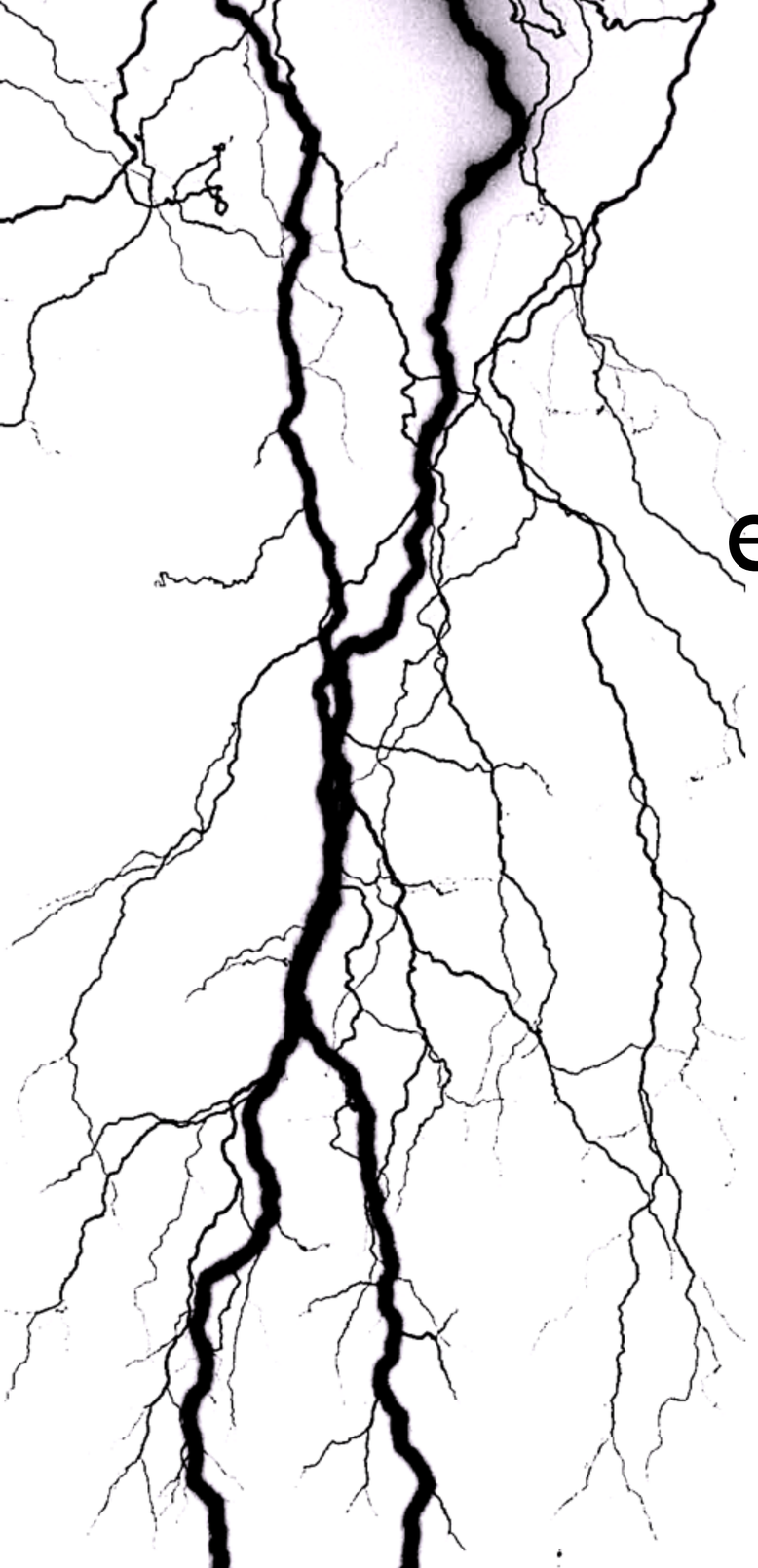

Cosmic rays, extensive air showers and thunderstorms

Benoît Revenu, SF2A 2015
pres.: Éric Defer

Subatech

cnrs IN2P3 Les deux infinis

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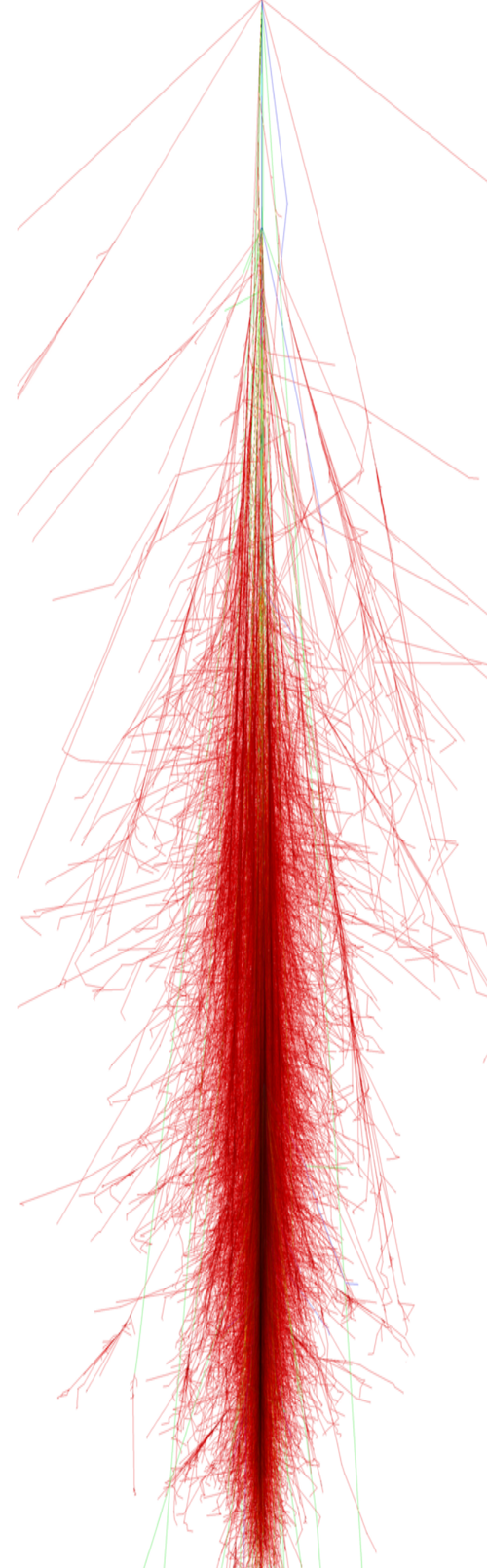
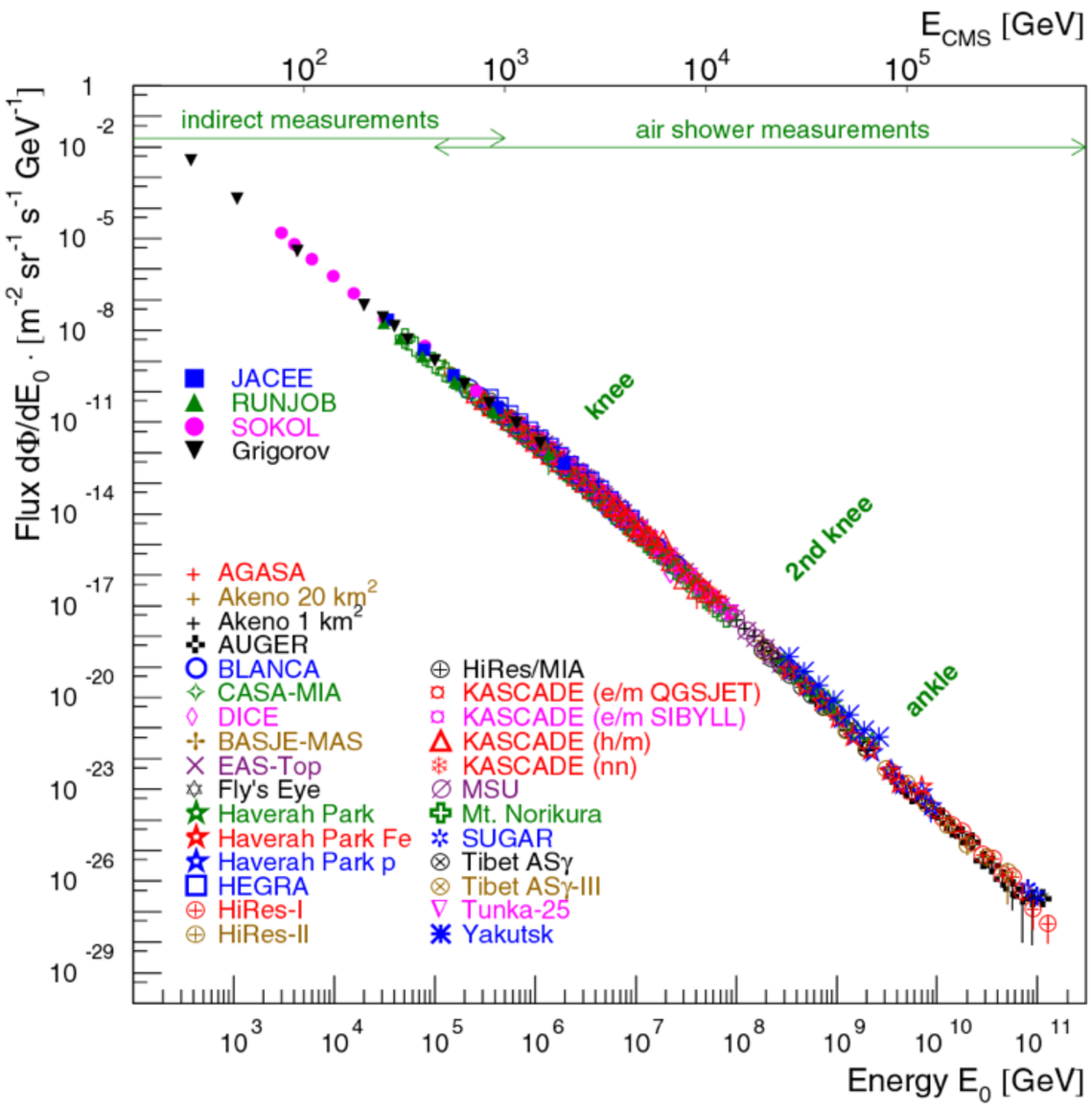


Cosmic rays



- galactic origin up to the ankle (3×10^{18} eV)
- between the knee (10^{15} eV) and the ankle: cosmic rays escape from our galaxy ($R_L > R_{Gal}$), from proton to iron
- above the ankle: extragalactic origin?

