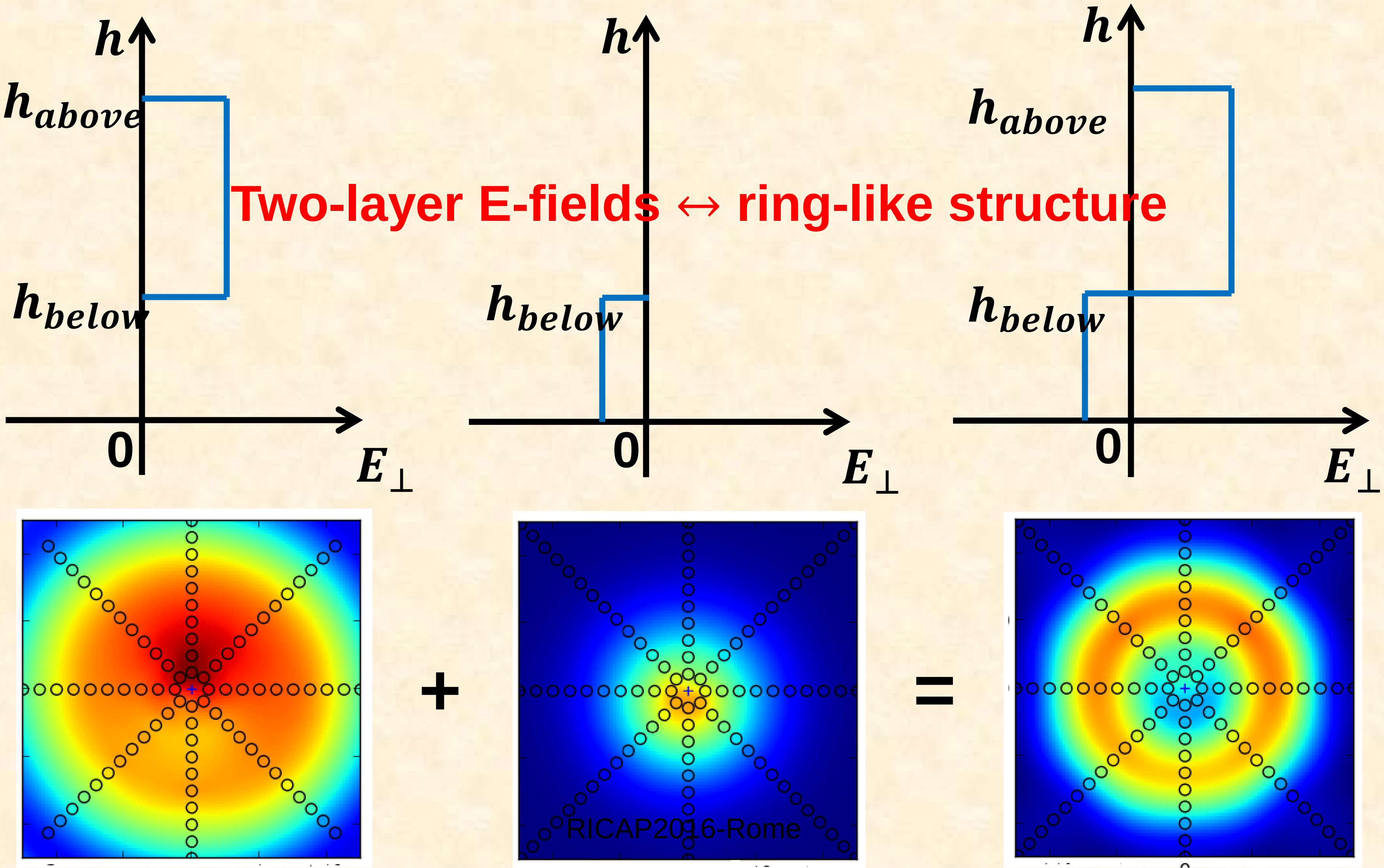
P. Schellart et al.,
PRL 114, 165001 (2015)



