

High-energy cosmic rays at LOFAR.

Olaf Scholten



LORA Scintillator



university of
 groningen

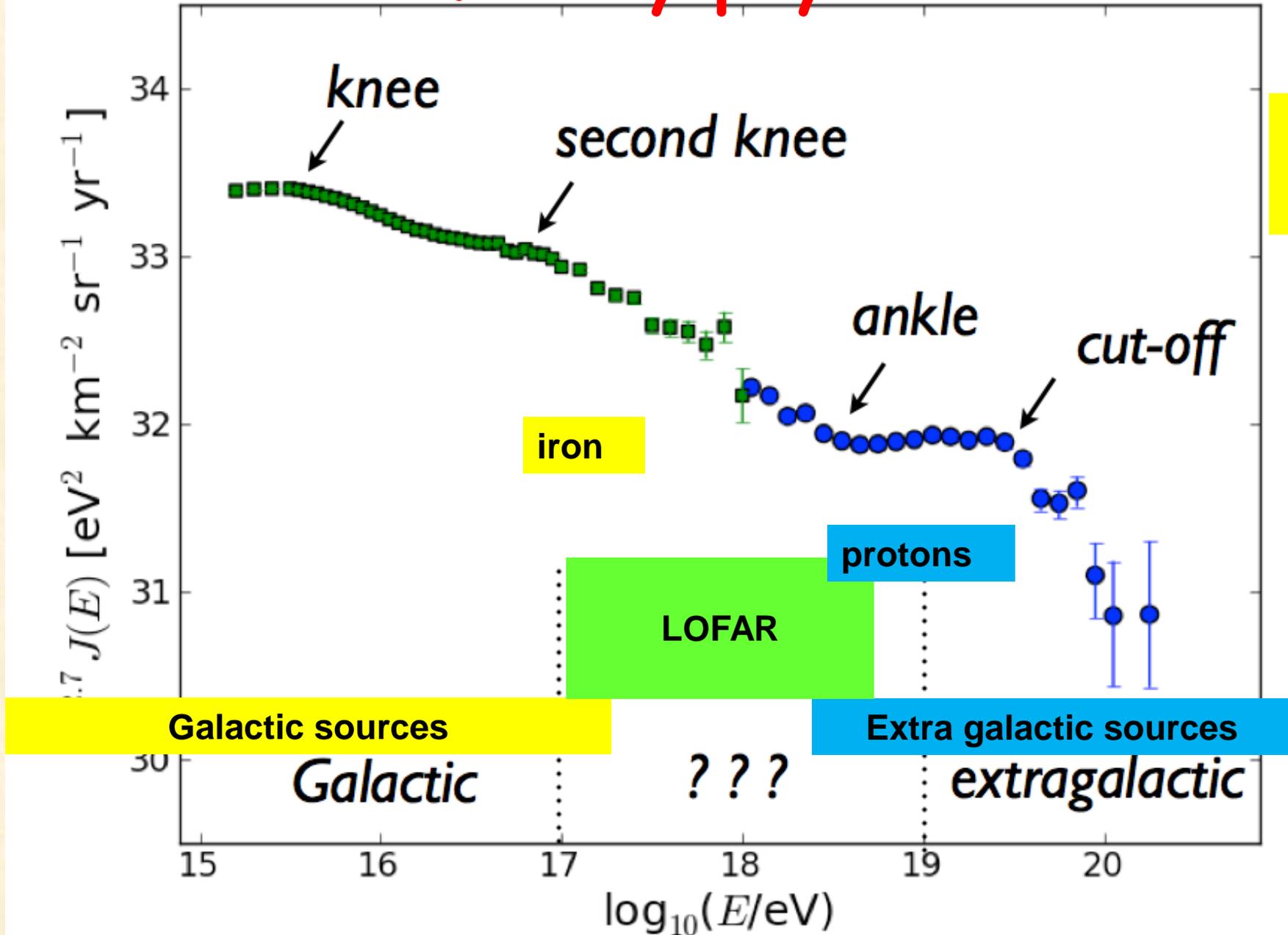
kvi - center for advanced
 radiation technology

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

A large light-mass component of cosmic rays at 10^{17} – $10^{17.5}$ electronvolts from radio observations

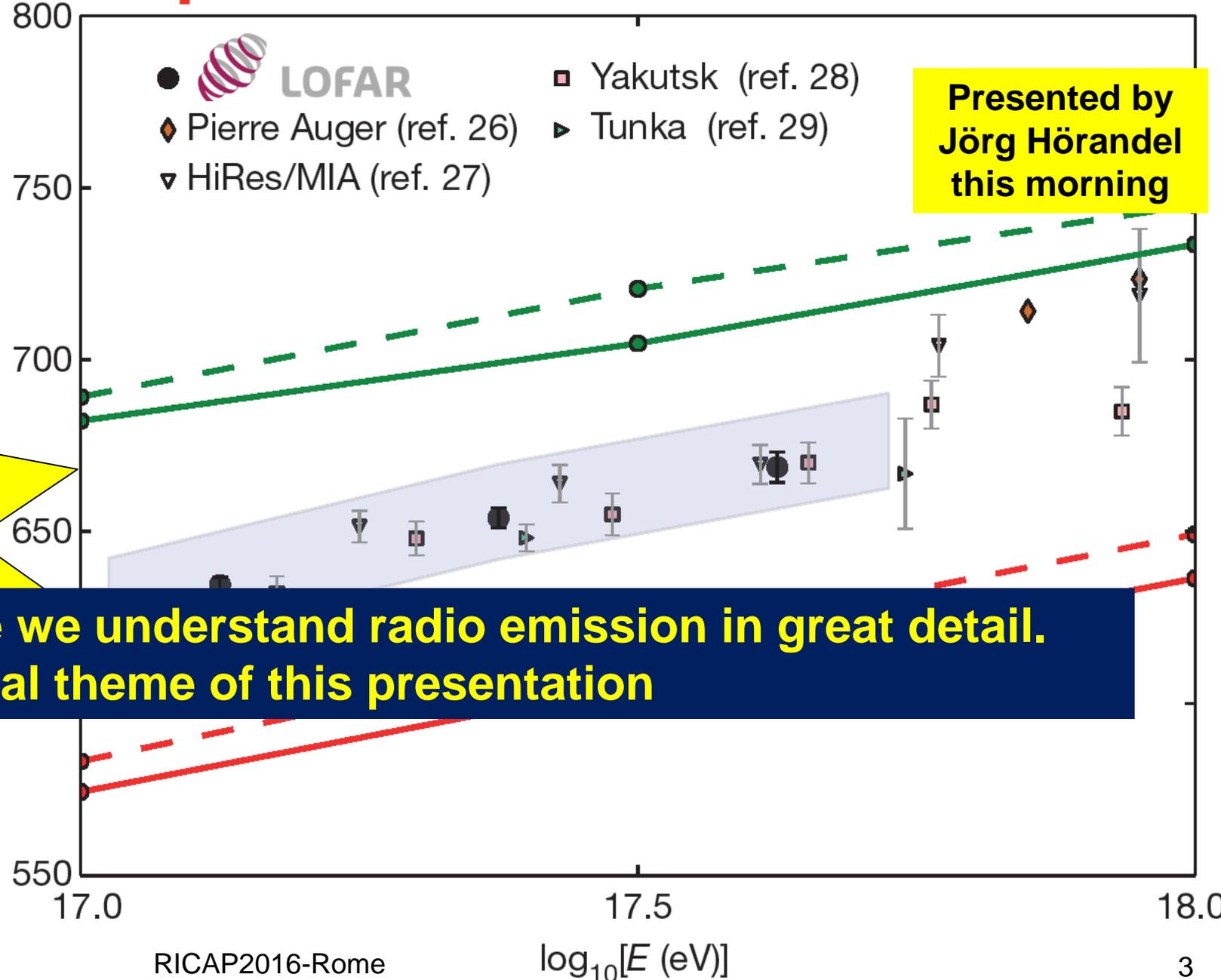
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Cosmic rays are the highest-energy particles found in nature. Measurements of the mass composition of cosmic rays with energies of 10^{17} – 10^{18} electronvolts are essential to understanding whether they have galactic or extragalactic sources. It has also been proposed that the astrophysical neutrino signal¹ comes from accelerators capable of producing cosmic rays of these energies². Cosmic rays initiate air showers—cascades of secondary particles in the atmosphere—and their masses can be determined from measurements of the atmospheric depth of the shower maximum, X_{max} , the depth of the air shower when it contains the most particles. The composition of shower particles reaching the ground depends on the mass of the primary particle and the energy of the shower. Measurements³ have either high uncertainty or a high energy threshold. Radio detection of air showers is a rapidly developing technique⁴ for determining X_{max} with a duty cycle of, in principle, nearly 100 per cent. It is generated by the separation of relativistic electrons and positrons in the geomagnetic field and a negative charge excess in the shower front^{5,12}. Here we report radio measurements of X_{max} with an uncertainty of 16 grams per square g/cm² for energies between 10^{17} and $10^{17.5}$ eV. This high resolution in X_{max} enables us to determine the mass spectrum of the cosmic rays: we find a mixed composition, with a light-mass fraction (protons and helium nuclei) of about 80 per cent. Unless contrary to current expectations, this indicates that galactic cosmic rays contribute substantially to the total flux of cosmic rays below $10^{17.5}$ eV. Our measurements also indicate the existence of an additional light component of cosmic rays with energies between 10^{17} and $10^{17.5}$ eV. Observations with the LOFAR radio telescope, built in the Netherlands, and the MWA radio telescope, built in Australia, are essential to understand the origin of cosmic rays.

published in nature

Nature

Depth of the shower maximum



Multiple emission mechanisms

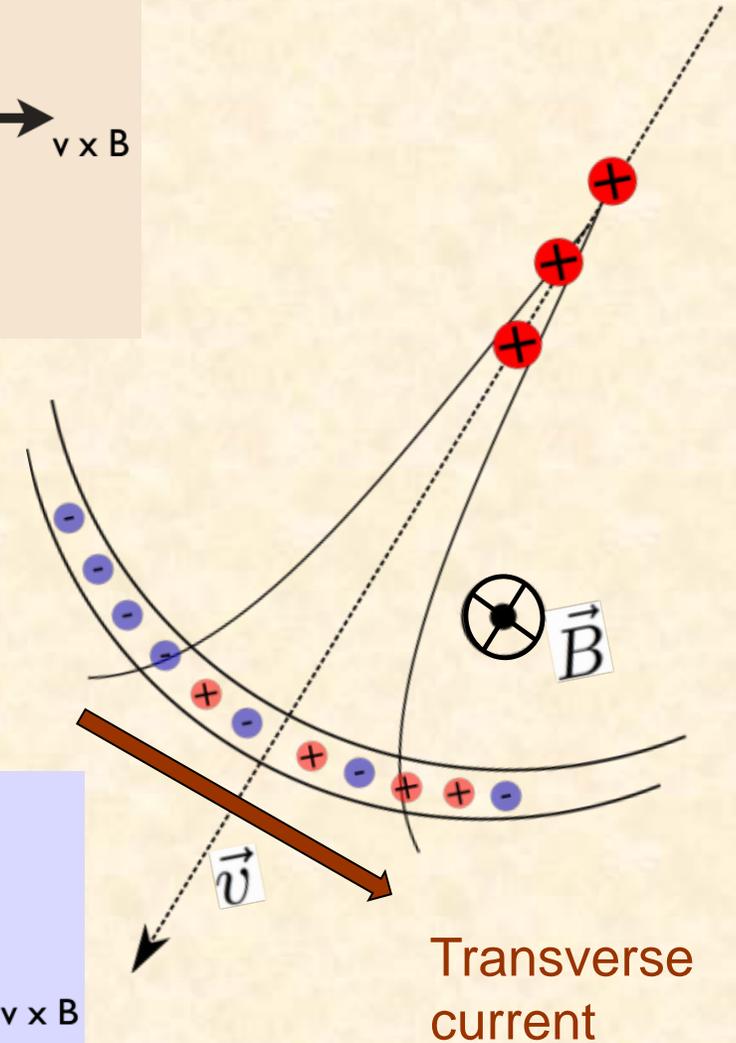
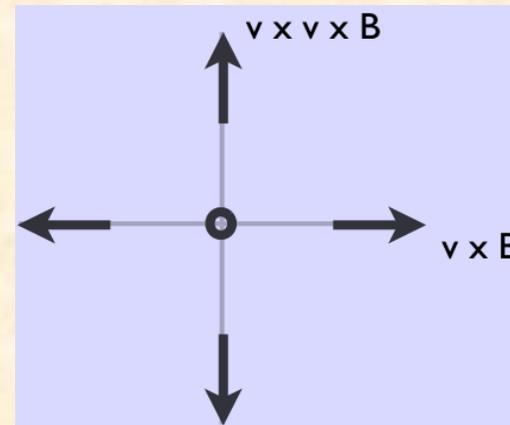
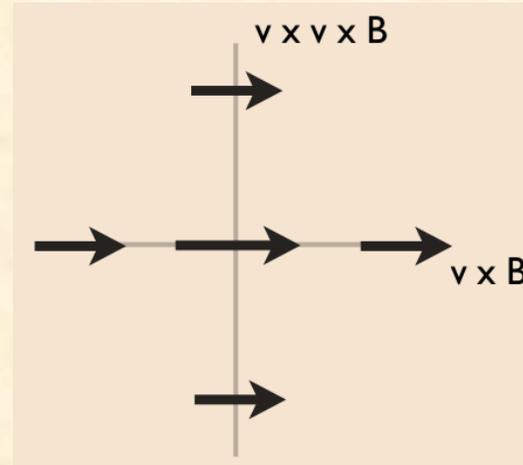
Geomagnetic:

- Electrons & positrons have transverse drift, induced by geomagnetic field.
- Linearly polarized, Unidirectional along $\mathbf{v} \times \mathbf{B}$

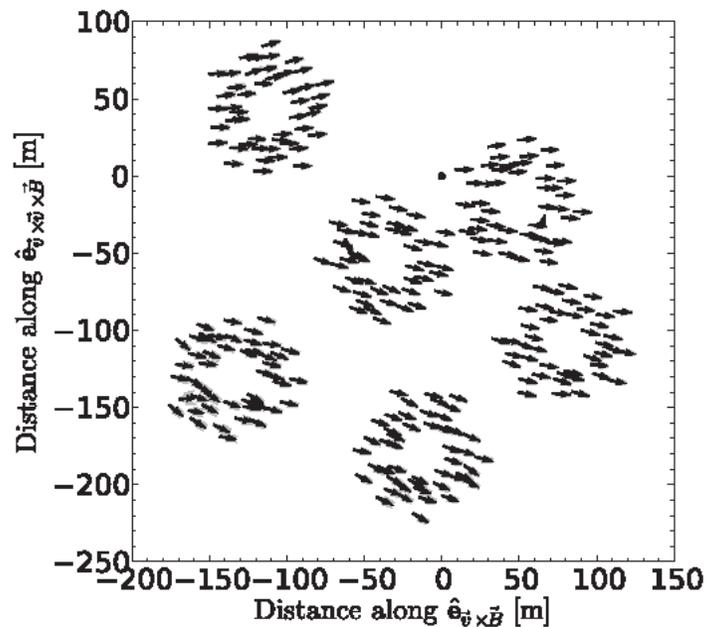
Charge excess:

- Negative charge buildup at shower front.
- Linearly polarized, Radially from shower axis

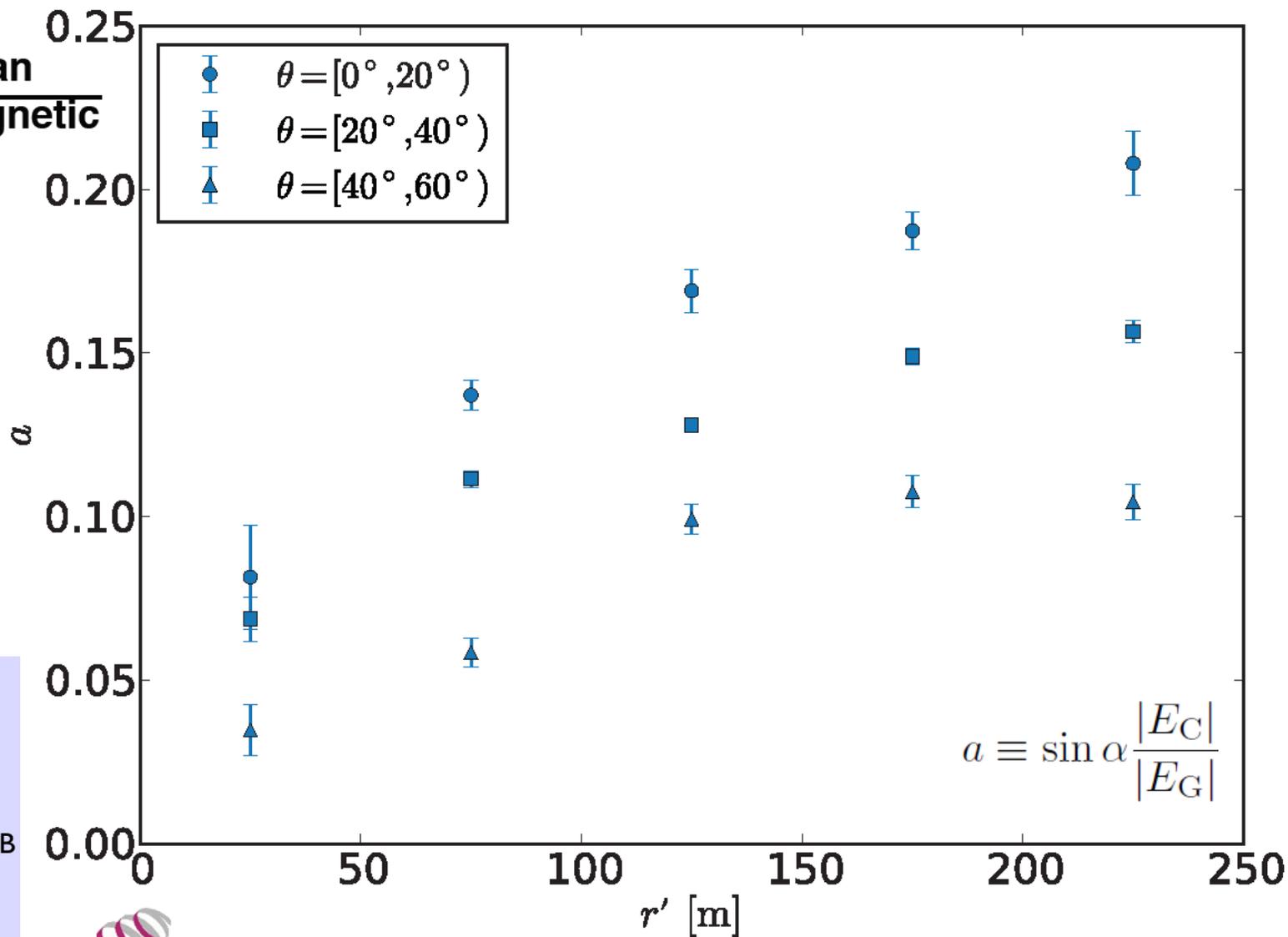
The full signal: $\vec{E} = \vec{E}_G + \vec{E}_C$ modified by Time-compression effects.



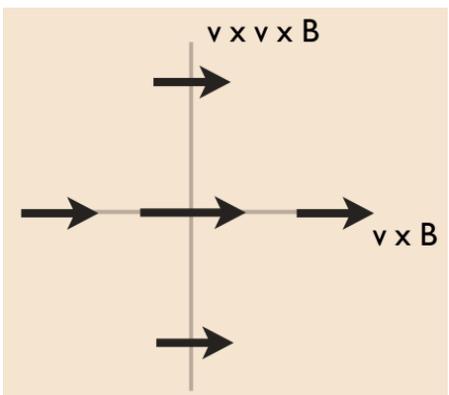
Charge excess fraction



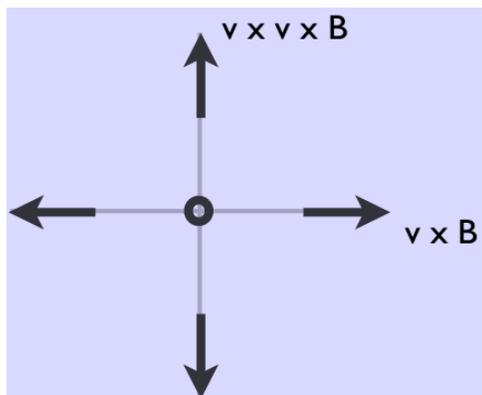
Askaryan
geomagnetic



geomagnetic



Askaryan



23-Jun-16

Full polarization, Stokes

$$I = \frac{1}{n} \sum_0^{n-1} \left(|\mathcal{E}|_{i, \vec{v} \times \vec{B}}^2 + |\mathcal{E}|_{i, \vec{v} \times \vec{v} \times \vec{B}}^2 \right)$$

$$Q = \frac{1}{n} \sum_0^{n-1} \left(|\mathcal{E}|_{i, \vec{v} \times \vec{B}}^2 - |\mathcal{E}|_{i, \vec{v} \times \vec{v} \times \vec{B}}^2 \right)$$

$$U + iV = \frac{2}{n} \sum_0^{n-1} \left(\mathcal{E}_{i, \vec{v} \times \vec{B}} \mathcal{E}_{i, \vec{v} \times \vec{v} \times \vec{B}}^* \right) .$$

Stokes parameters: I, Q, U, V

Linear polarization angle: $2\varphi = \text{atan}(U/Q)$

NEW: Circular polarization = V/I

Interesting results:

➤ **Fair weather:**

confirmation of emission mechanisms

➤ **Thunderstorm:**

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

Interpretation circ-pol for fair weather

Transverse current: constant near core,

Charge excess: vanishes at core, thus:

→ Proportional to $\sin(\text{viewing angle}) = d/h$

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

→ Pulse maximum arrives slightly later

→ $V/U = \tan(\text{phase diff})$ is measure of time shift

Delay is frequency and distance dependent

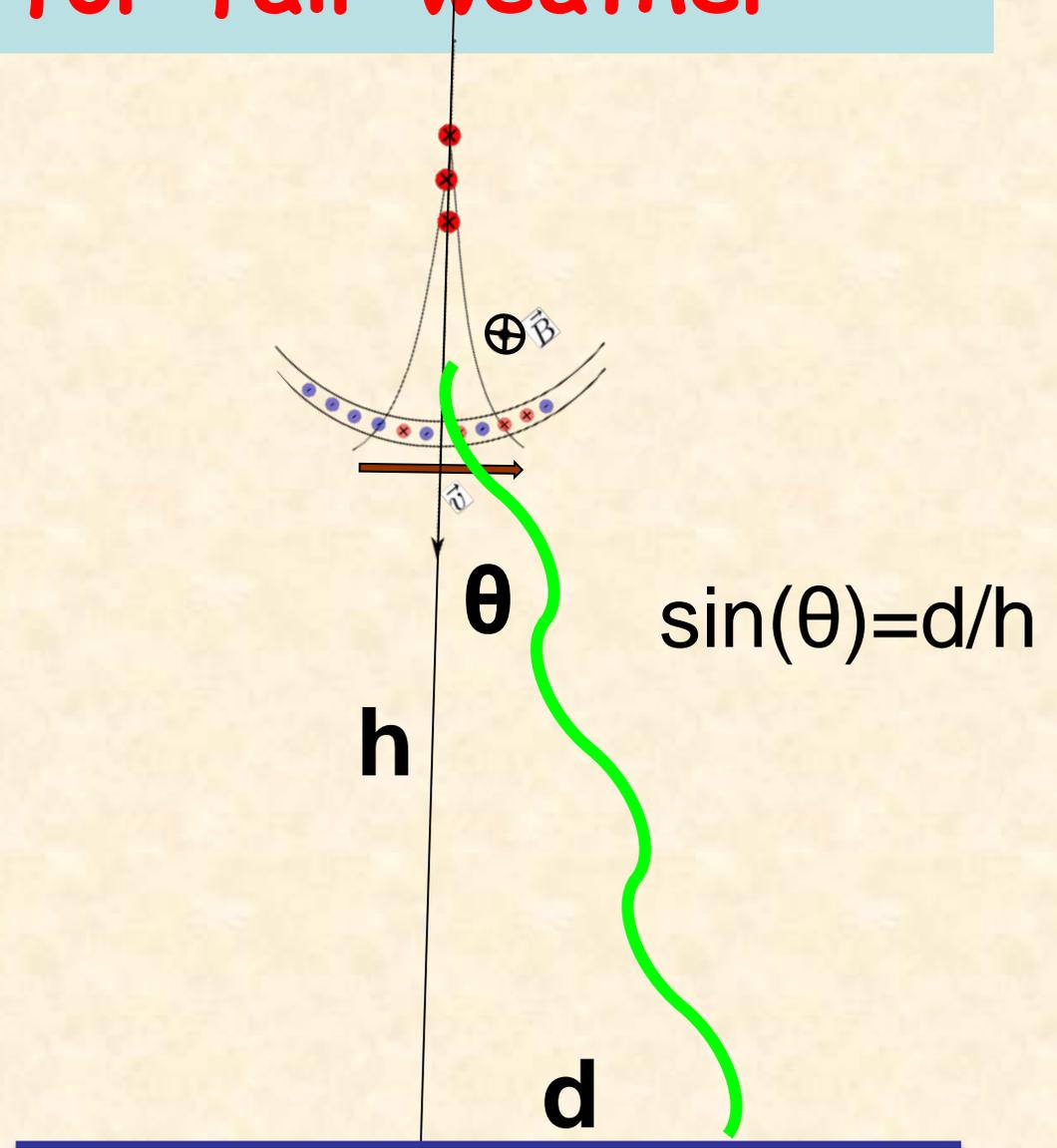
At 100 m, 30-80 MHz, delay = 1 ns

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

$$\rightarrow E_{\text{ch}}(t) = t (2c/d) E_{\text{tc}}(t)$$

$$t = d^2/(2hc) \rightarrow h = d^2/(2tc)$$

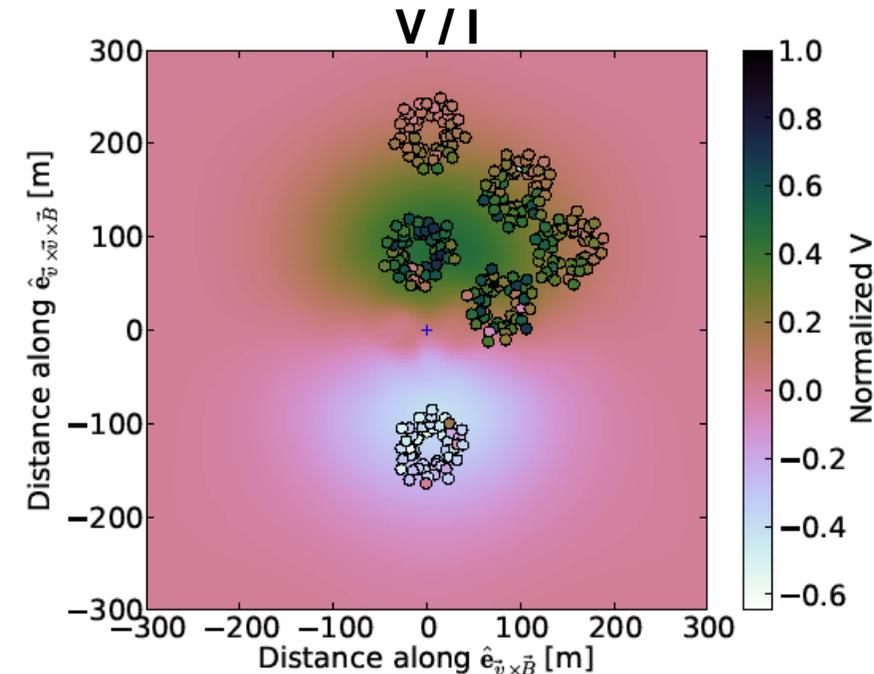
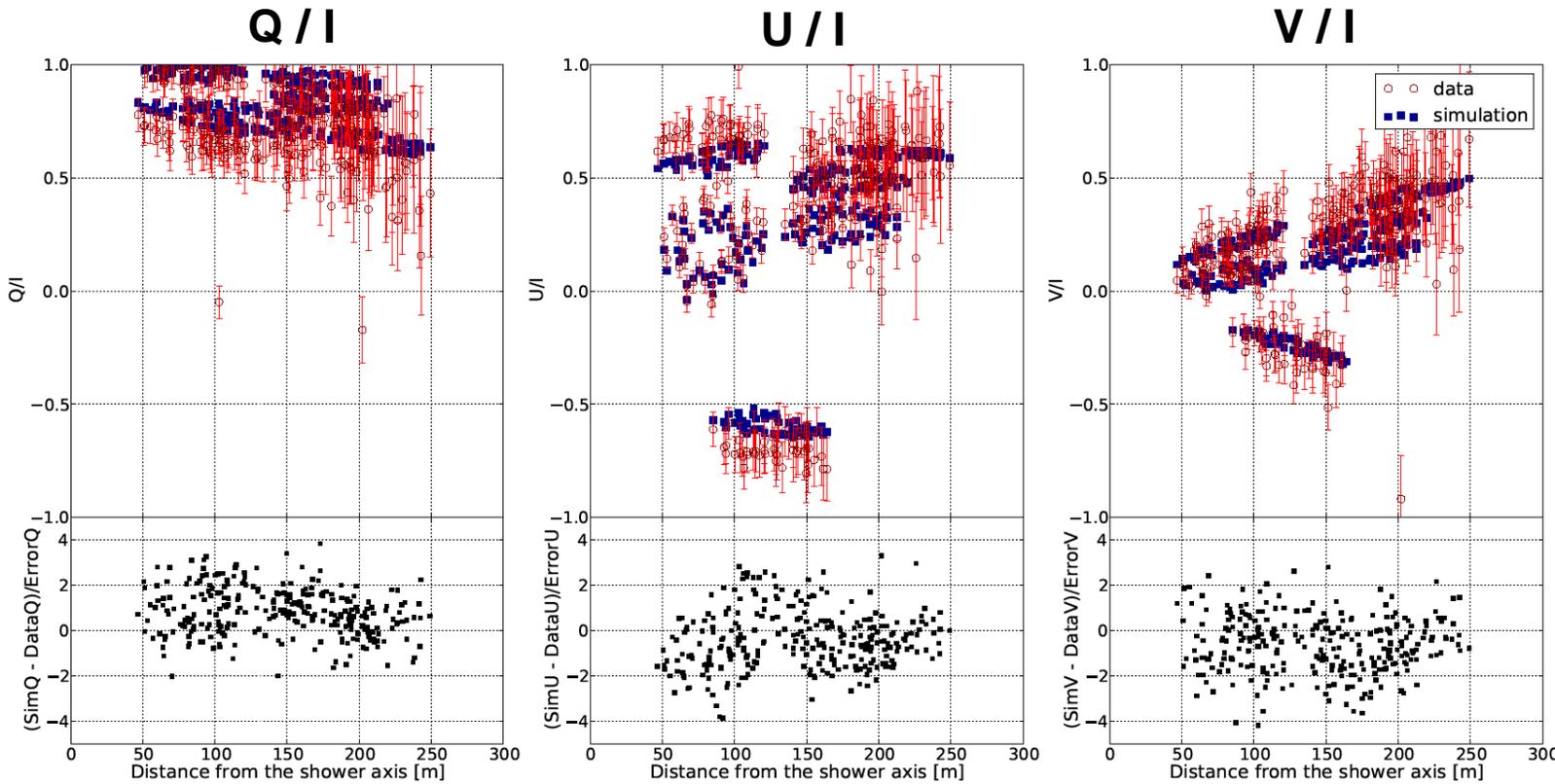
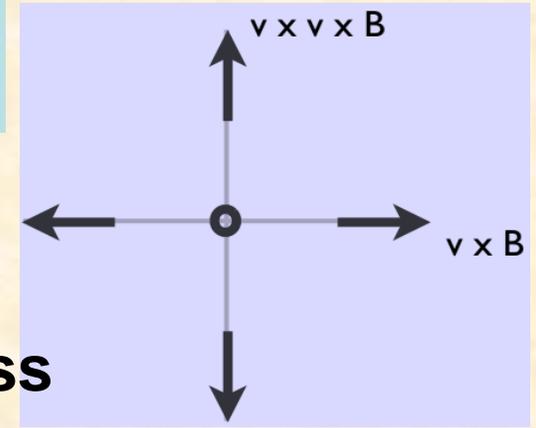
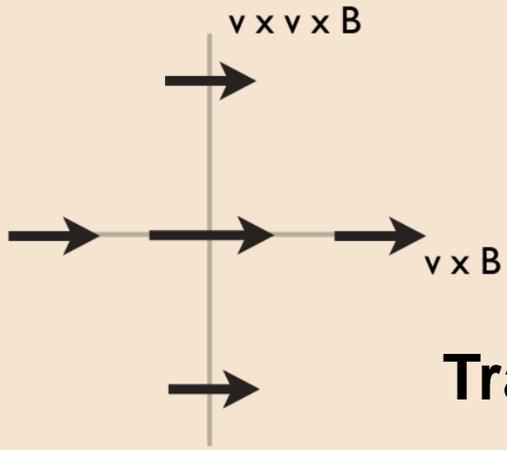
N.B. formula does not apply when $d=0=t$



LOFAR data v.s. CoREAS

Reason for fair-weather circular polarization:

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

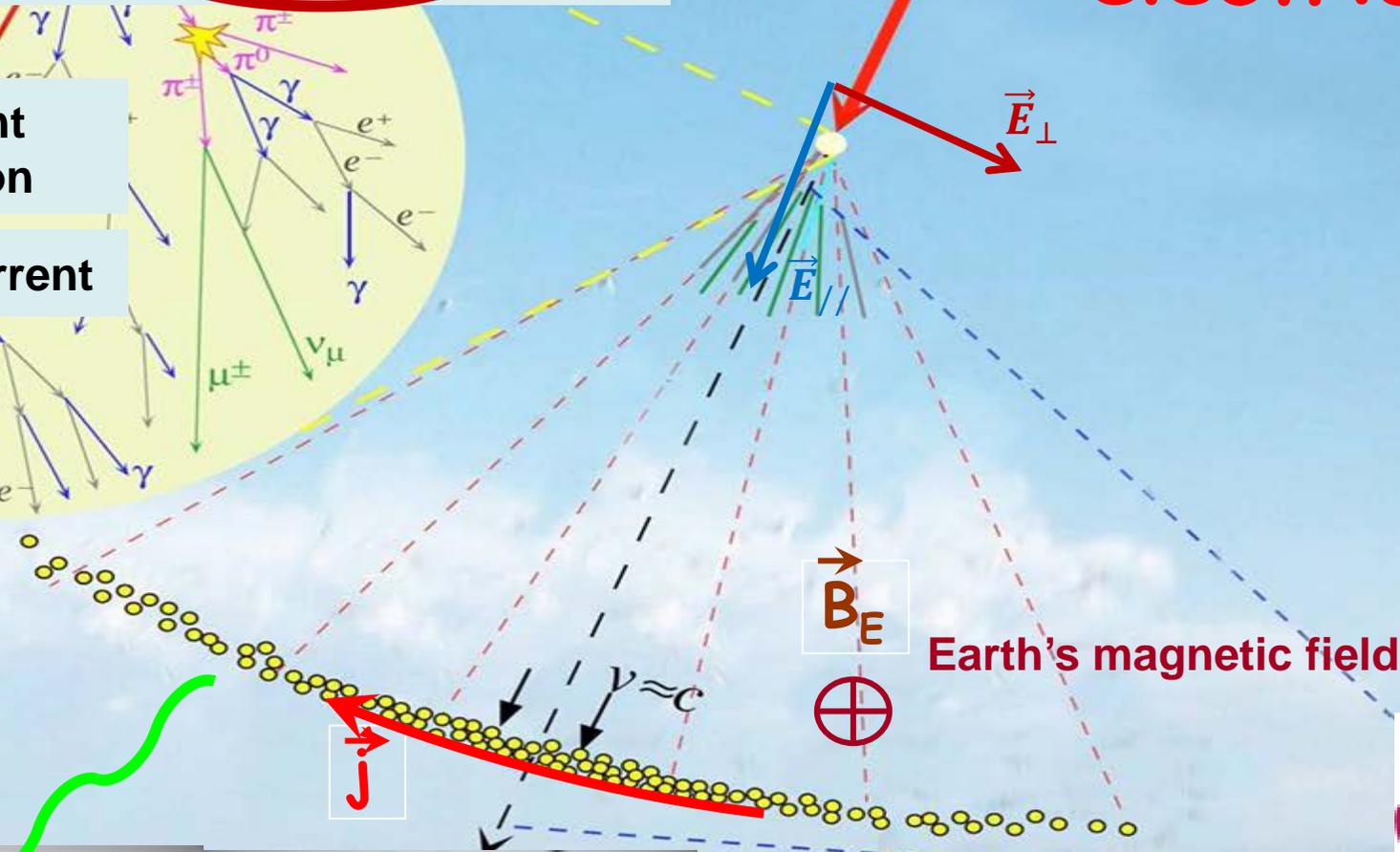
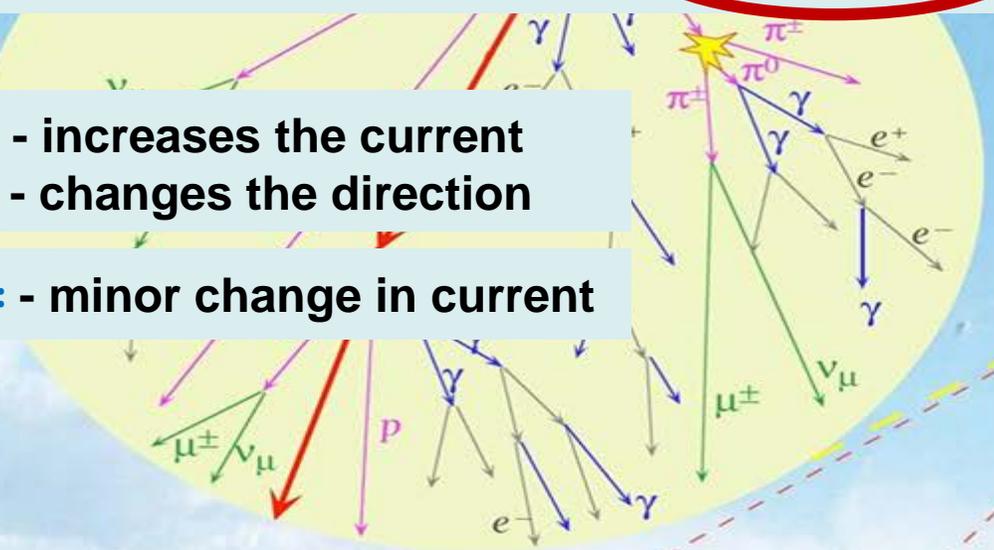


The Earth magnetic field in combination with the electric field induces an electric current \vec{j} in the air-shower pancake in the direction $\vec{F} = \vec{v} \times \vec{B} + \vec{E}_\perp$