<u>If extragalactic origin:</u>

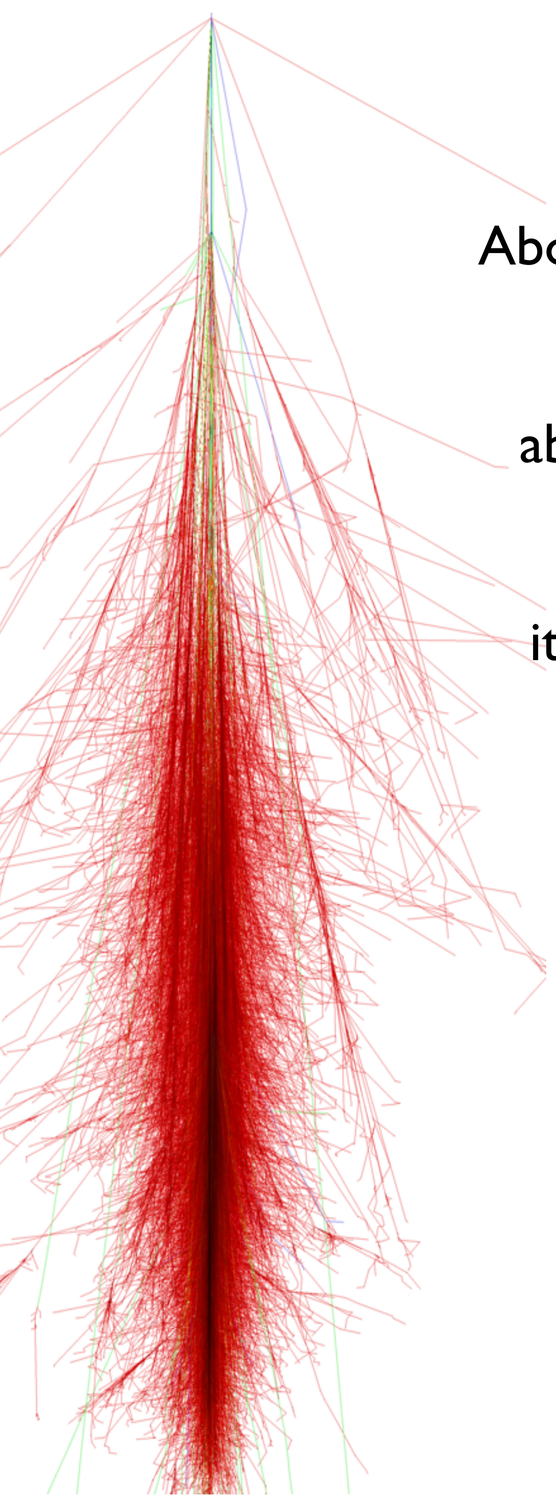
- we expect the GZK cutoff (interaction with CMB)
- sources must be close

⇓

understand the most violent phenomena in the Universe
give access to particle physics at energies 3 orders of magnitude above the LHC energy

at the highest energies: sources, nature studied in giant observatories (Auger, Telescope Array)

Extensive air showers (EAS)



Above 10^{15} eV: detection of the extensive air shower created by the collision of the cosmic ray with atmospheric constituents