P. Schellart et al., PRL 114, 165001

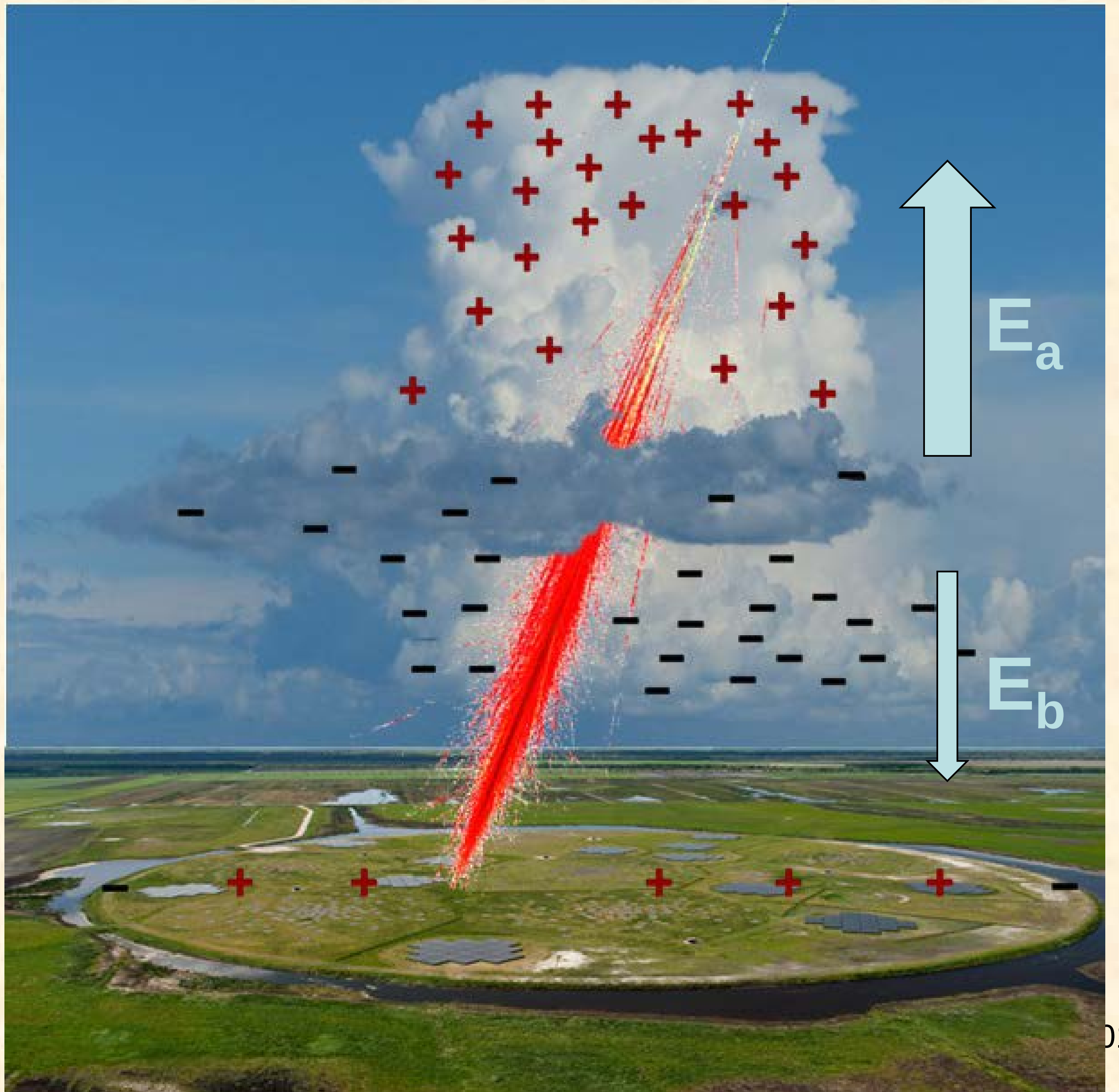


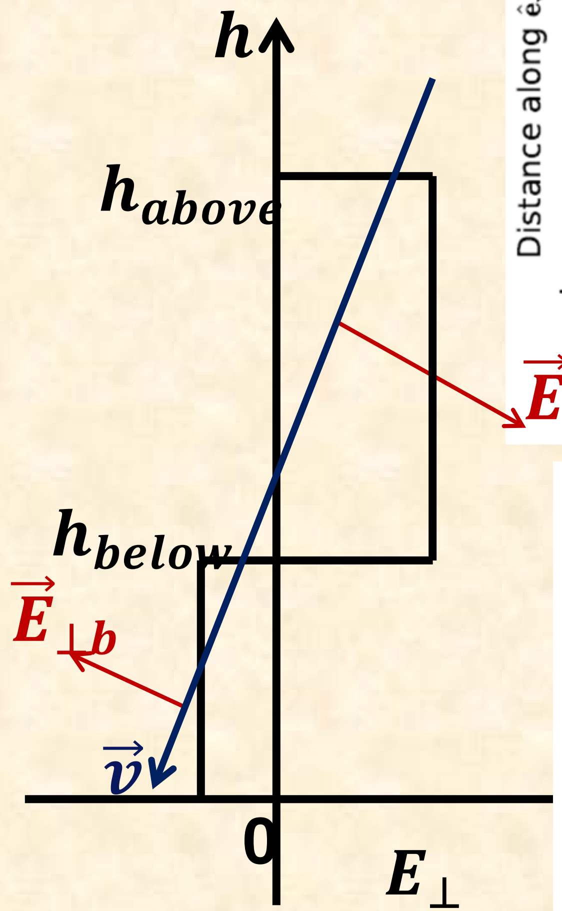
Ring structure through interference

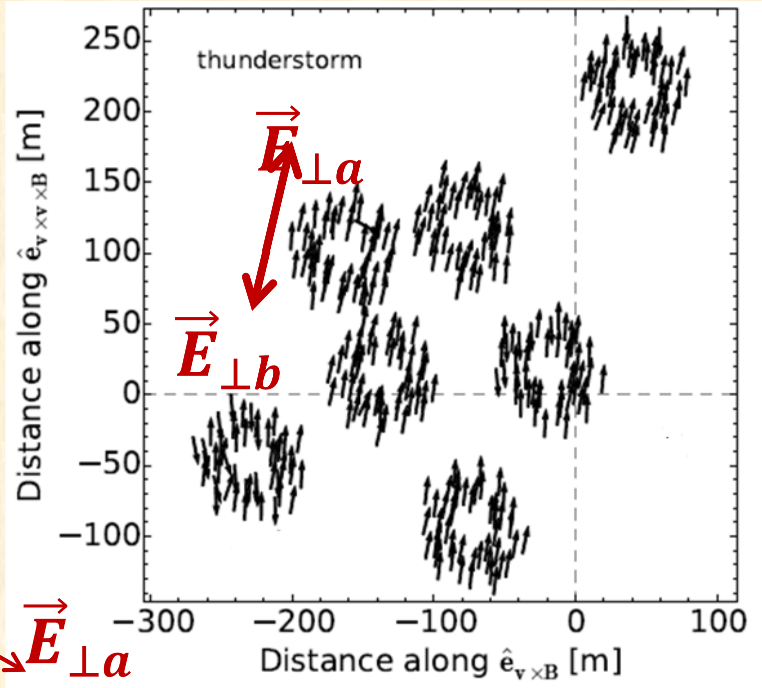


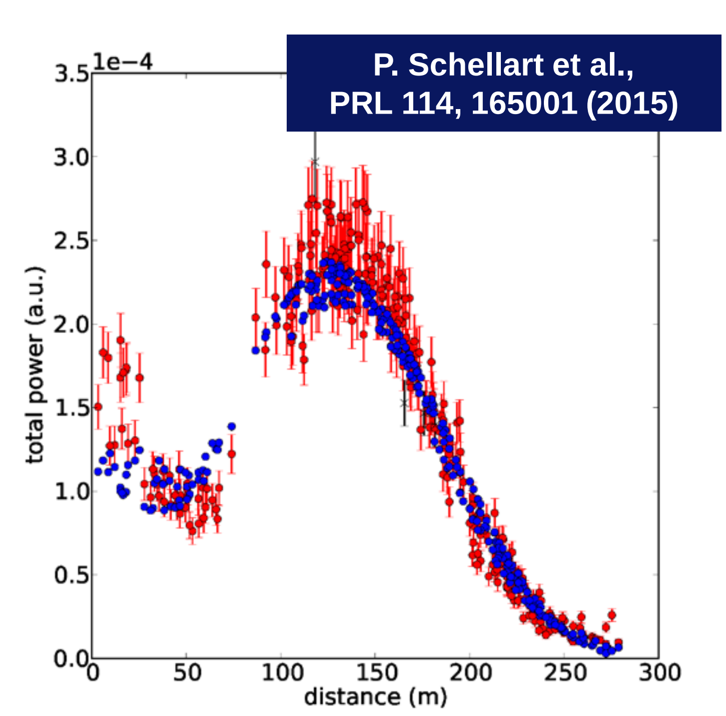
Two-layer E-fields ↔ ring-like structure