Radio emission in presence of an electric field

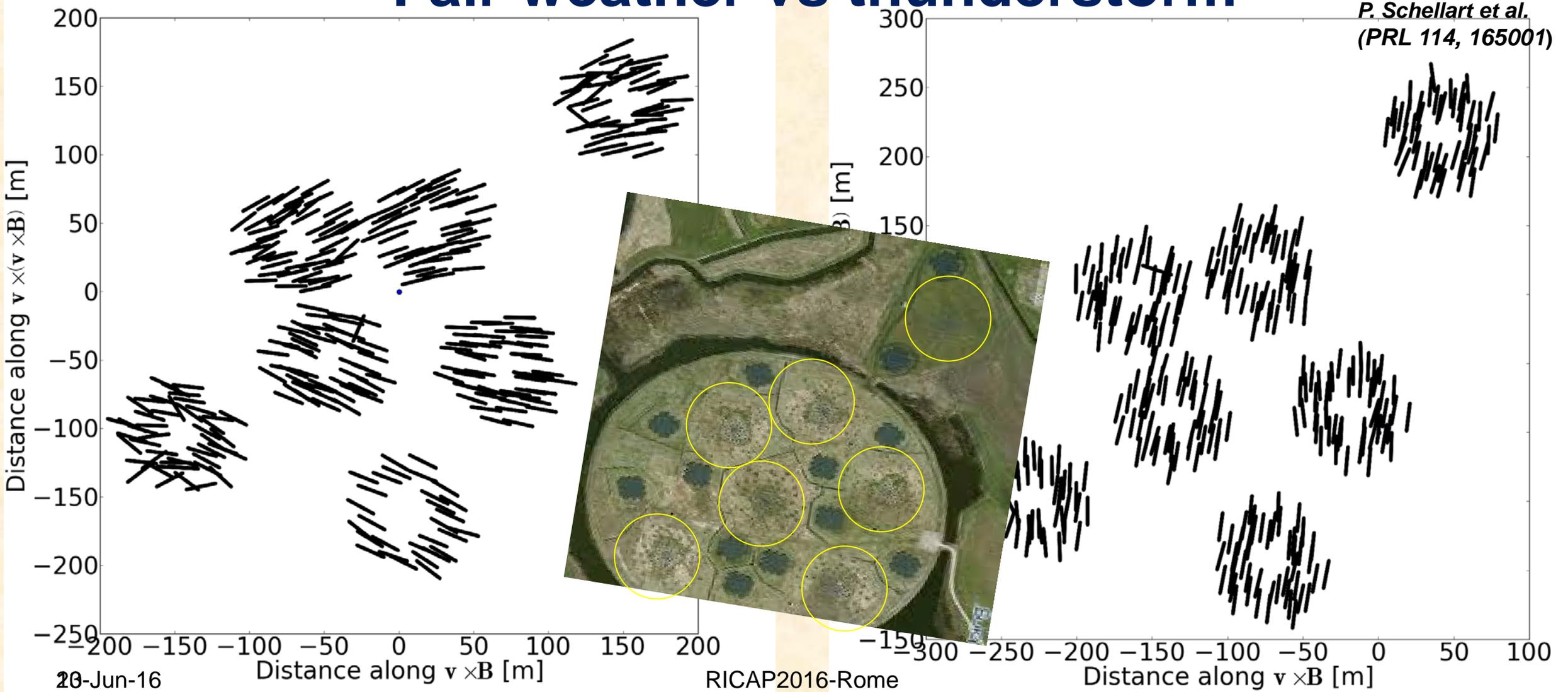
\vec{E}_\perp : - increases the current
- changes the direction

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



Observations: polarization footprint

Fair weather vs thunderstorm

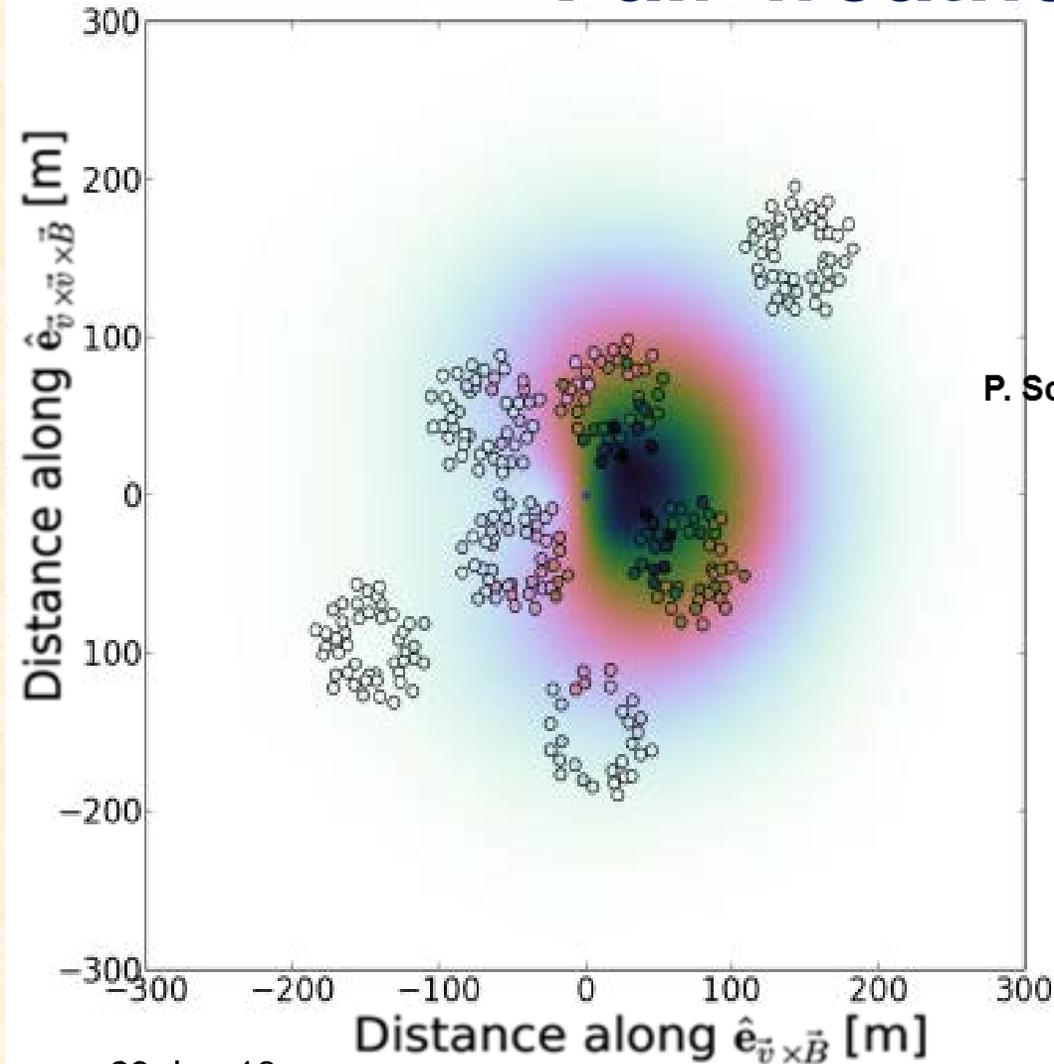


Observations; intensity footprint

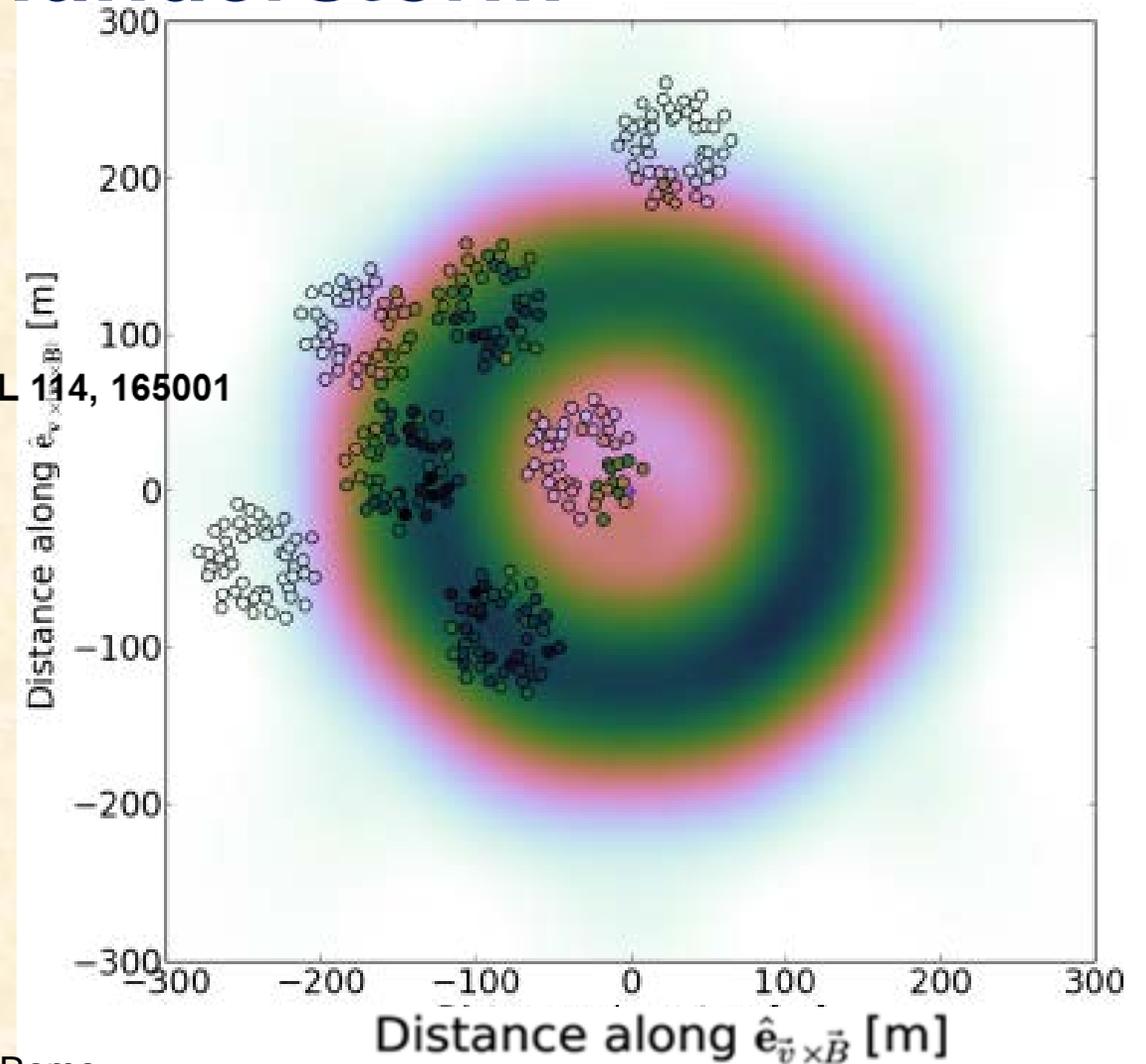
S. Buitink et al.
PRD 90, 082003 (2014)