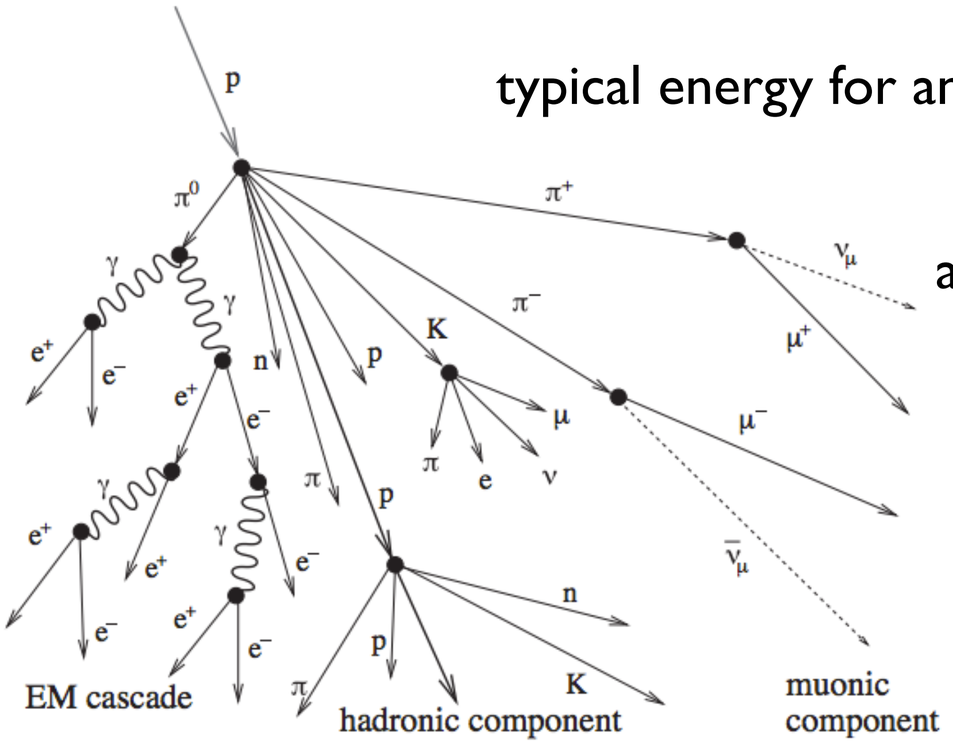
Around 10^{15}-10^{17} eV, primary cosmic rays are mostly light nuclei (proton…)

above 10^{17} eV, the flux is below 1 cosmic ray / km^2 / year (scales roughly as $E^{-2.7}$)

A shower is produced by the cascade of interactions

it is made of many secondary particles: hadrons, pions, muons, e+/e-, photons…

90% of the total energy goes into the electromagnetic part of the shower



typical energy for an e-: 30 MeV

at 10^{16} eV, $N_{max} = 7 \times 10^6$, footprint = 500 m

N_{max} is proportional to E

Electric field from extensive air showers

Many relativistic e- and e+ exist in the shower.
Two mechanisms are observed in the shower for electric field production:

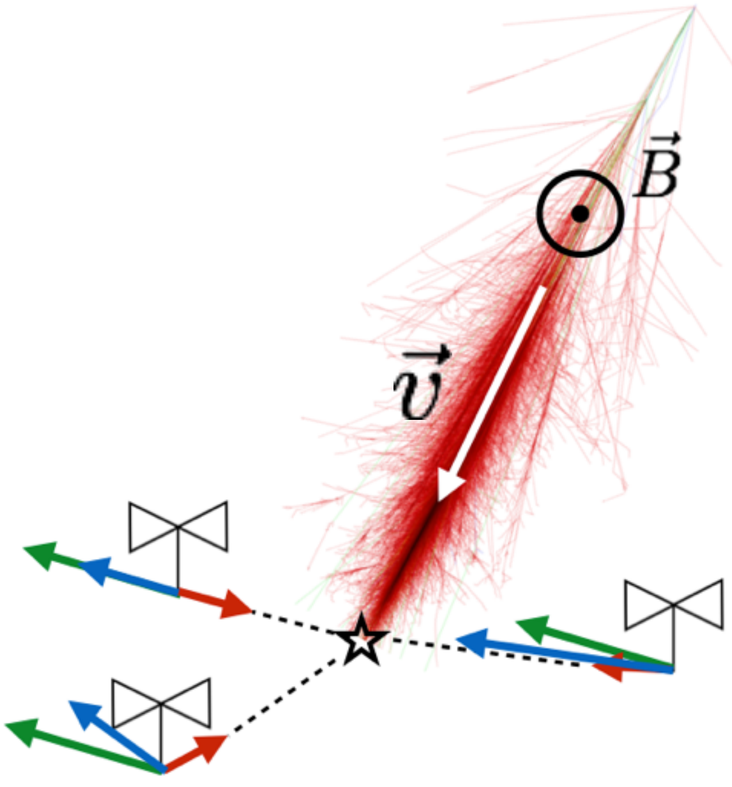
1. e- and e+ are **systematically** deflected in opposite directions under the influence of the geomagnetic field through the Lorentz force
2. e- and in excess wrt e+; this excess varies in time during the shower development leading to a radiated electric field. This mechanism is sub-dominant (between 3%-20% according to the arrival direction)

Geomagnetic mechanism:
linear polarization along vXB, duration ~ ns

Charge-excess mechanism:
radial polarization with respect to the shower axis

total electric field:
superposition of both contributions, interferences!

<u>At first order: the electric field is aligned with vXB</u>



Cosmic rays and lightnings?

Observation of X ray flashes created by high energy electrons in thunderclouds:
Wilson (1924): electric fields in thunderclouds can accelerate electrons (concept of runaway electrons)
McCarthy & Parks (1985): X ray detector on an aircraft; the X ray signal was 2-3 orders of magnitude above the prediction of Wilson

<u>runaway electron:</u>
electron in a thundercloud electric field for which the energy gain by acceleration (a=-eE/m) is larger than the energy loss by ionisation of the medium
possible if ε_{e-} > 0.1-1 MeV and E>Ec (200 kV/m), $l_c > l_a$ (50 m)

Conventional air electric breakdown: 2 MV / m

no need to reach such high fields (idea from Gurevich et al (1992))

<u>runaway breakdown (RB) = avalanche:</u>
the runaway electron ionizes air molecules; most of the freed electrons have small energies but some of them have enough energy to become runaway electrons also: this is the avalanche process.
This process can explain the observed X ray flashes.

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OK in thunderstorms!

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Cosmic rays and lightnings?