Structure E-fields





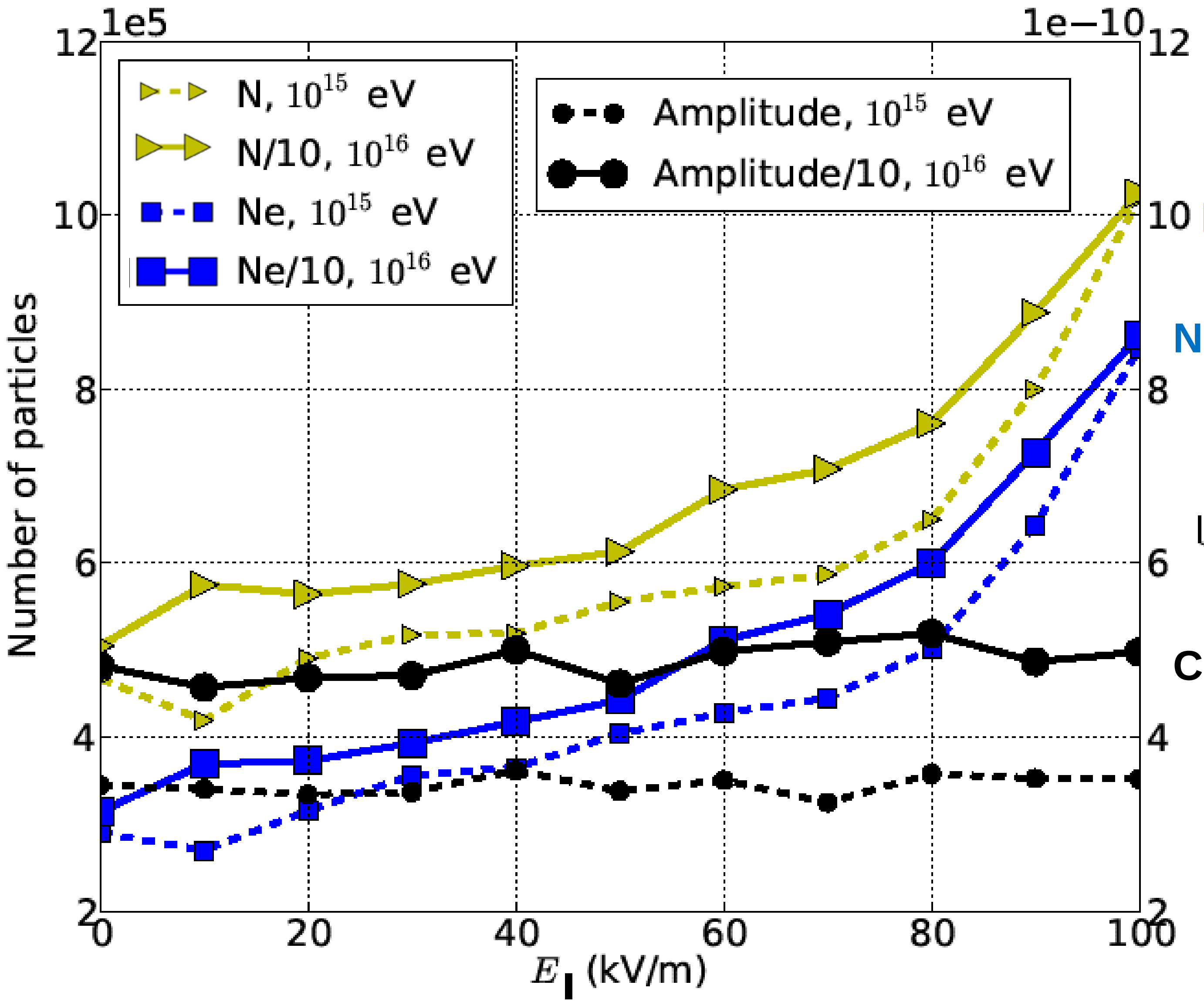




P. Schellart et al., PRL 114, 165001 (2015)

Dependence on electric field strength

T.N.G. Trinh et al., Phys Rev D 93 (2016) 023003



$\vec{E}_{//}$

Expect:
Amplitude= N v_d

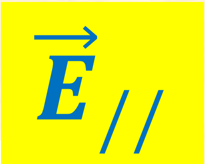
N-electrons+positrons (CORSIKA)

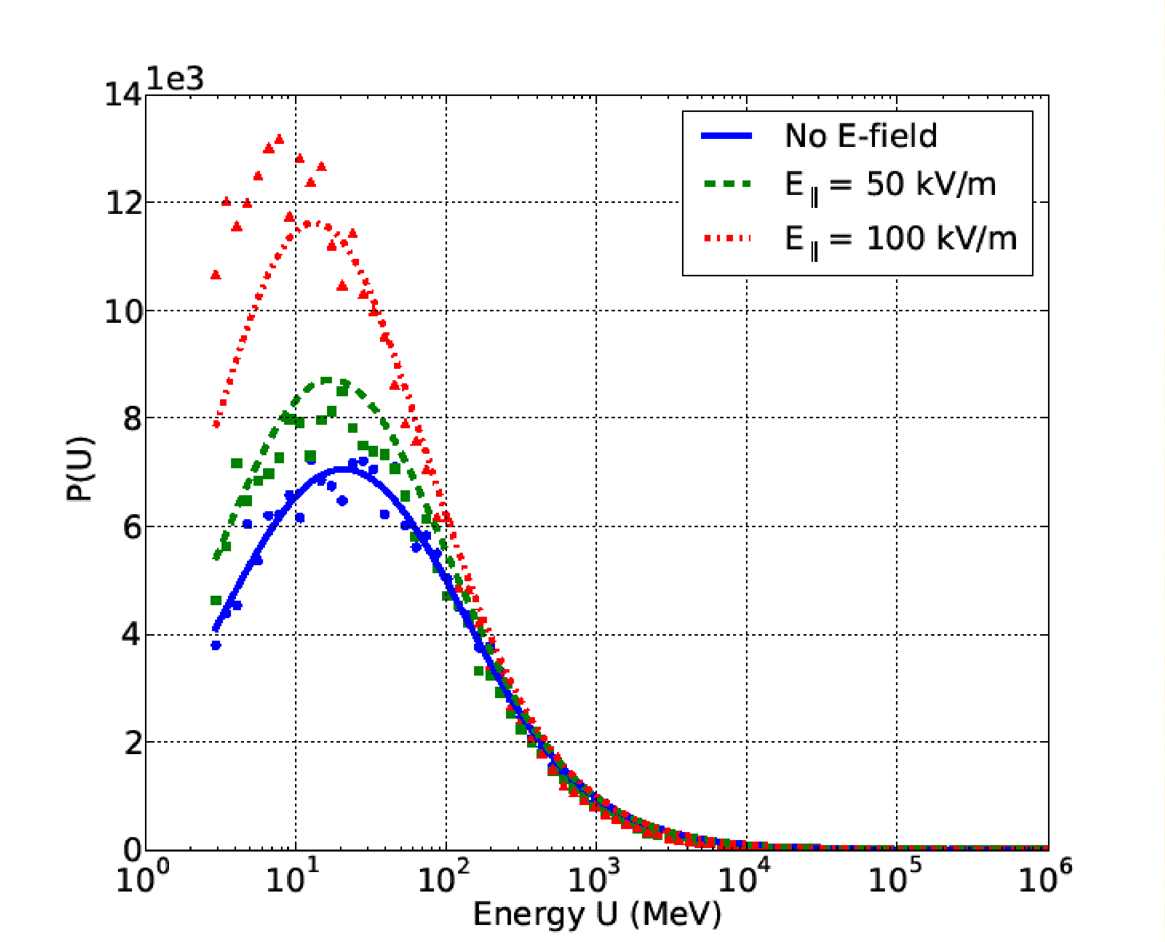
N-electrons (CORSIKA)