Fair weather vs thunderstorm

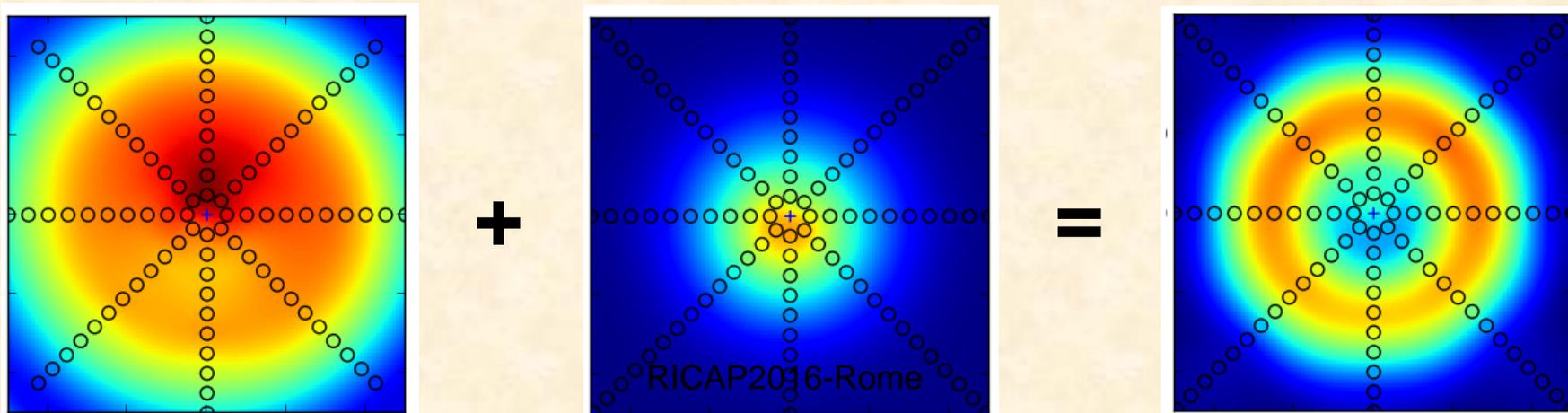
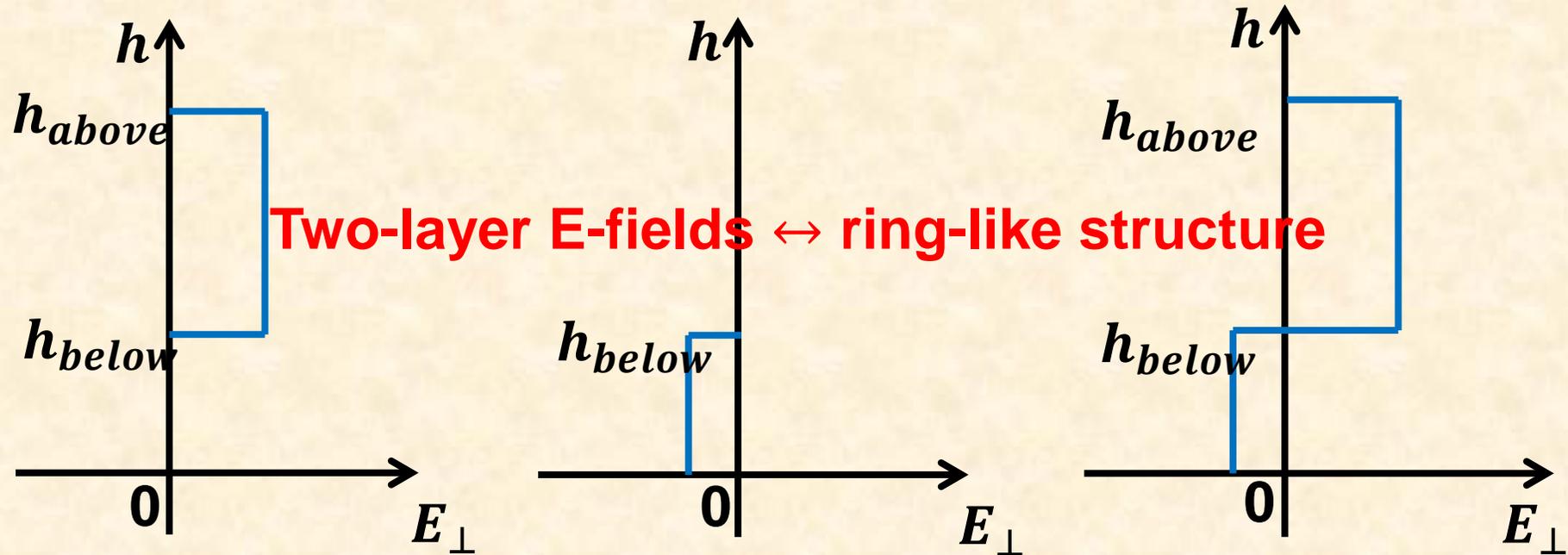
P. Schellart et al.,
PRL 114, 165001 (2015)



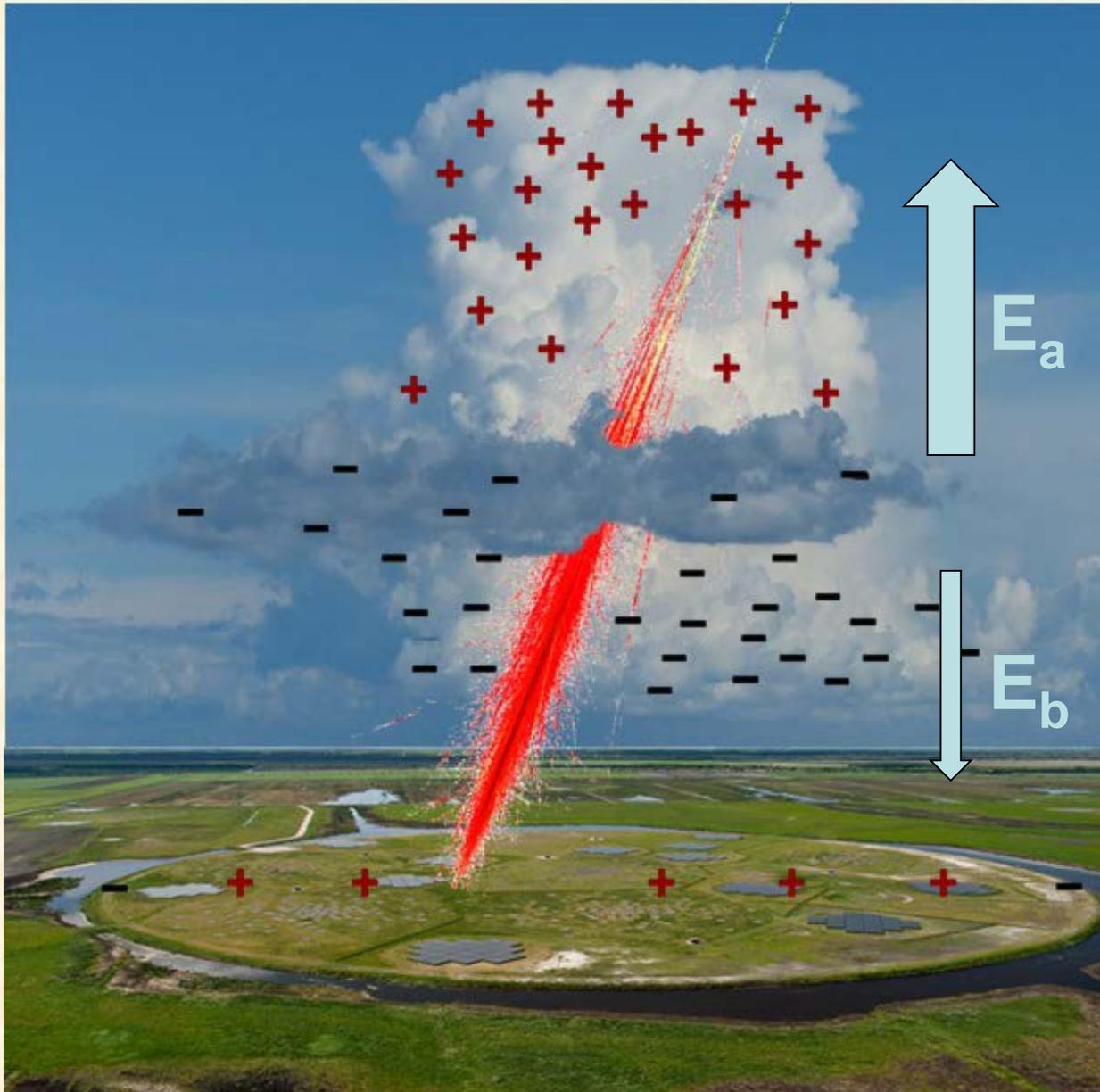
P. Schellart et al., PRL 114, 165001



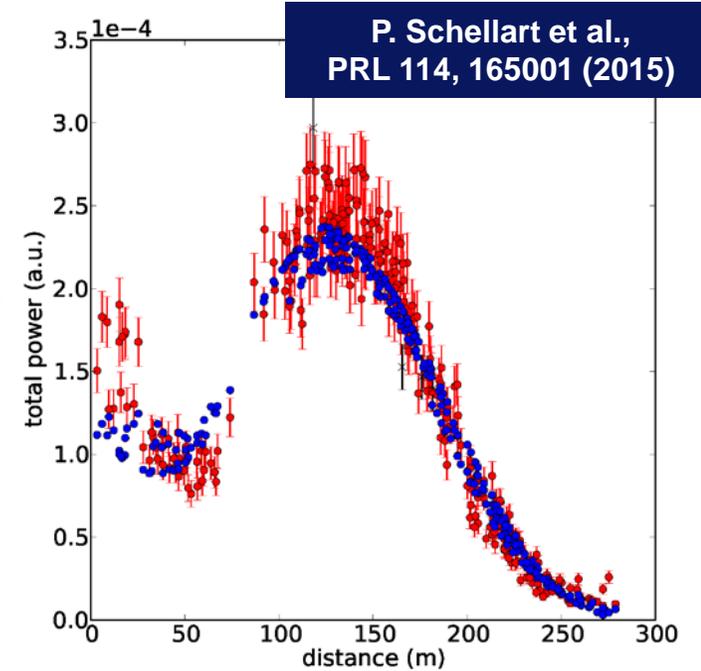
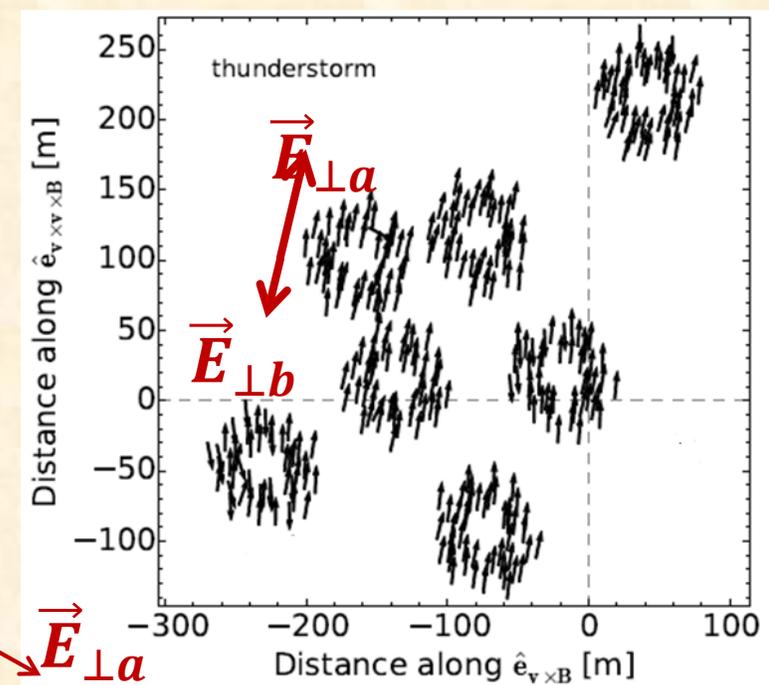
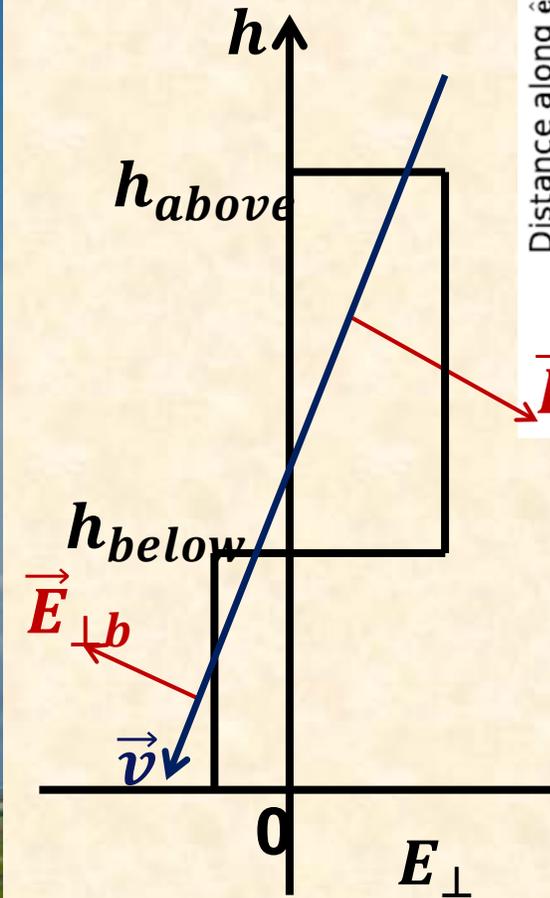
Ring structure through interference