Idea from Gurevich et al (1992)

Seed for RB in a thundercloud: the high energy (30 MeV) secondary e- in air showers

where E>Ec, the number of runaway electrons increases exponentially
W: energy dissipated by runaway e-
a large fraction of W is used to ionize the air, this creates a huge number of slow e-
these slow e-, under the influence of E, generate a **strong bipolar radio pulse**, the most powerful natural radio pulse (300 GW), this triggers the lightning

this pulse has a large power at MHz frequencies, duration: 400-700 ns, amplitude: 0.05-1 V/m

Observation of thunderstorms in radio CR experiments

Many cosmic-ray radio experiments observe thunderstorms indirectly:

- the radio signal from showers is modified by thunderstorms (amplified signal, modified polarization pattern)

or directly:

- transient radio signals are emitted by thunderstorms and can trigger the radio acquisition of these experiments

Report of thunderstorm influence on radio data by many recent experiments
CODALEMA, LOPES, RAuger, AERA, LOFAR…
we usually discard thunderstorm periods from the data

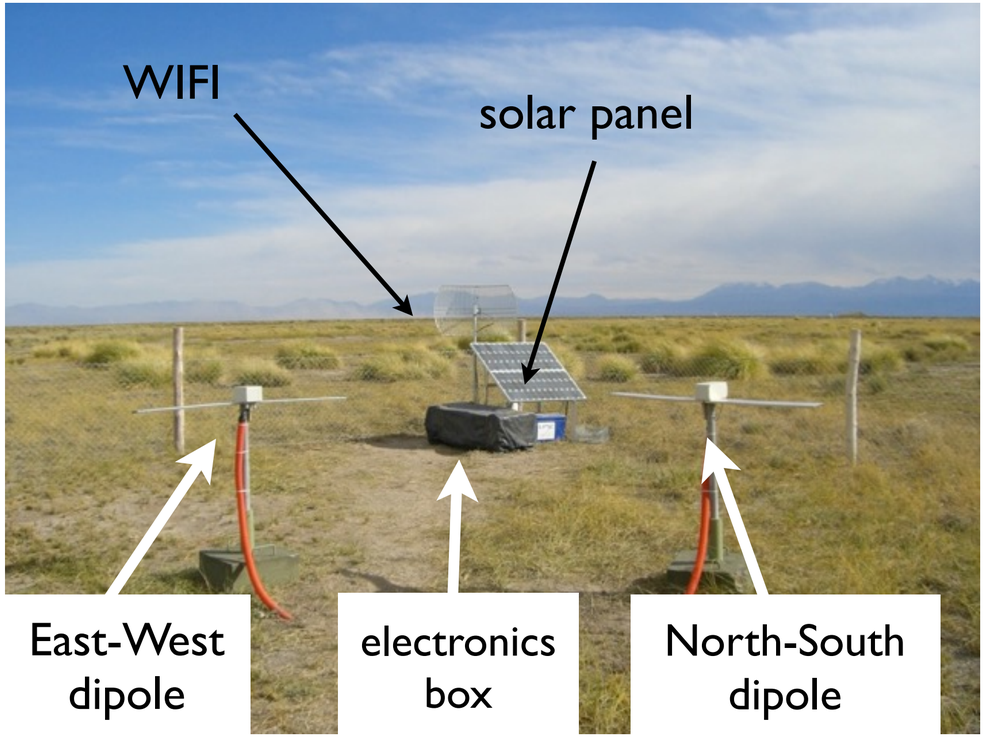
new approach: focus on thunderstorm periods!
(ongoing efforts on Auger, LOFAR, Nançay…)

Observation of thunderstorms in radio CR experiments

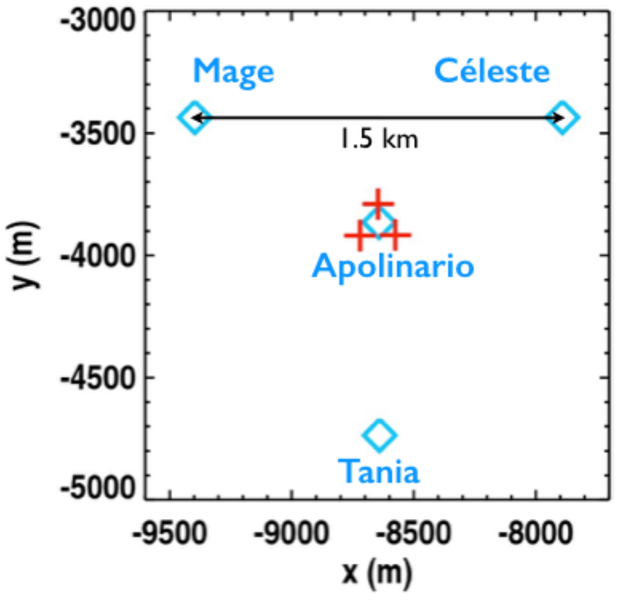
Example of the RAuger1 experiment, Pierre Auger Observatory, Argentina, 2007-2010

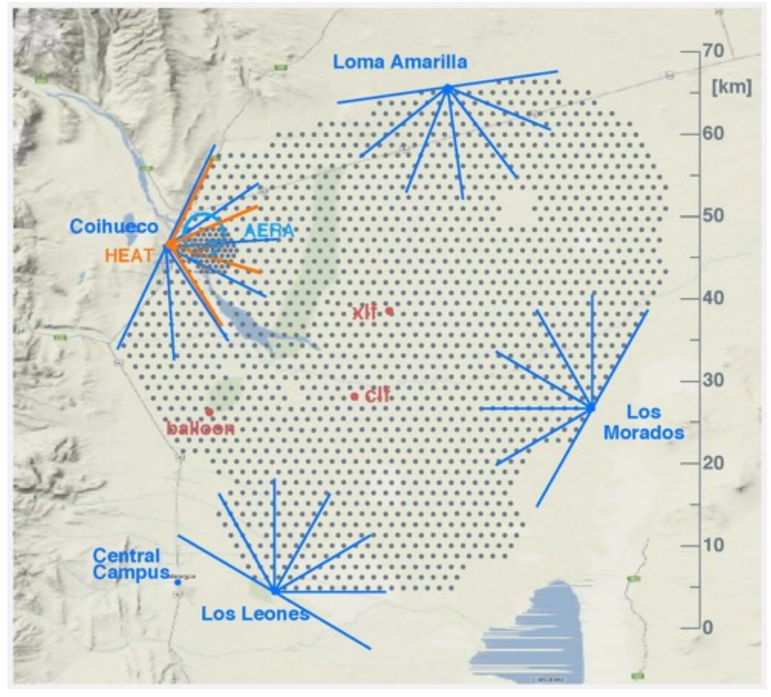
- 2 CODALEMA dipolar antennas (EW and NS polarizations)
- trigger with a simple threshold in the 50-70 MHz band, EW polarization (analogic filter)
- record the **transient** electric field between 30 MHz and 250 MHz (not only cosmic rays!)
- time resolution of ~ 10 ns

RAuger1 dedicated to the autonomous and independent cosmic ray detection but detection of many natural and anthropic transient



(JINST, 7(11):P11023, 2012)