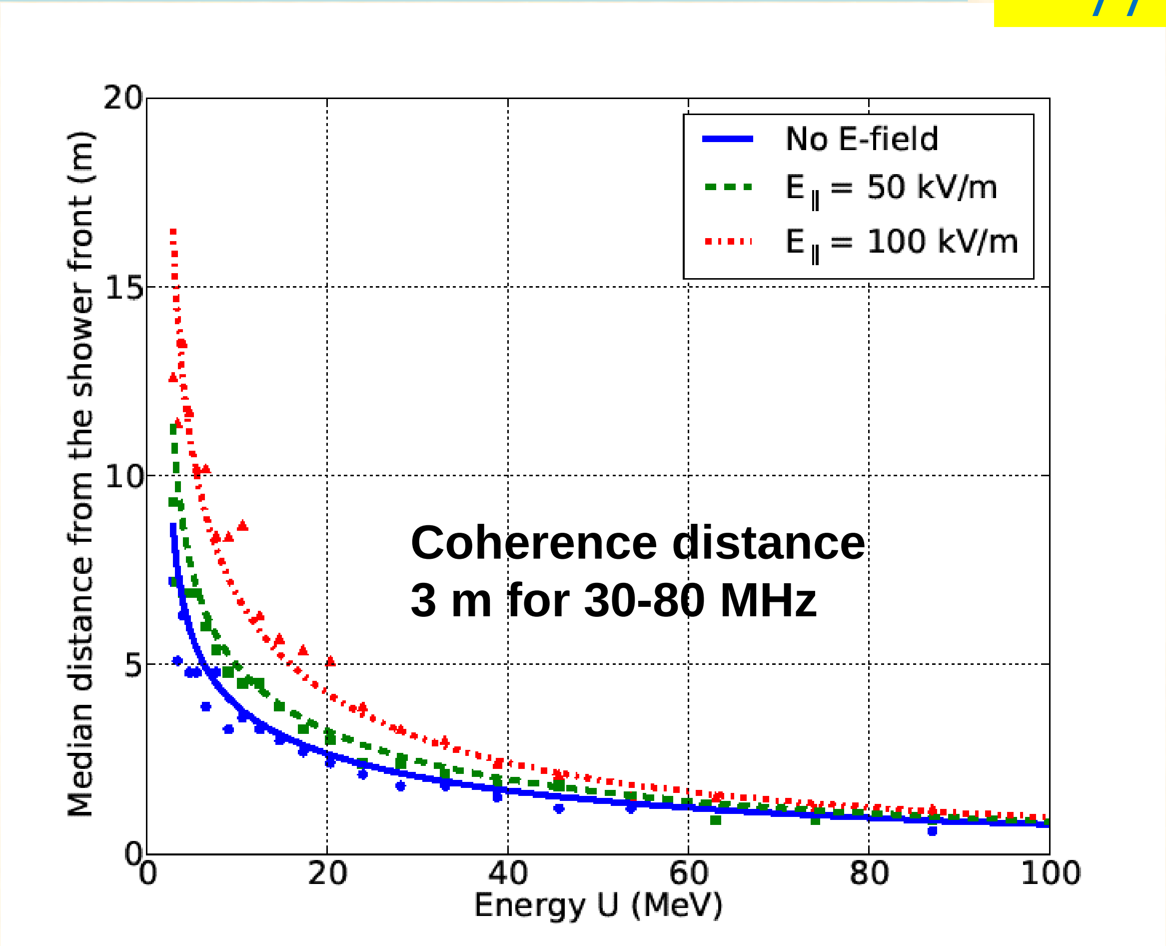
Calculated amplitude (30-80 MHz) (CoREAS)

With increasing $E_{//}$ little changes in pulse height

Shower physics with parallel E-field







Enhancement of lower energy particles

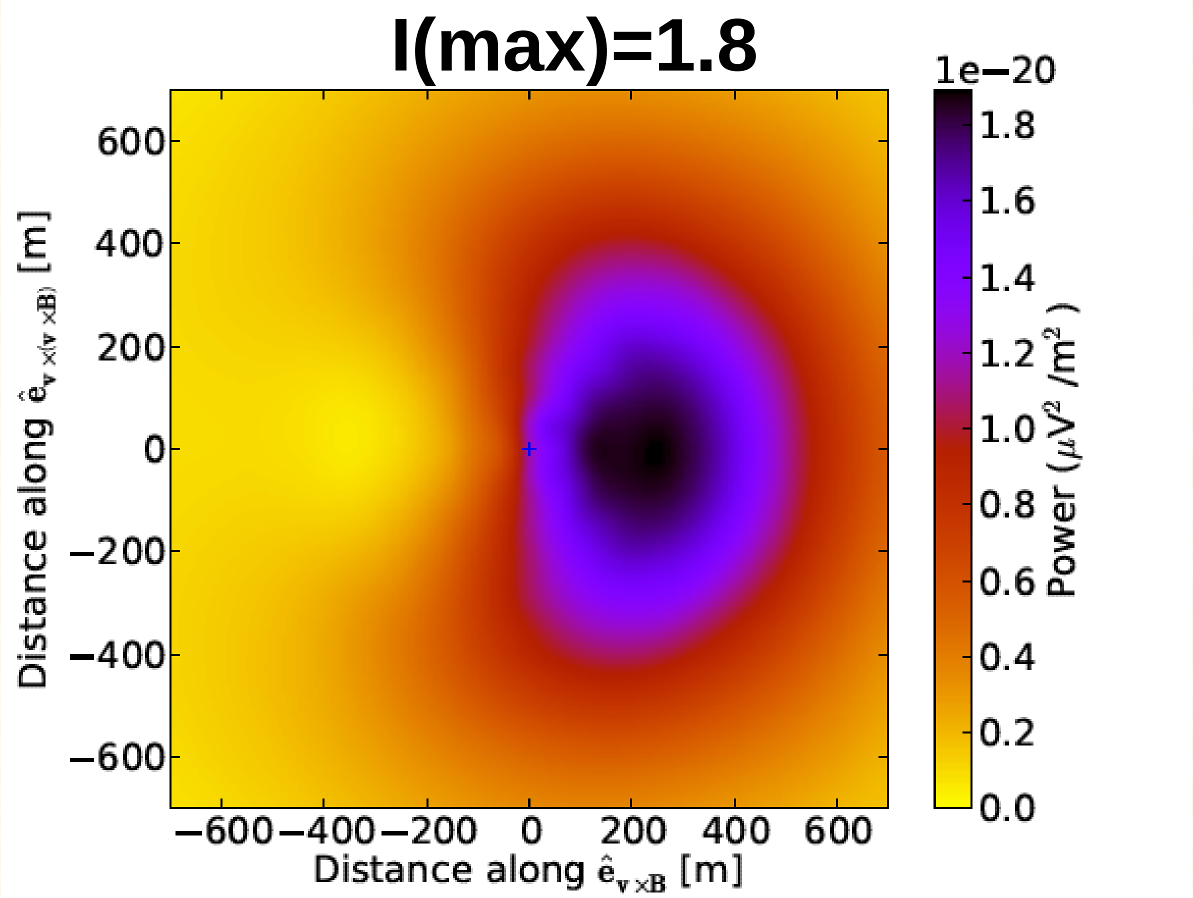
Lower energy particles at large distance behind shower-front