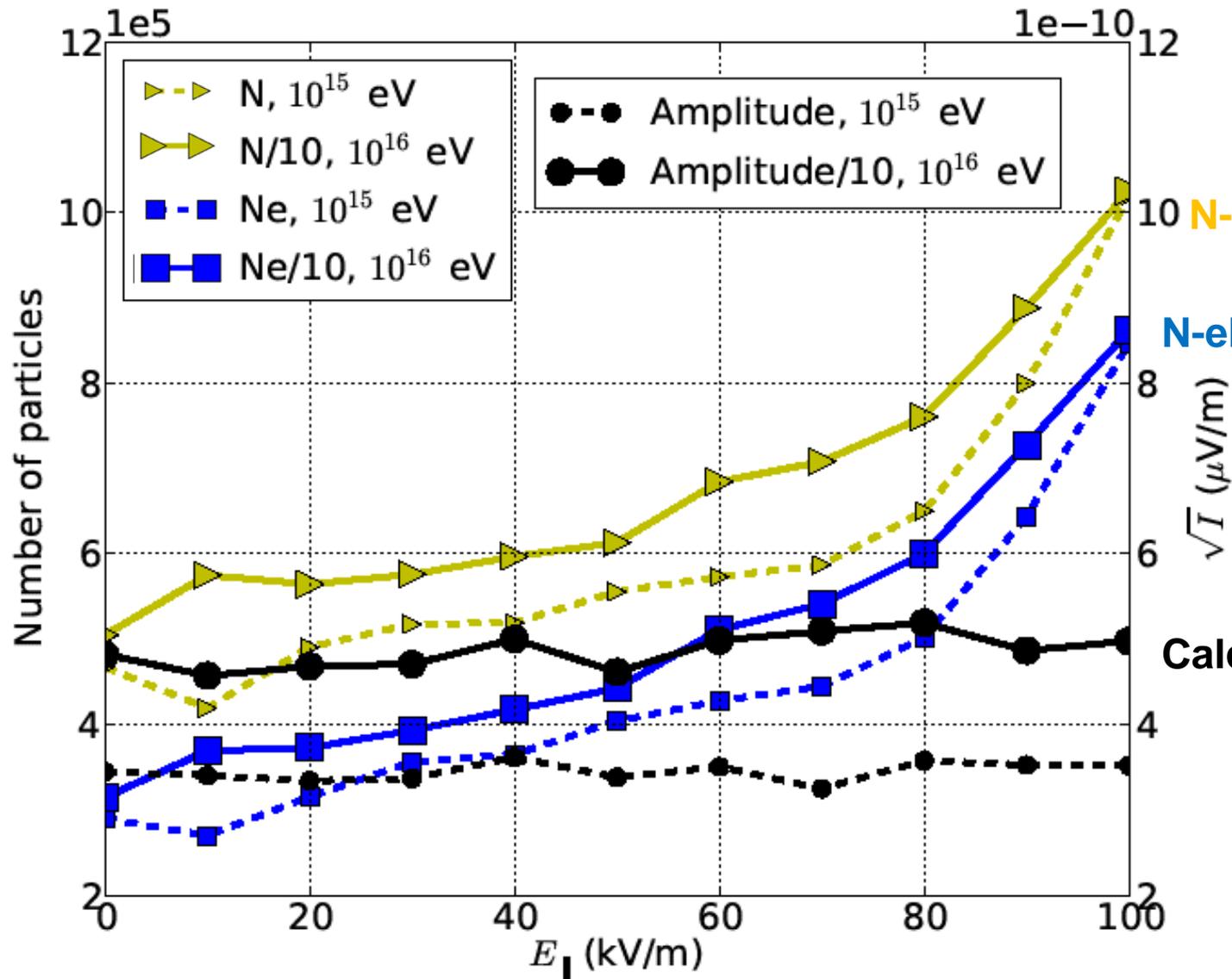
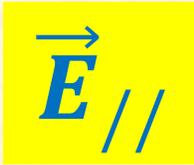
Structure E-fields



016-Rome



Dependence on electric field strength



Expect:
Amplitude = $N v_d$

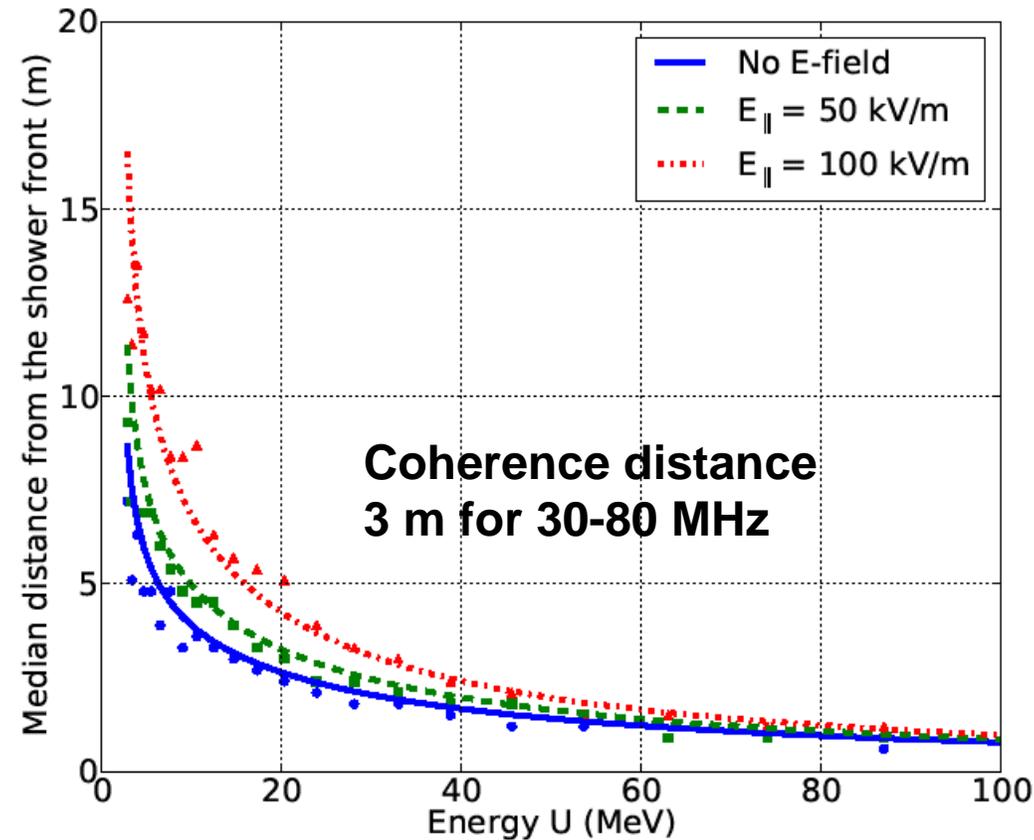
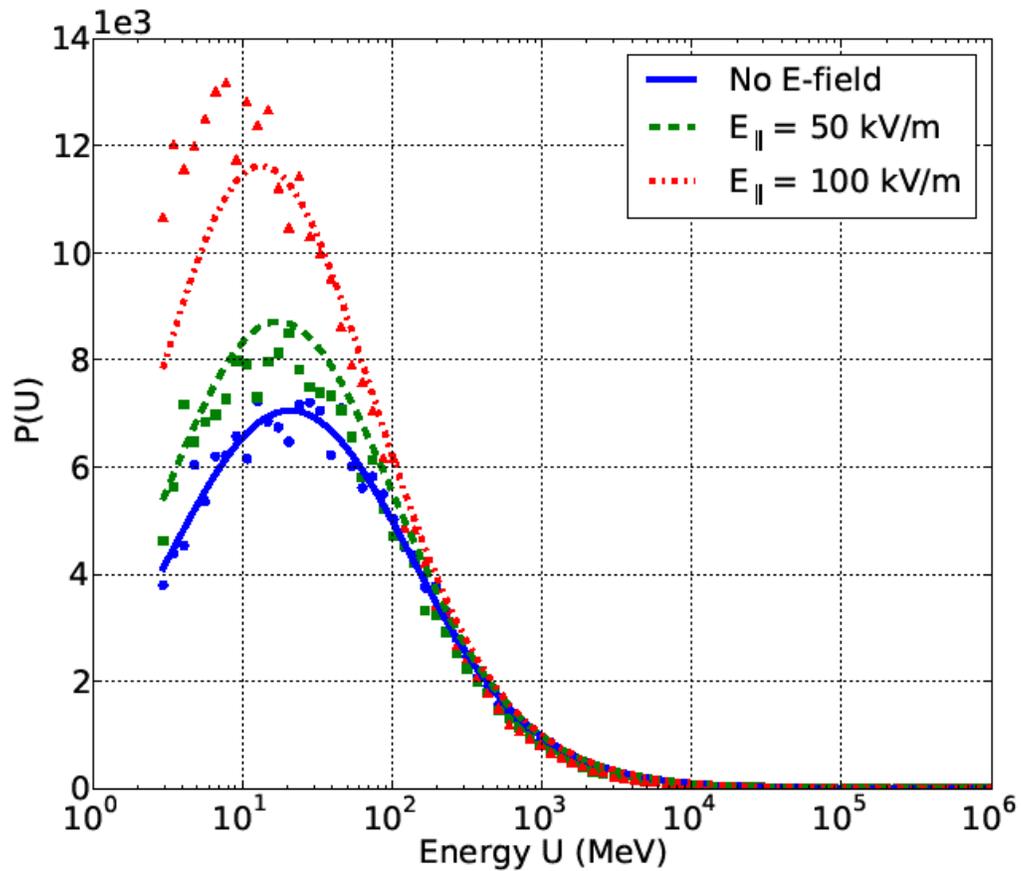
N-electrons+positrons (CORSIKA)

N-electrons (CORSIKA)

Calculated amplitude (30-80 MHz) (CoREAS)

With increasing E_{\parallel} 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