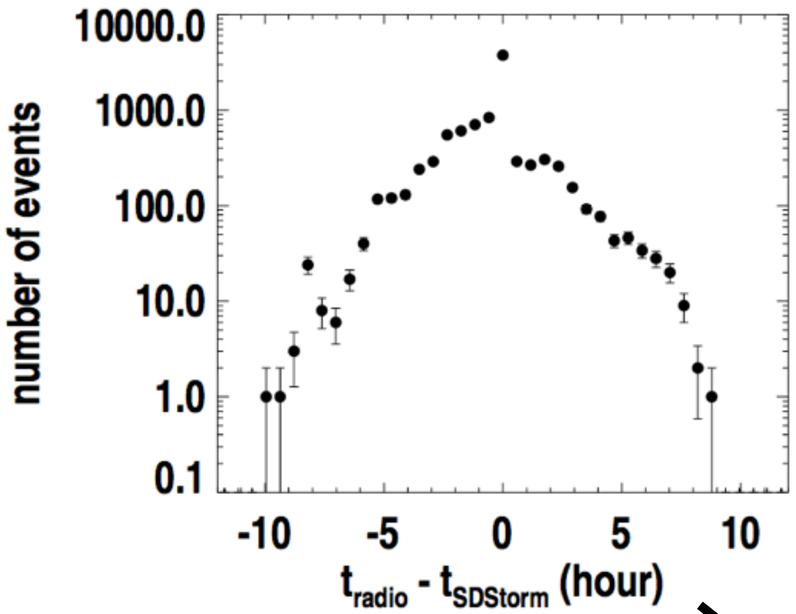


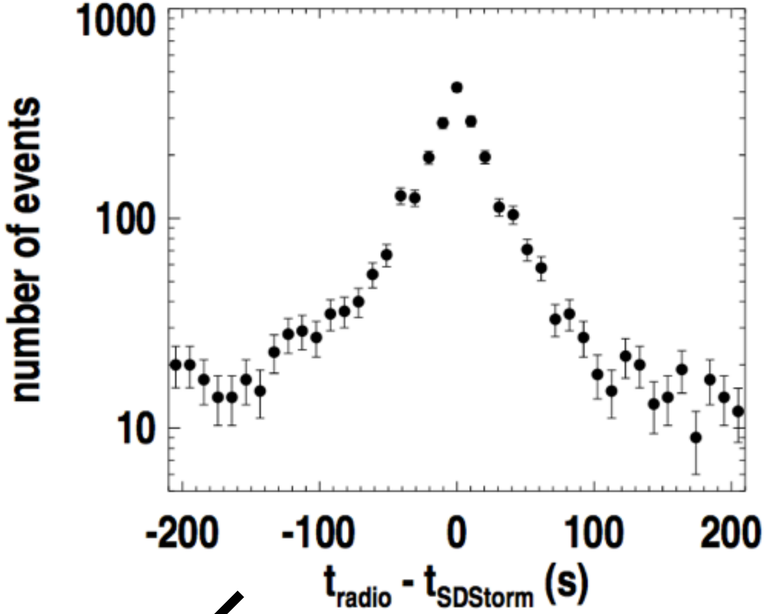


Observation of thunderstorms in radio CR experiments

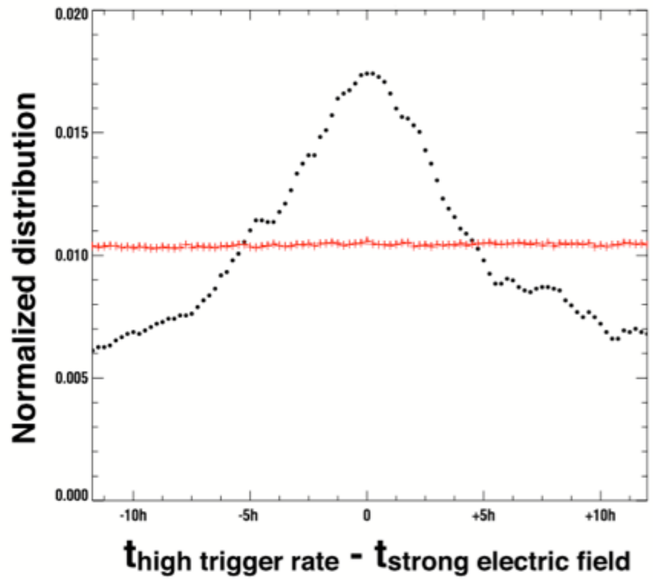
Example of the RAuger1 experiment, Pierre Auger Observatory, Argentina, 2007-2010

dataset: ~13000 triangulated events between 12/2007 and 04/2009
72% of these events are at less than 12h from a thunderstorm
distribution of the time difference between a triangulated radio transient in RAuger1 and a thunderstorm event in Auger surface detector