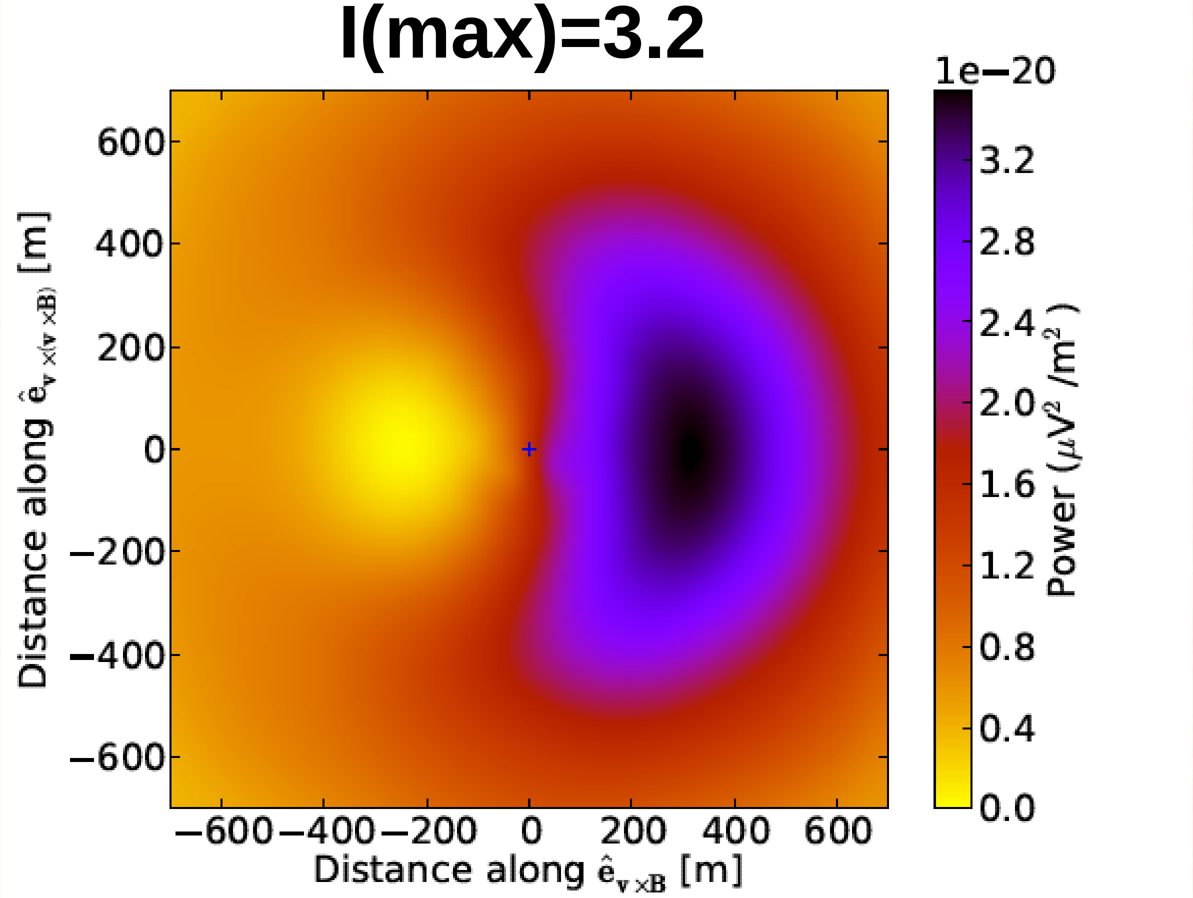
Loss of coherence for 30=80 MHz

Strength seen at lower frequencies

$\vec{E}_{//}$

$\vec{E}_{//} = 50\ kV$ **2-9 MHz** $\vec{E}_{//} = 100 kV$

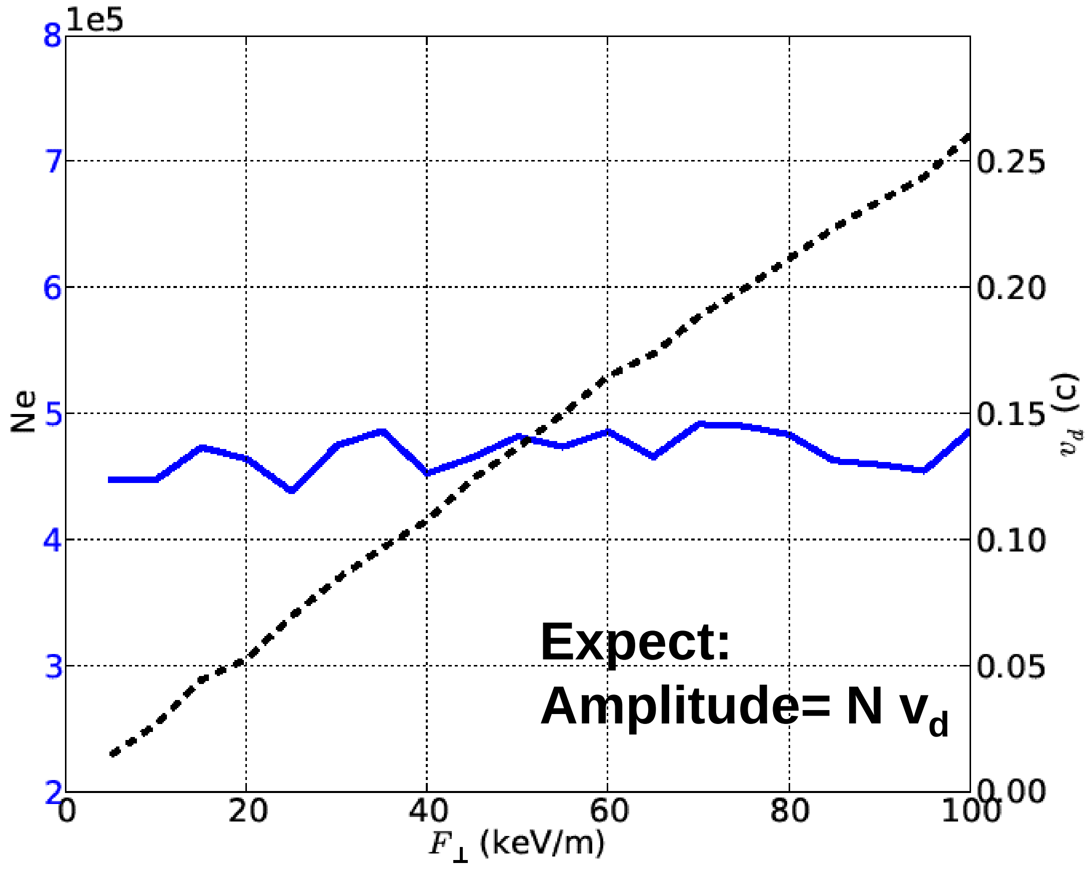


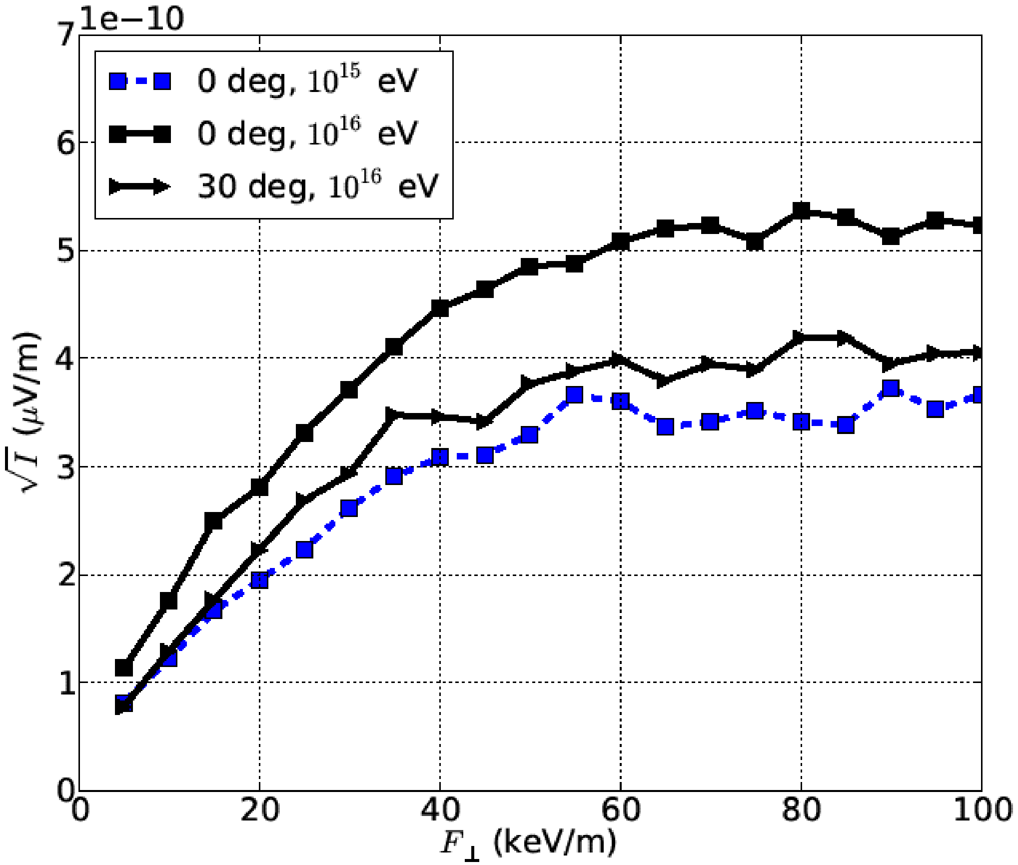