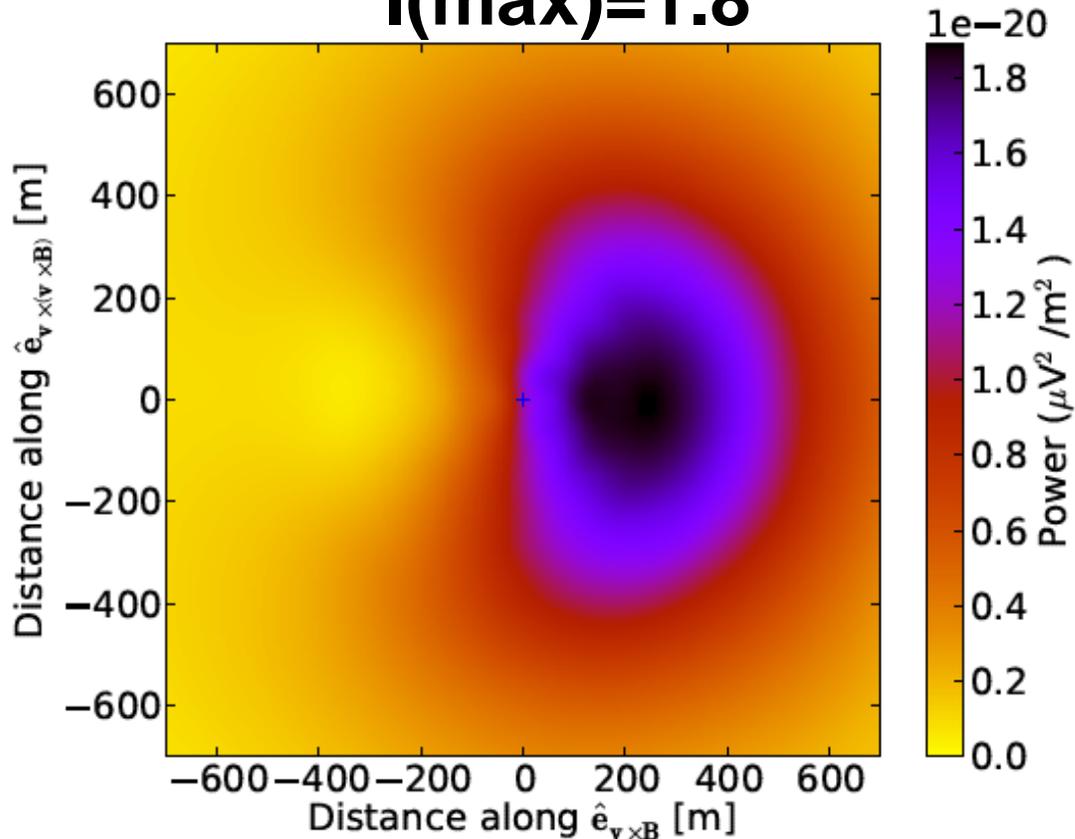
$$\vec{E}_{//}$$

$$\vec{E}_{//} = 50 \text{ kV}$$

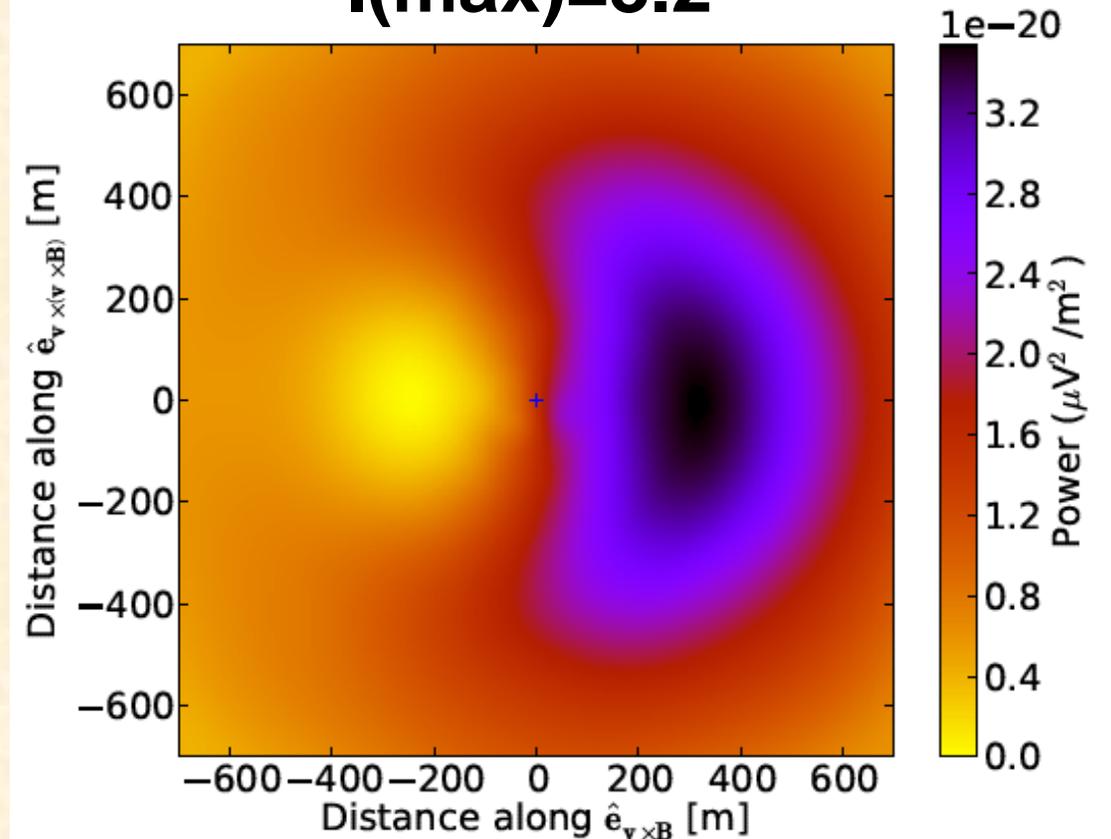
2-9 MHz

$$\vec{E}_{//} = 100 \text{ kV}$$

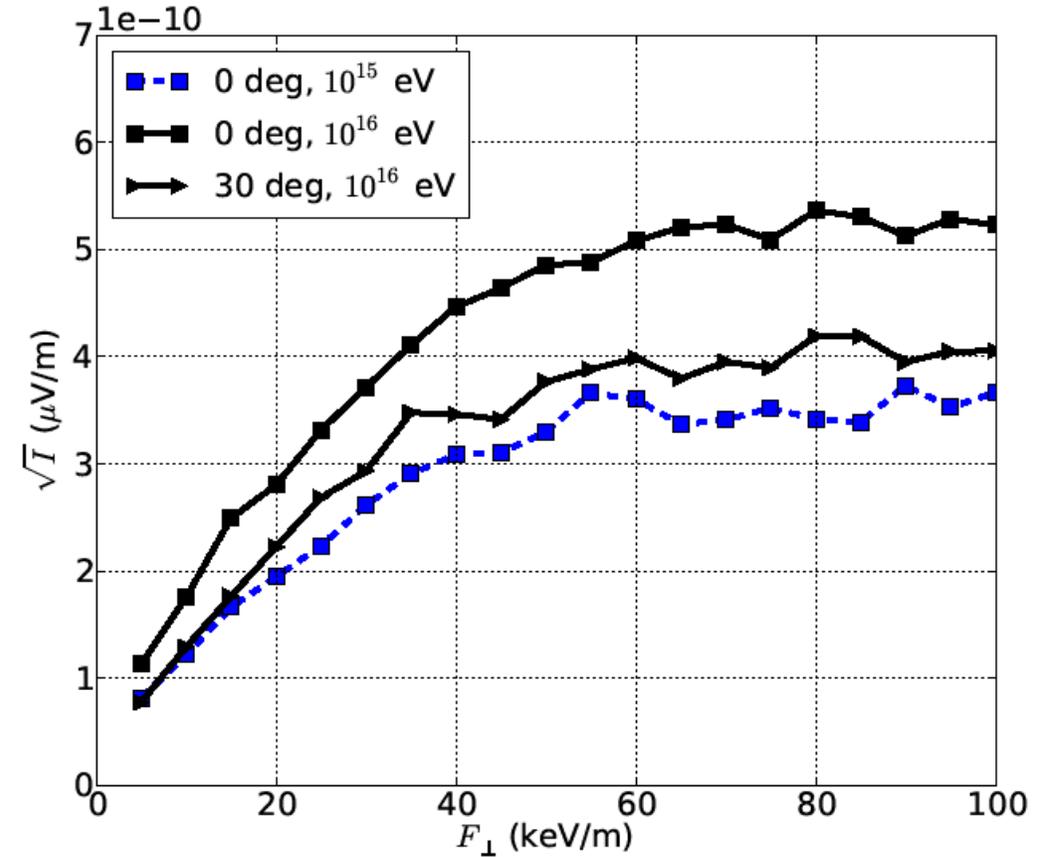
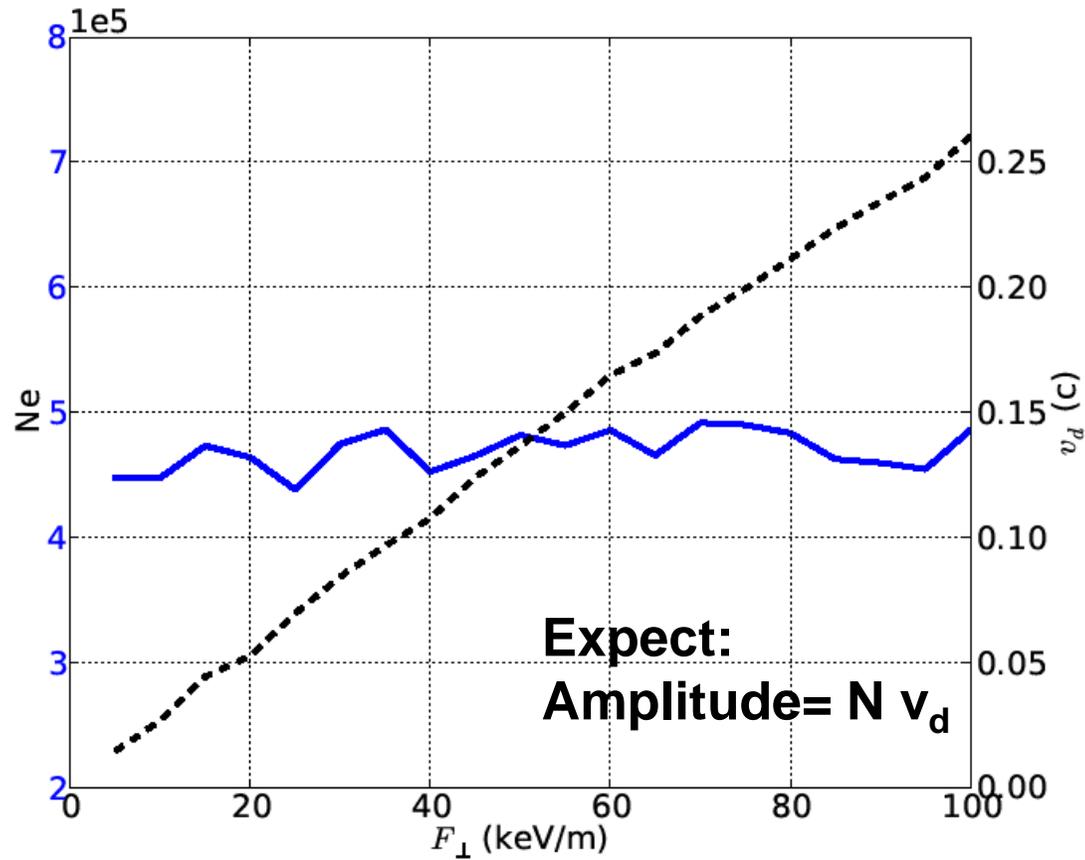
$I(\text{max})=1.8$



$I(\text{max})=3.2$



Dependence on \vec{E}_\perp

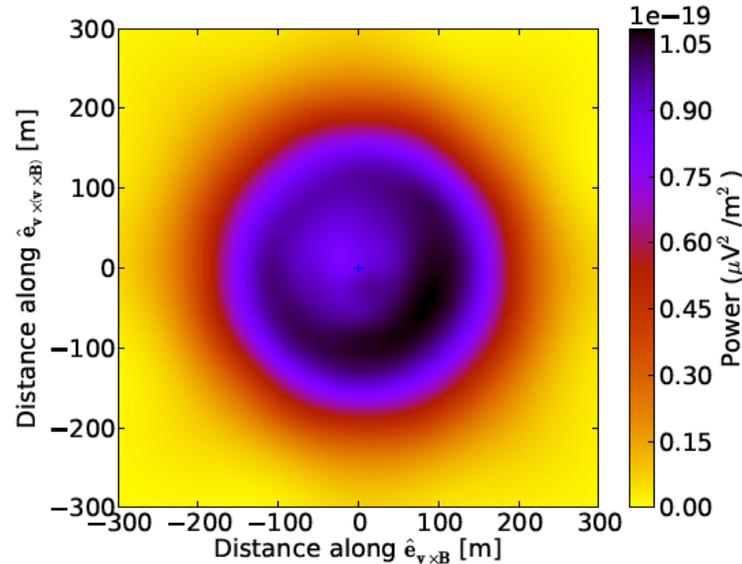
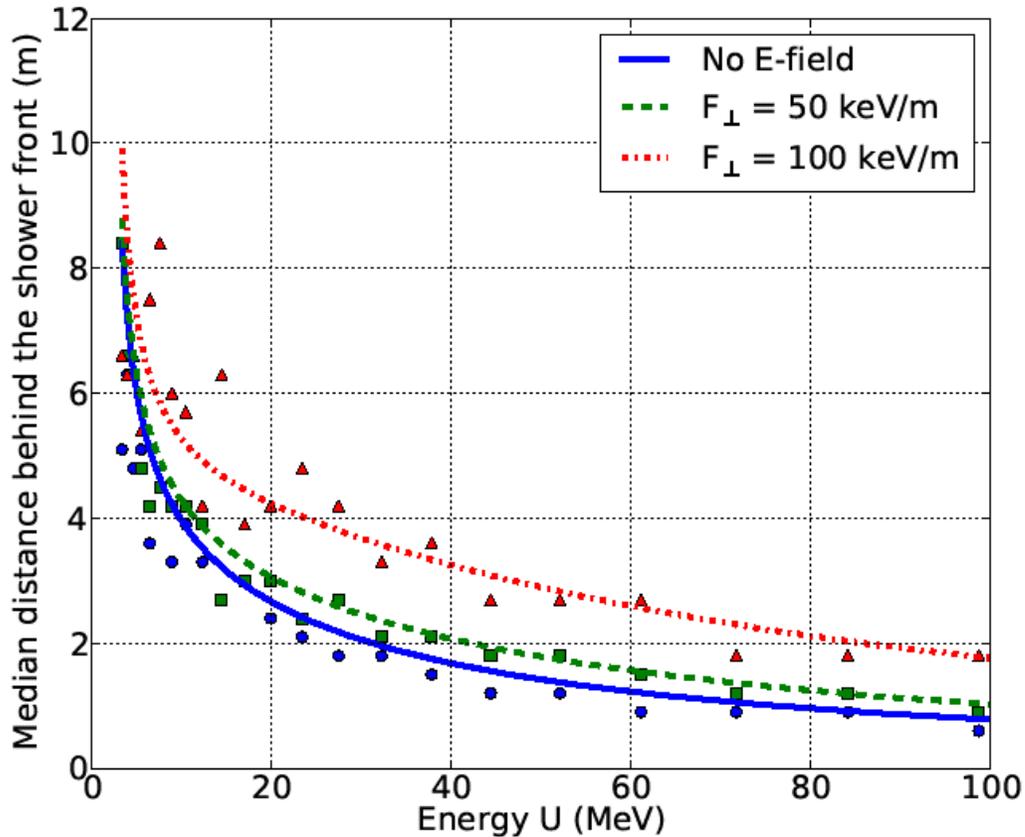