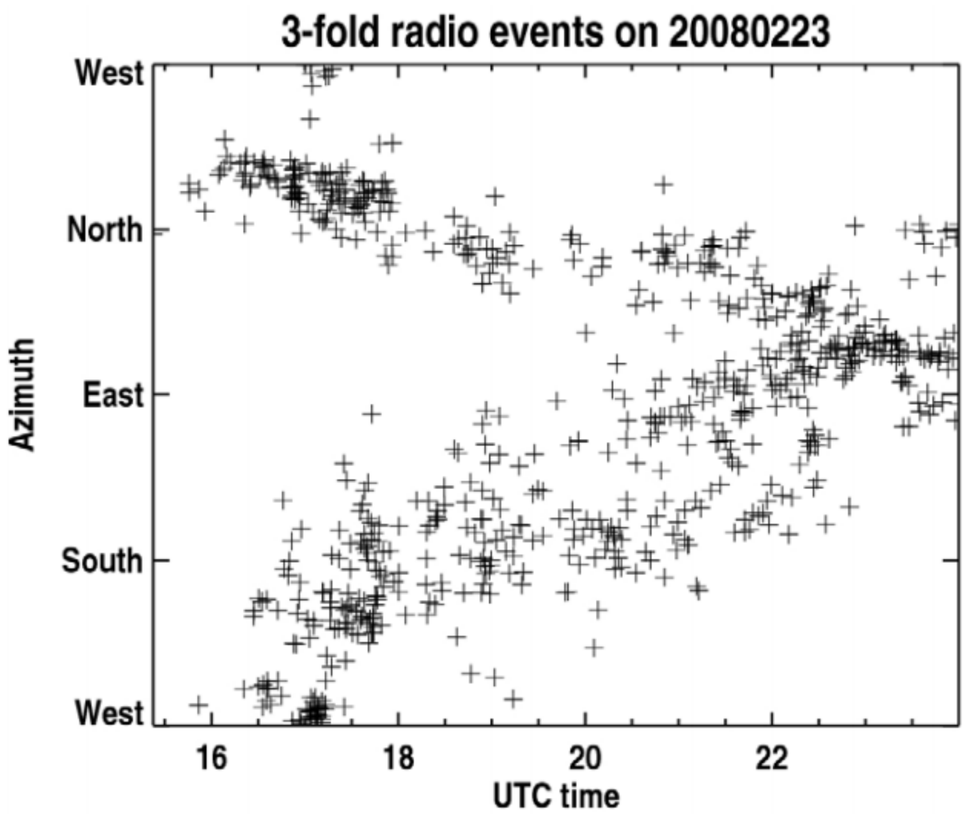
triangulated events

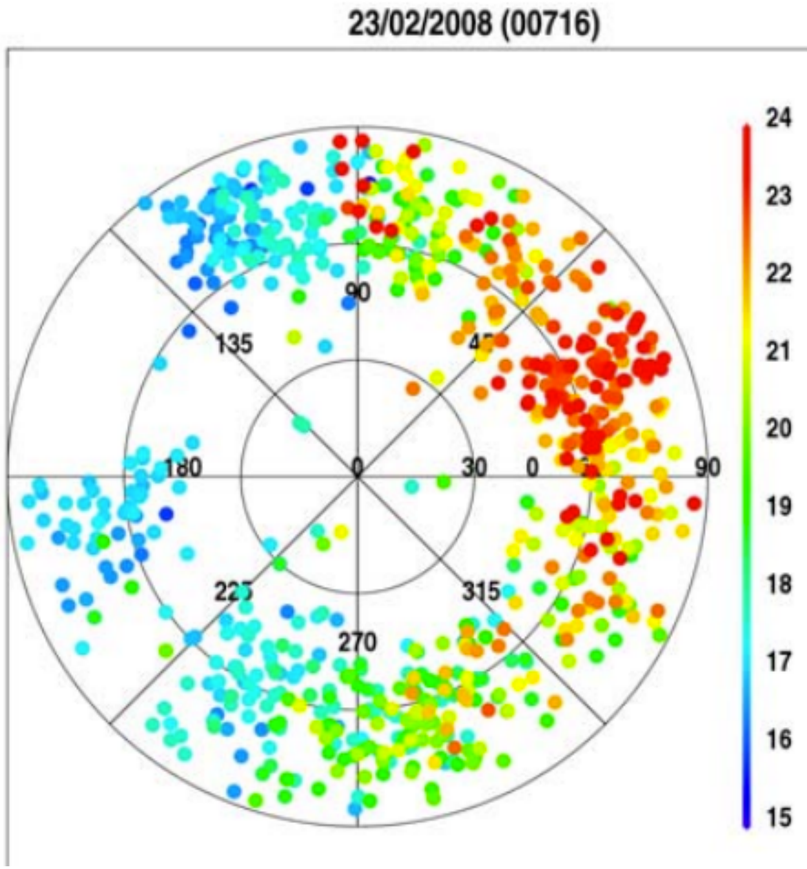


more high trigger rate periods when the atmospheric electric field is high

Observation of thunderstorms in radio CR experiments

Example of the RAuger1 experiment, Pierre Auger Observatory, Argentina, 2007-2010





Possible to triangulate the direction of the incoming wave (for cosmic rays, thunderstorms, airplanes…)

two thunderstorm clouds merging?

conclusion: we can observe thunderstorms and have access to the associated 3D electric field

Observation of cosmic rays during thunderstorms conditions

Example of the LOFAR experiment, Netherlands (Schellart et al, Phys. Rev. Lett. 114, 165001, **April 2015**)

The arrival direction of the shower is NOT affected by the thunderstorm: we can compute the expected polarization pattern (vXB at first order)
given the measured polarization pattern, we can estimate Ethunderstorm

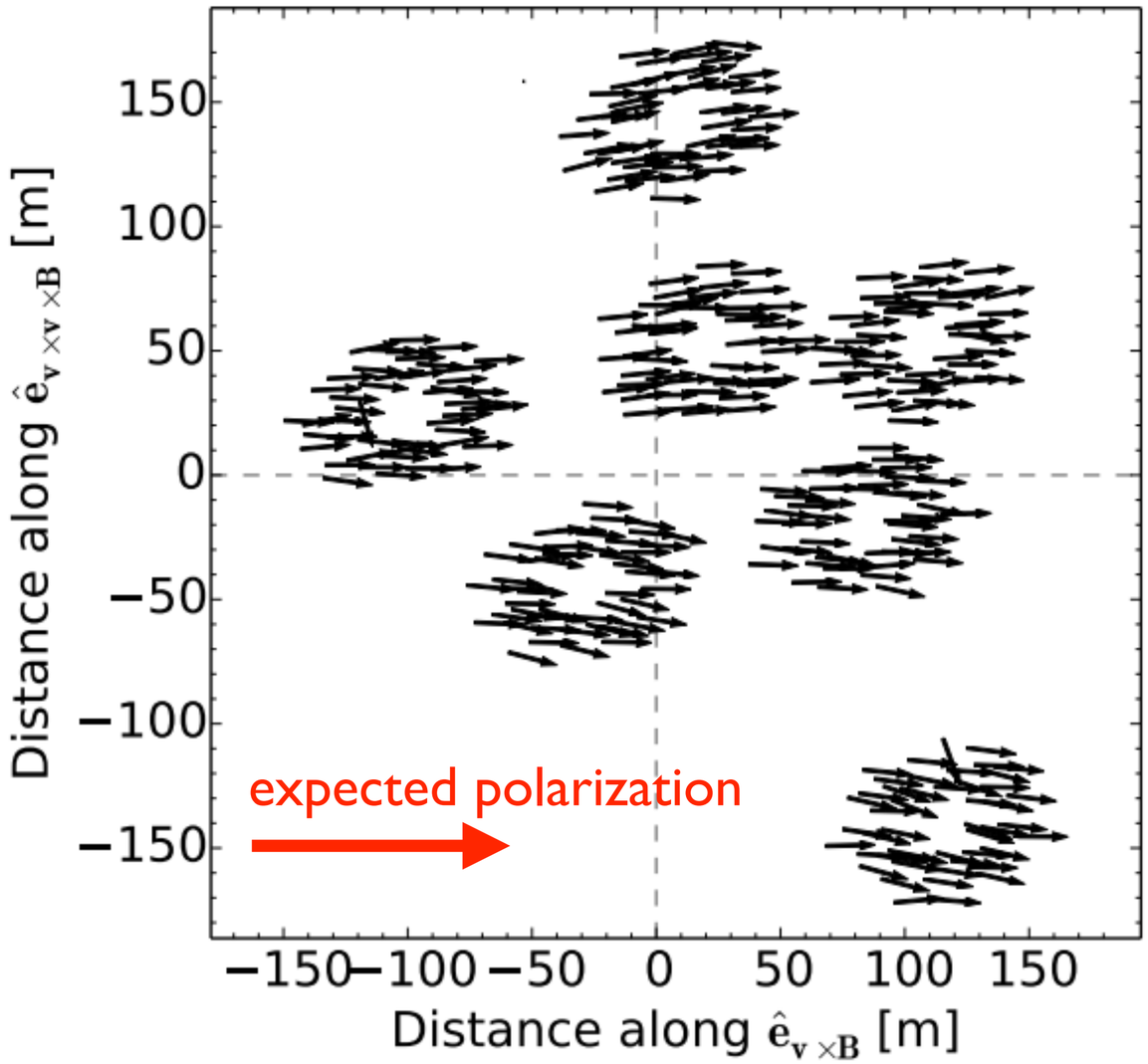
LOFAR data: in 10-90 MHz, 2 horizontal polarizations (June 2011-September 2014)

number of showers	**762**	
with strange footprints	**58**	polarization patterns far from vXB, sometimes ring structure, amplified field (no rings for CR in 10-90 MHz)
reconstruction OK (large SNR)	**31**	
coincidence with lightnings	**20**	distance to lightnings < 150 km
no association with lightnings	**11**	high atm. electric field but no lightnings