Dependence on $\vec{E}_\perp$

T.N.G. Trinh et al.,
Phys Rev D 93 (2016) 023003

$\vec{E}_\perp$



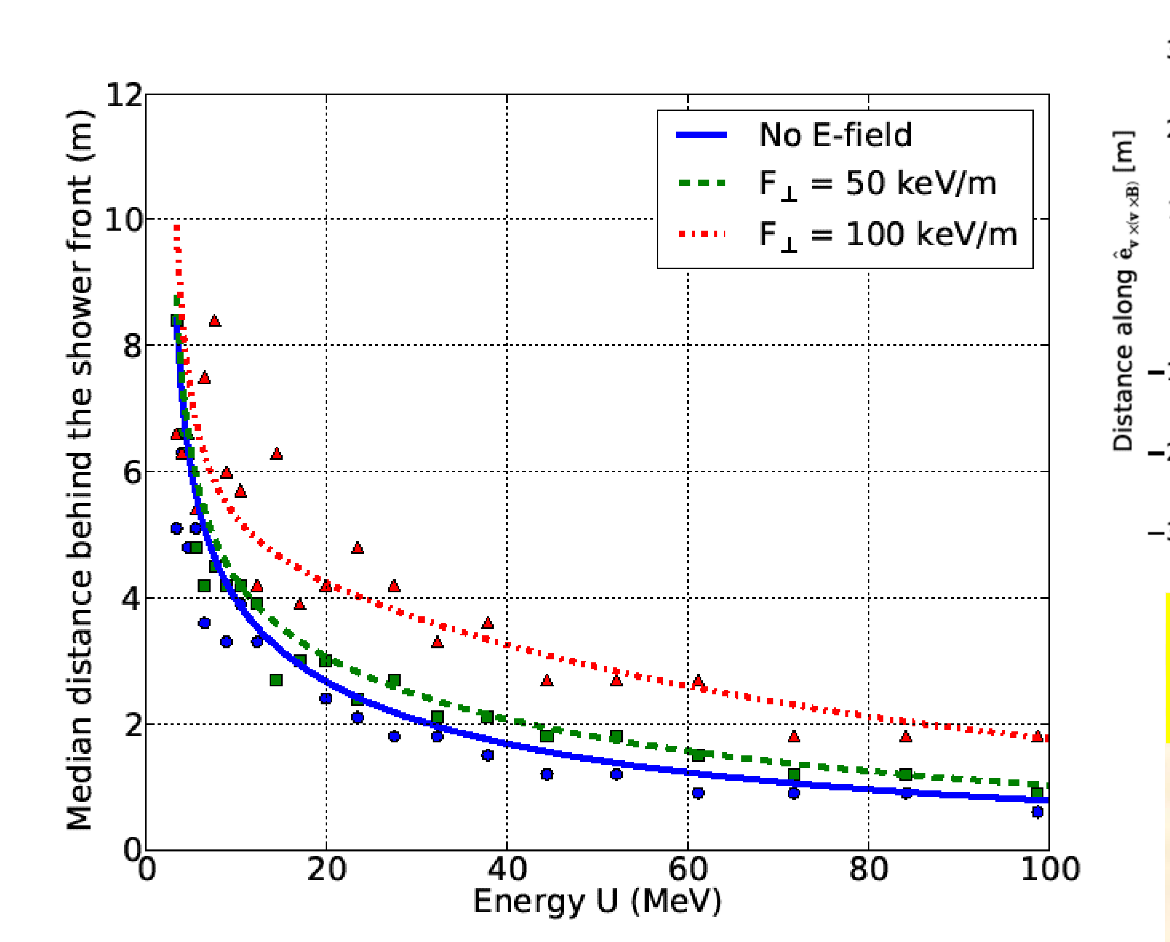


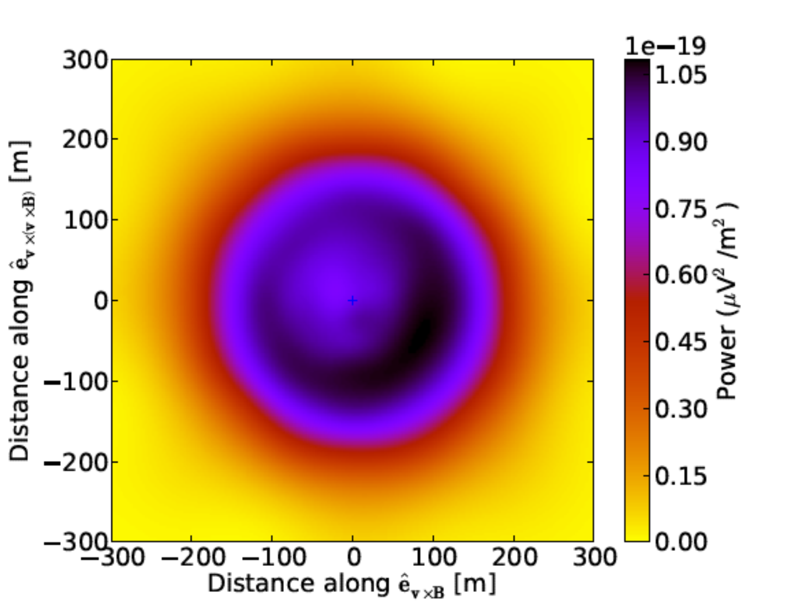
Drift velocity increasing E_{perp}
Number of electrons constant