Drift velocity increasing E_{perp}
Number of electrons constant

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

Effects of perpendicular force

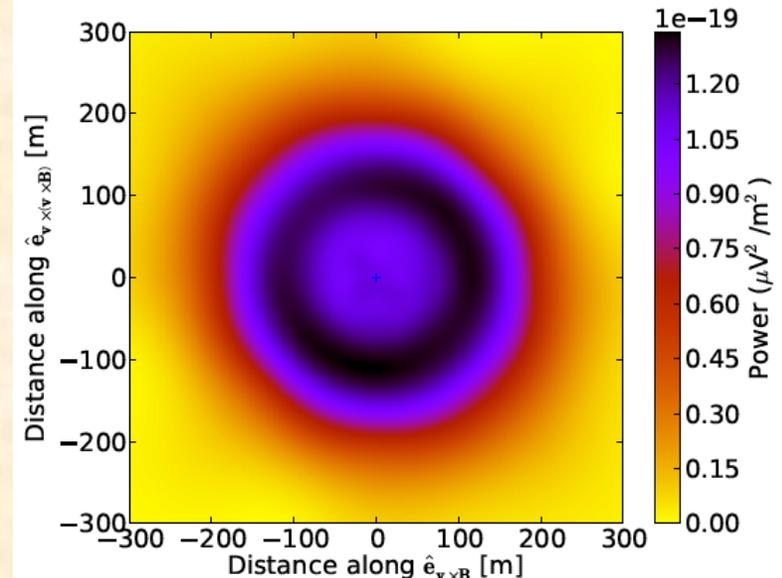
$$\vec{E}_\perp$$



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

2-9 MHz

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



With increased sideward drift the longitudinal velocity decreases

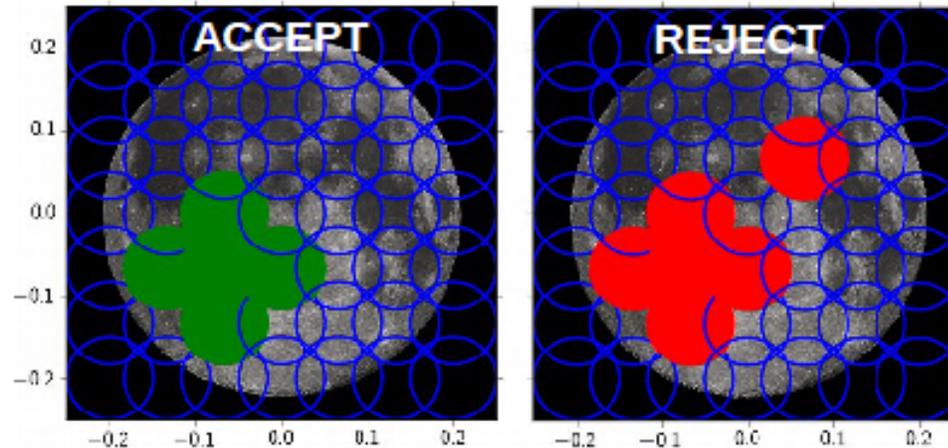
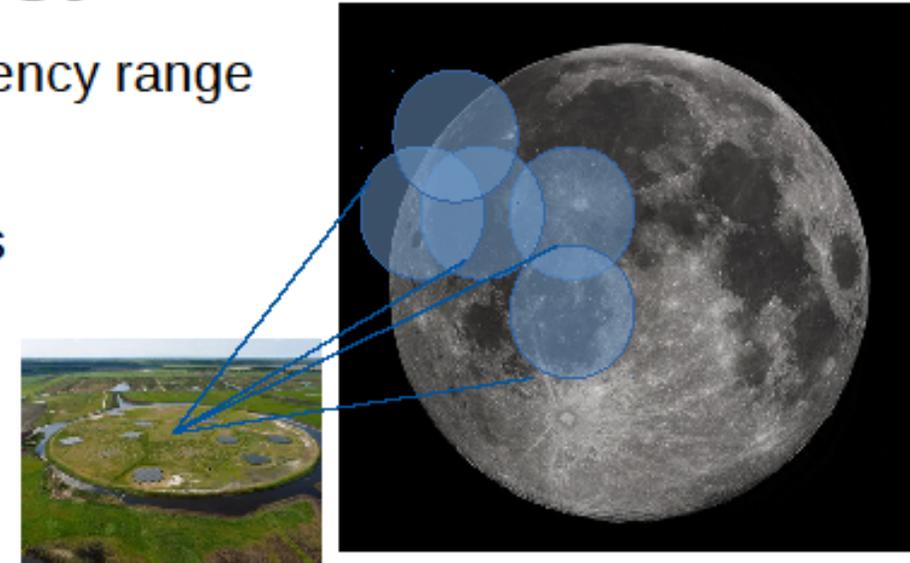
Loss of coherence in 30-80 MHz at large F

NuMoon @ LOFAR

Basic idea:
Moon is a pretty large ($=10^7 \text{ km}^2$) 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



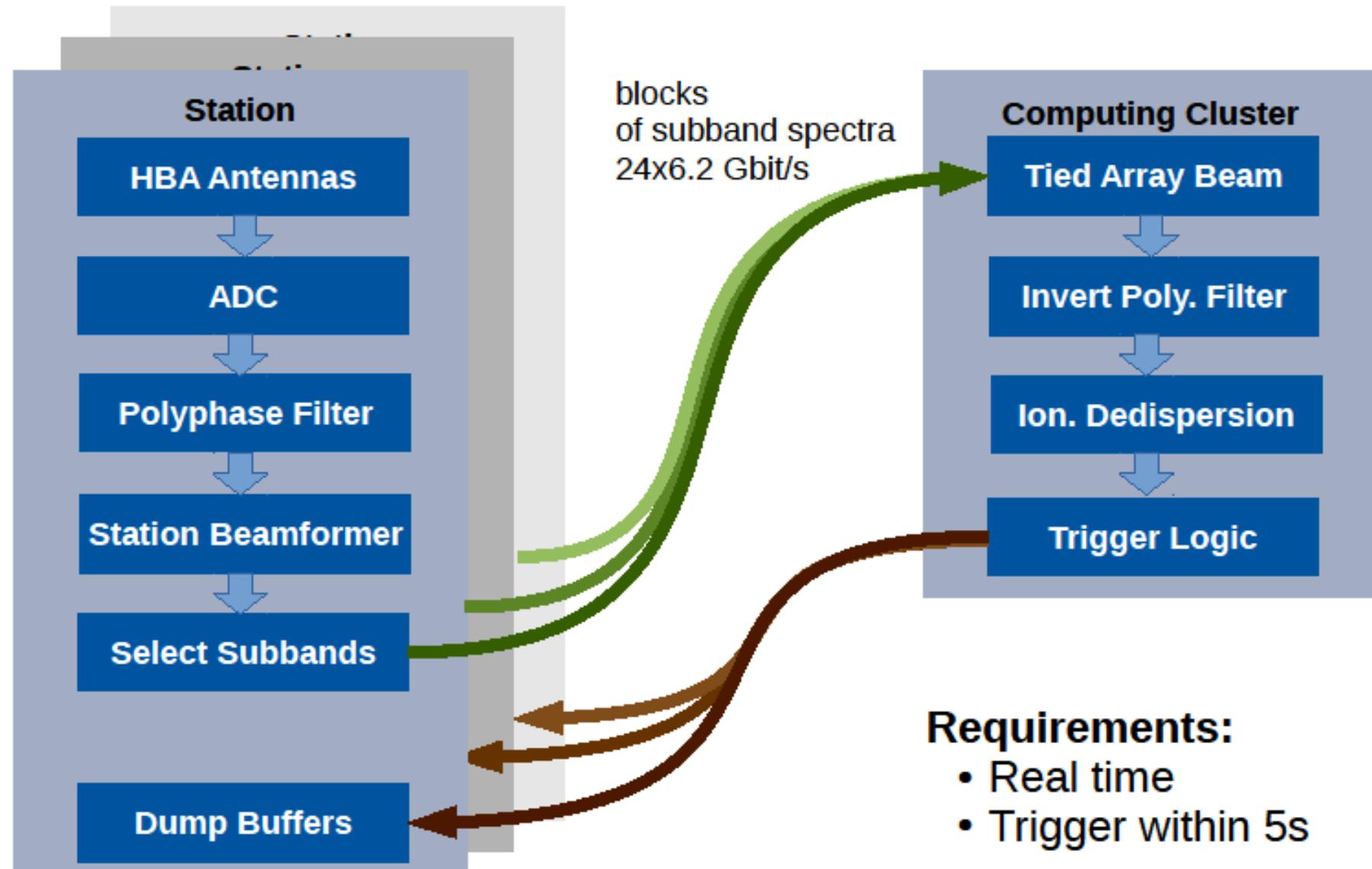
Challenges

- 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

THE Challenge

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

Online Data Analysis



- Requirements:**
- Real time
 - Trigger within 5s

THE Solution

A large GPU cluster designed for high data through put.

DRAGNET Cluster

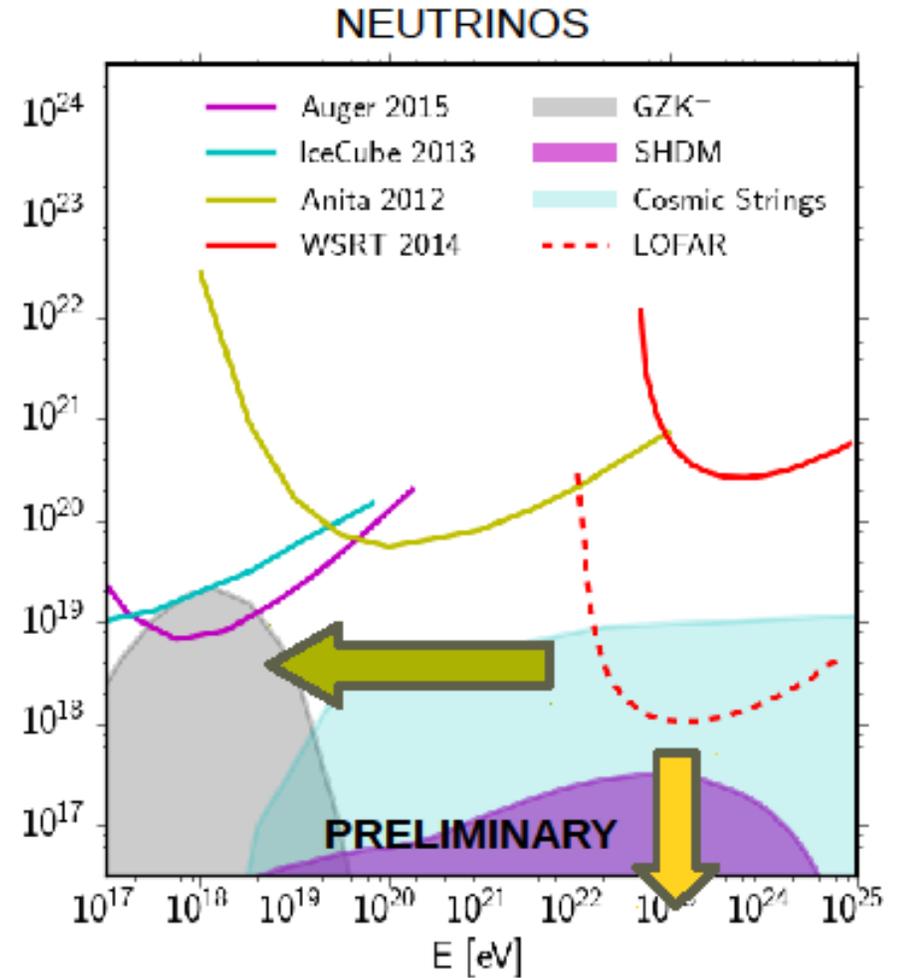
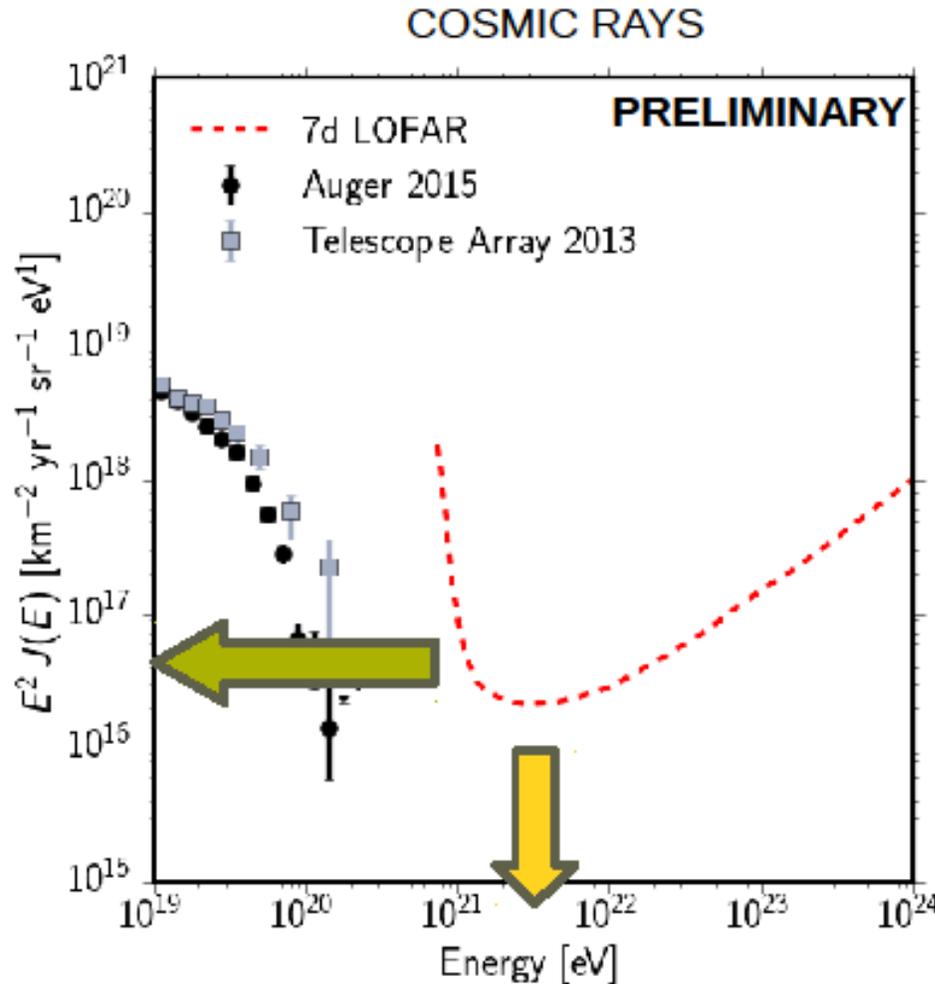
- Designed for Pulsar searches (J. Hessels et al.)
 - 23 worker nodes
 - 16 CPU cores (2x Xeon E5-2630v3 (2014))
 - 128 GiB ram
 - 4x TitanX GPU
 - 56 Gbit/s Infiniband connection to LOFAR
 - = 92 High-End GPUs + CPUs ; 0.5 PetaFLOPs
- Estimate based on prototype implementation:
 - 2 beams per node,
 - Computing power allows 46 beams total:
 - **Full coverage of the moon with .1 deg beams possible**

Sensitivity

Sensitivity Optimization

LOFAR → proof of concept.

Detection might be possible with SKA



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 shower parameters such as

X_{\max}

atmospheric electric fields

Lunar detection offers possibilities at the highest energies.