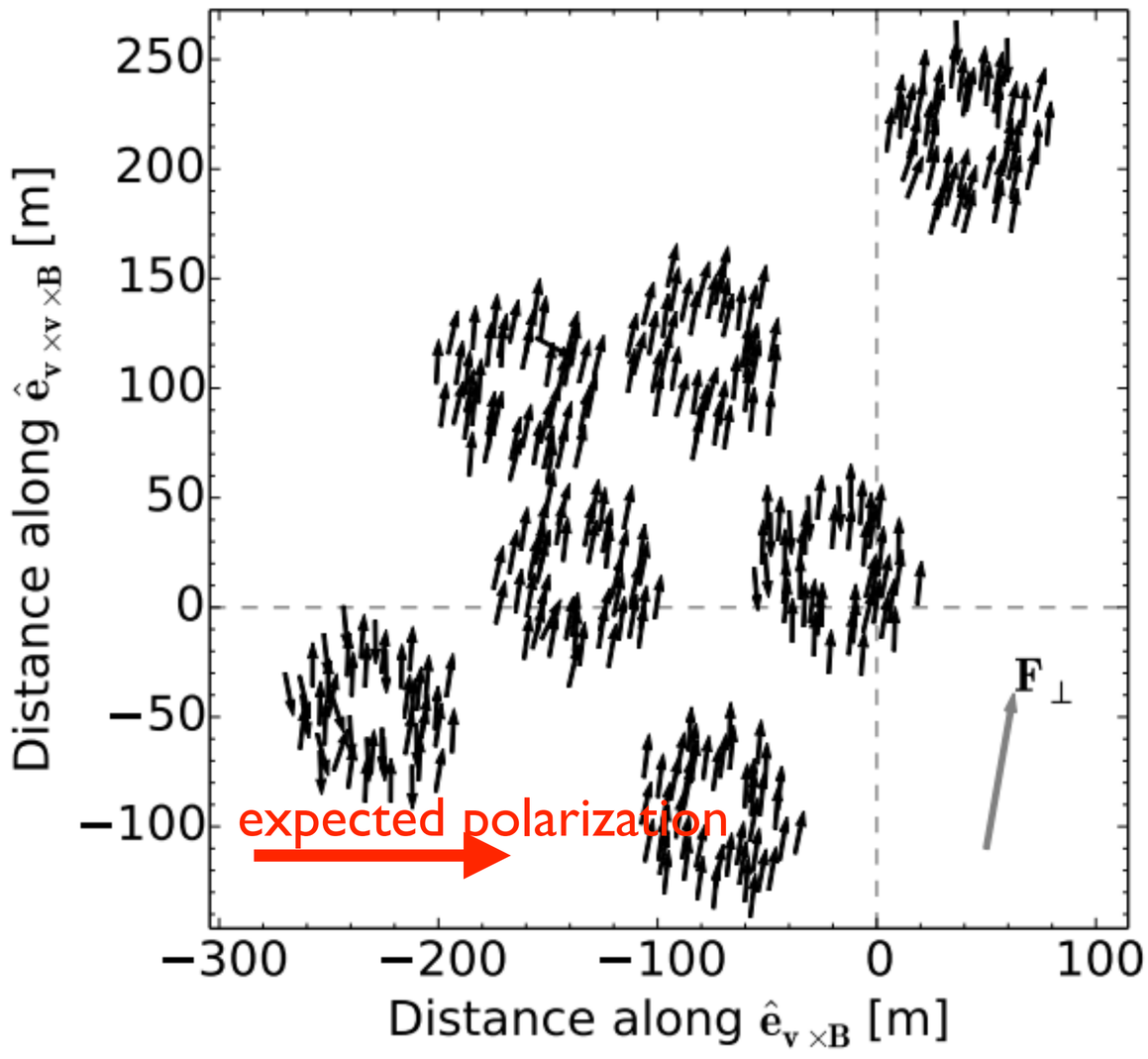
Observation of cosmic rays during thunderstorms conditions

Example of the LOFAR experiment, Netherlands (Schellart et al, Phys. Rev. Lett. 114, 165001, **April 2015**)

Polarization pattern from a CR, fair weather



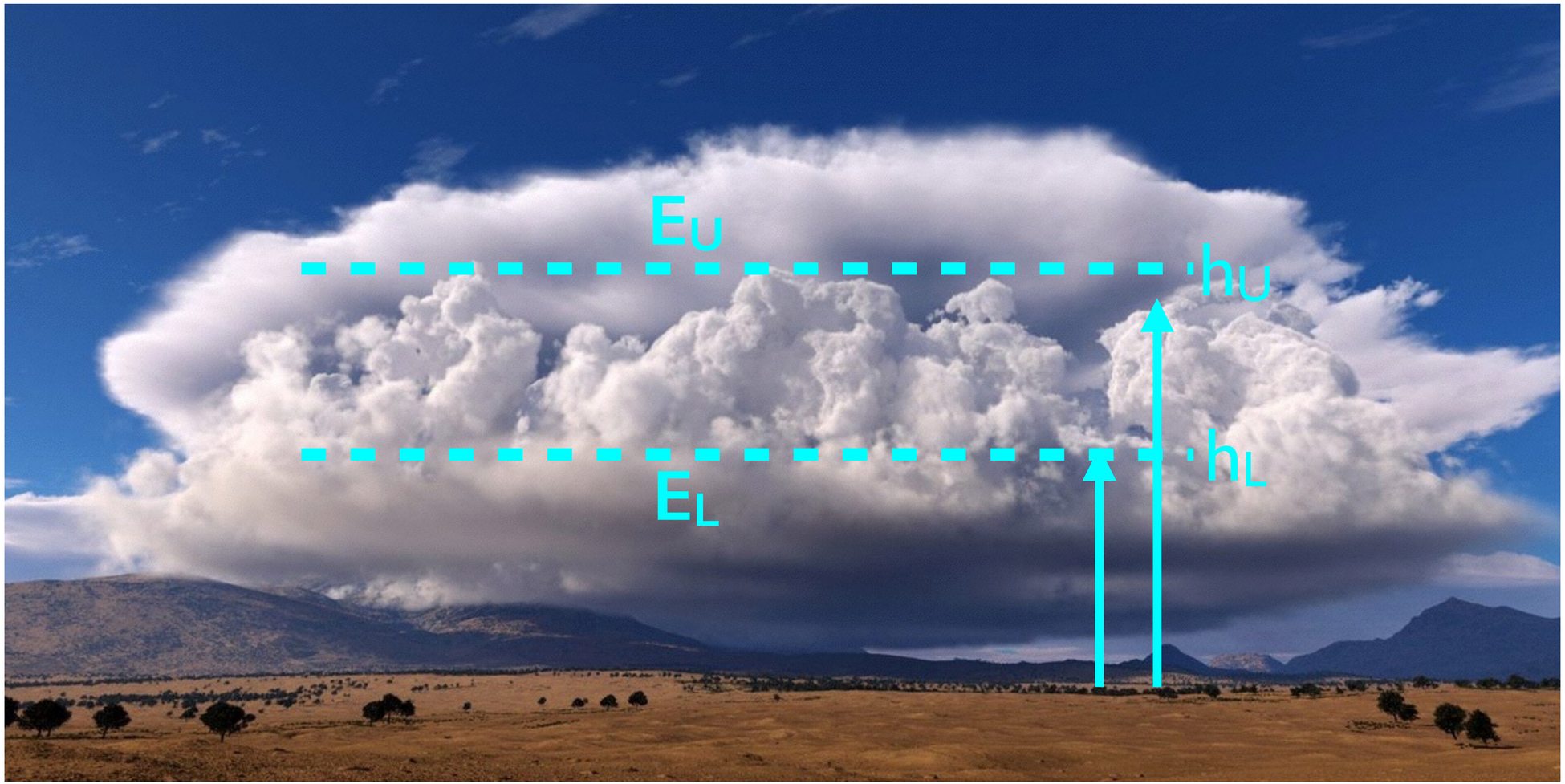
Polarization pattern from a CR, thunderstorm