Amplitude (30-80 MHz) saturates at 50 keV/m

Effects of perpendicular force

$\vec{E}_\perp$

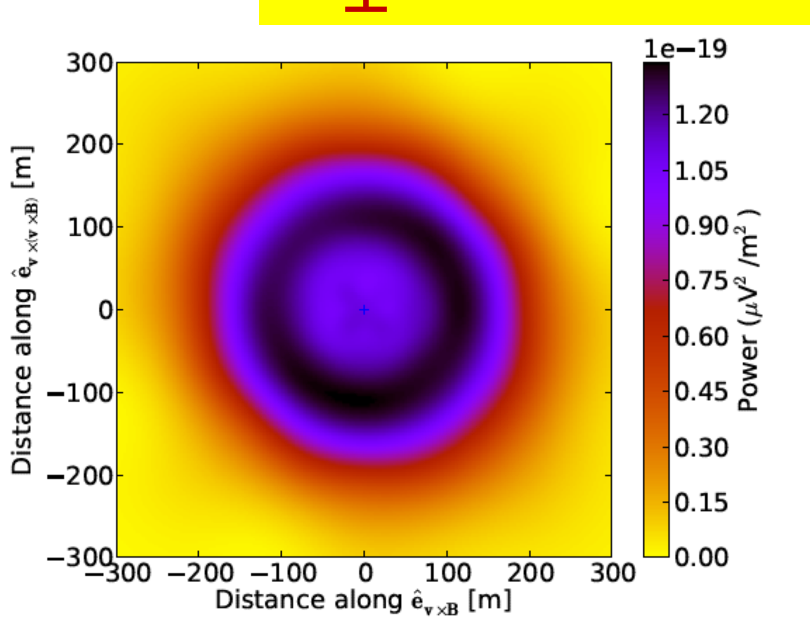




2-9 MHz

$\vec{E}_\perp$= 50 kV

$\vec{E}_\perp$= 100 kV



With increased sideward drift the longitudinal velocity decreases

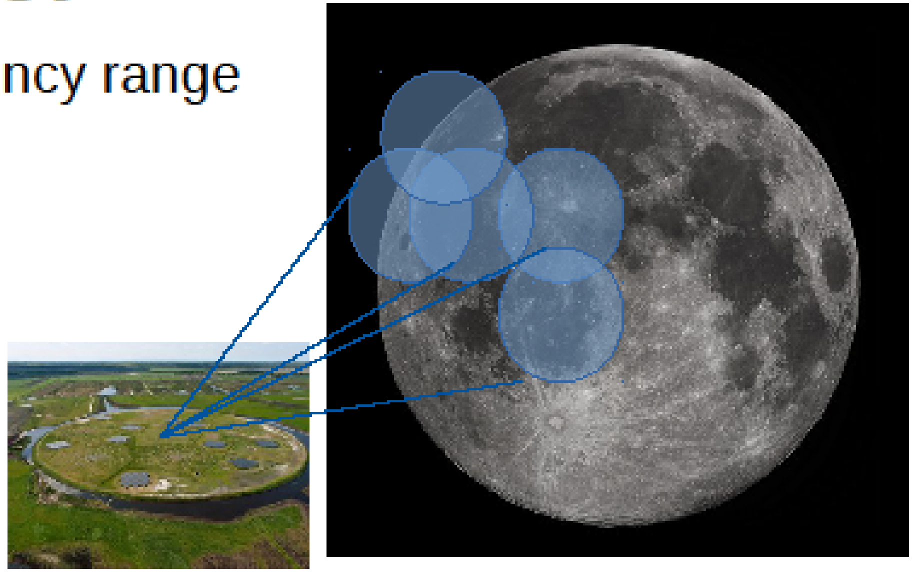
Loss of coherence in 30-80 MHz at large F

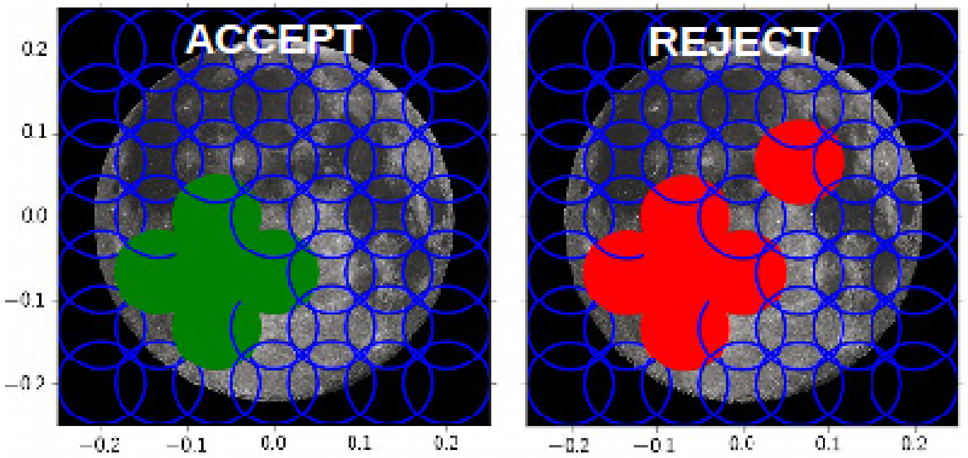
NuMoon @ LOFAR

Basic idea:
Moon is a pretty large (=10^7 km^2) target for ultra-high energy particles.
Observe emitted radio signals.

Observation Strategy

- HBA Antennas have optimal frequency range
- Form multiple beams on the Moon
- Search for ns pulses in time-series
- Anti coincidence to suppress RFI
- Analyze Faraday rotation and dispersion to check lunar origin





Challenges

- Data rate 0.8 GiB/s per station/beam

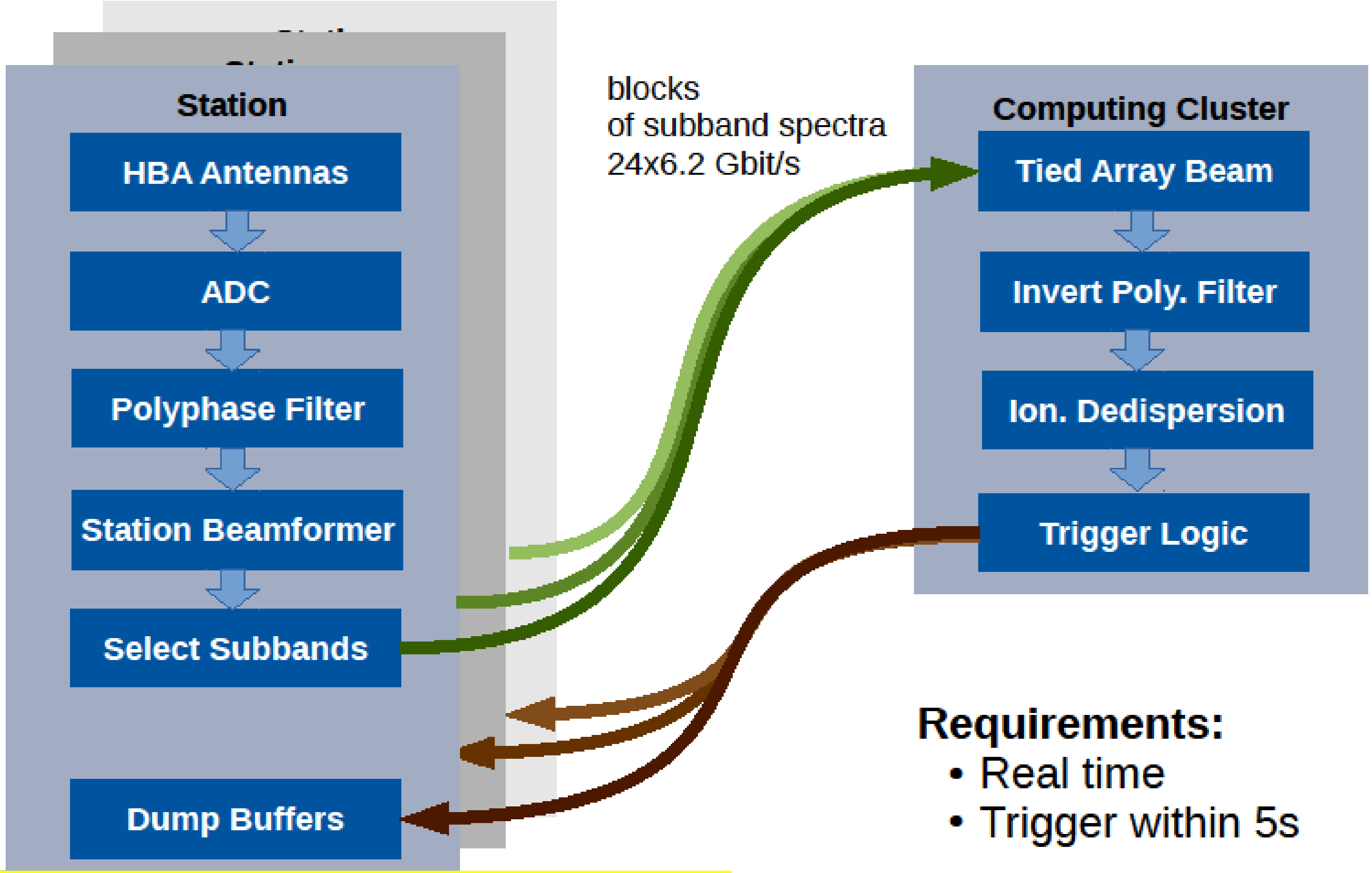
  → Trigger required
- LOFAR designed to integrate flux
  - Reconstruct time series from filtered signal for trigger
  - Use buffered traces for analysis

Slide prepared by Tobias Winchen, VUBrussels, for the LOFAR Cosmic Ray Key Science program

THE Challenge

Huge amounts of data need complicated treatment to search for lunar trigger.