Observation of cosmic rays during thunderstorms conditions

Example of the LOFAR experiment, Netherlands (Schellart et al, Phys. Rev. Lett. 114, 165001, **April 2015**)

Good agreement simulations/data if we assume a two-layer atmospheric electric field

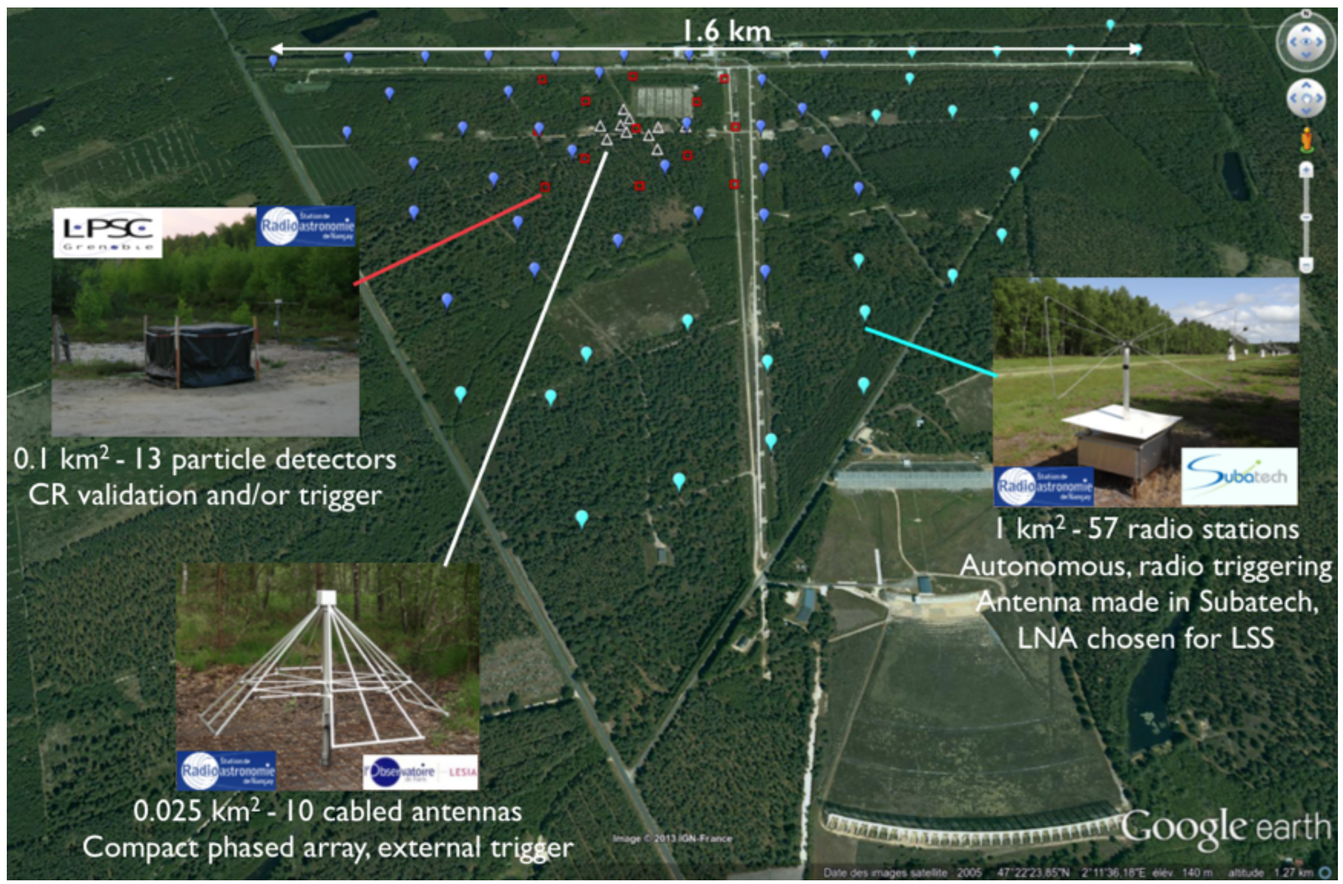


Optimal reconstruction for h_U = 8 km, h_L = 2.9 km, $|E_U|$ = 50 kV / m, $|E_L|$ = 26.5 kV / m

The LICORNE project

Project funded by the Interdisciplinary program of École des Mines de Nantes

Study the correlation of cosmic ray data by EXTASIS GROUPE ASTRO / CODALEMA GROUPE ASTRO and lightning data by Météorage



- array of 13 scintillators to identify cosmic rays
- array of 57 autonomous stations to measure the electric field from showers (20-250 MHz)
- array of 10 stations triggered by the scintillator array
- new developments in 2-9 MHz to detect the signal from the disappearance of the shower front below the ground level (EXTASIS)
- atmospheric electric field meter
- weather station

EMN/CNRS/IN2P3
CNRS/INSU LERMA
CNRS/INSU LA
CNRS/INSU LPC2E
CNRS/INSU LATMOS
Météorage