Online Data Analysis



Requirements:

- Real time
- Trigger within 5s

Slide prepared by Tobias Winchen, VUBrussels, for the LOFAR Cosmic Ray Key Science program

THE Solution

A large GPU cluster designed for high data through put.

DRAGNET Cluster

- Designed for Pulsar searches (J. Hessels et al.)
  - 23 worker nodes
    - 16 CPU cores (2x Xeon E5-2630v3 (2014))
    - 128 GiB ram
    - 4x TitanX GPU
    - 56 Gbit/s Infiniband connection to LOFAR

  = 92 High-End GPUs + CPUs ; 0.5 PetaFLOPs
- Estimate based on prototype implementation:
  - 2 beams per node,
  - Computing power allows 46 beams total:

  → **Full coverage of the moon with .1 deg beams possible**

Slide prepared by Tobias Winchen, VUBrussels, for the LOFAR Cosmic Ray Key Science program

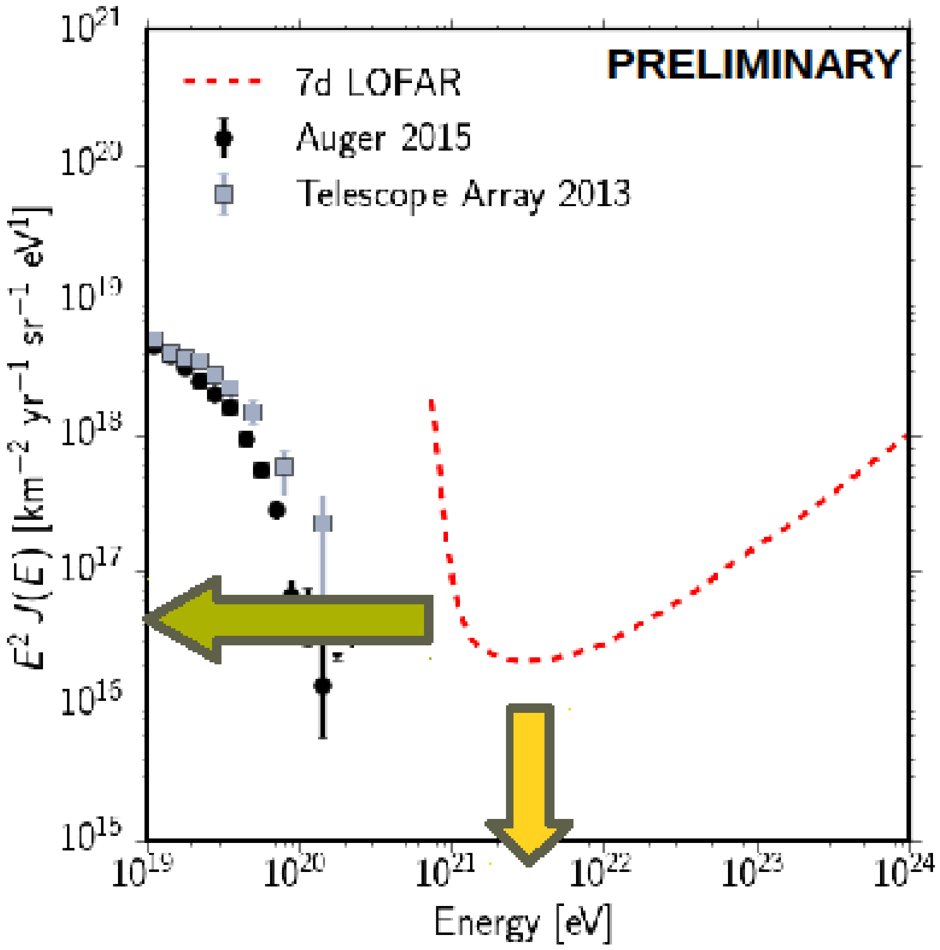
Sensitivity

Sensitivity Optimization

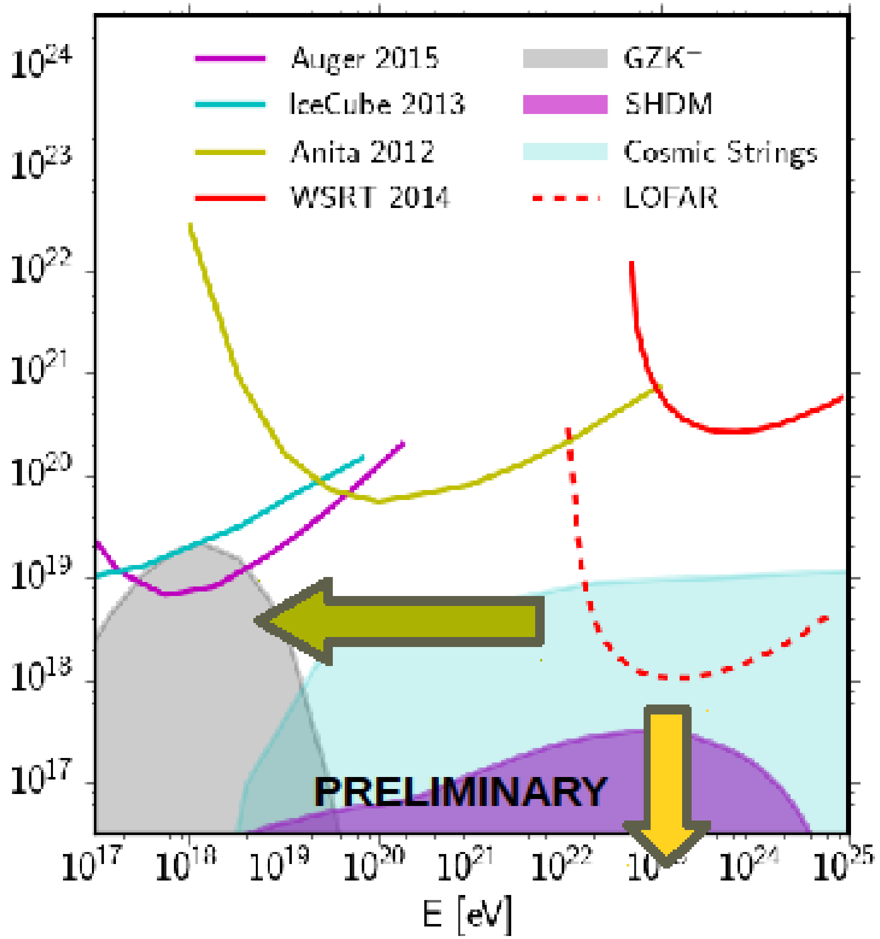
LOFAR → proof of concept.

Detection might be possible with SKA

COSMIC RAYS



NEUTRINOS



Energy Threshold:
- Number of Stations
- Shape of beams
- ...

Sensitivity:
- Number of Beams
- Observation Time
- ...

Slide prepared by Tobias Winchen, VUBrussels,

Conclusions

Radio emission from air showers is very well understood

example: circular polarization for fair weather

→ Can be used as diagnostic tool to extract sower parameters such as

X_max

atmospheric electric fields

Lunar detection offers possibilities at the highest energies.