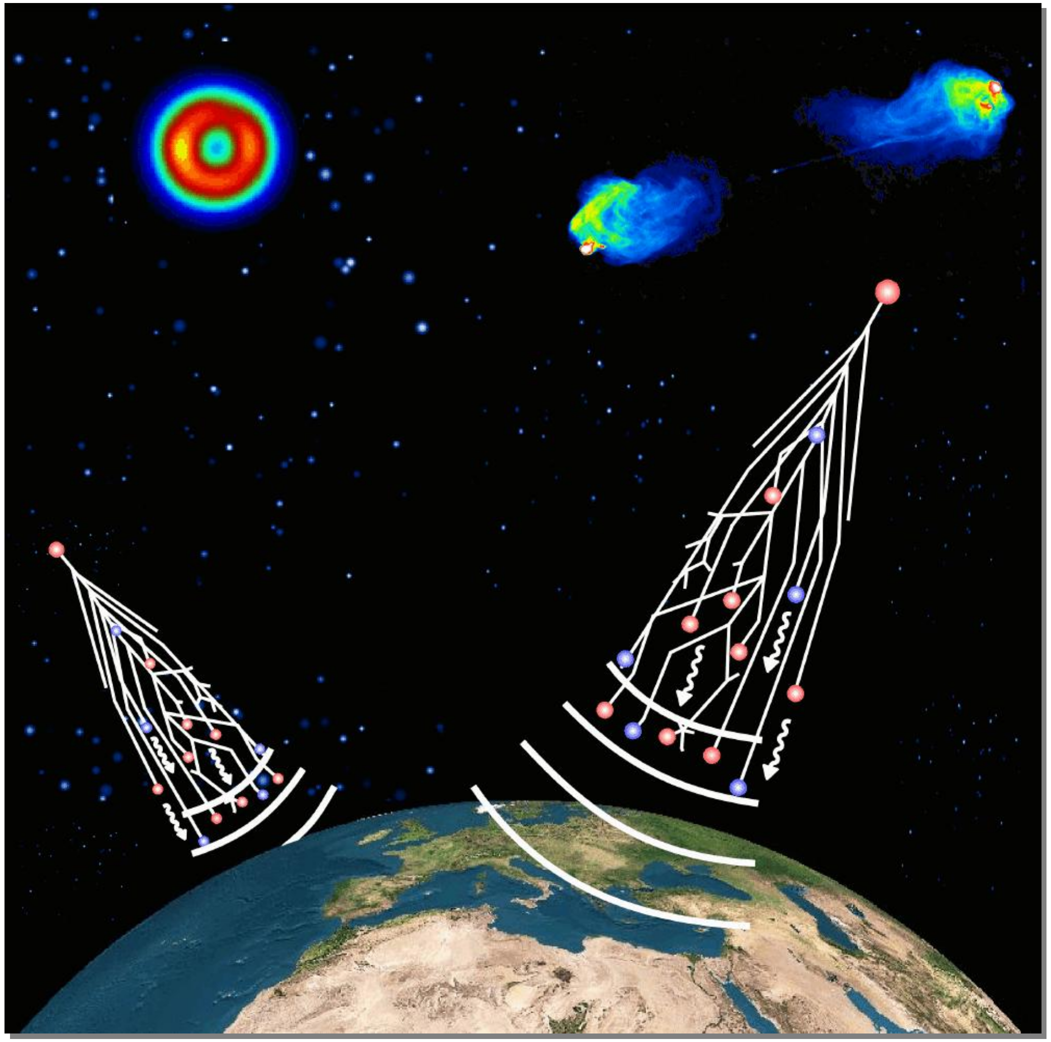
Advanced Techniques for the detection of ultra-high energy cosmic rays

Tim Huege
Karlsruhe Institute of Technology (KIT)

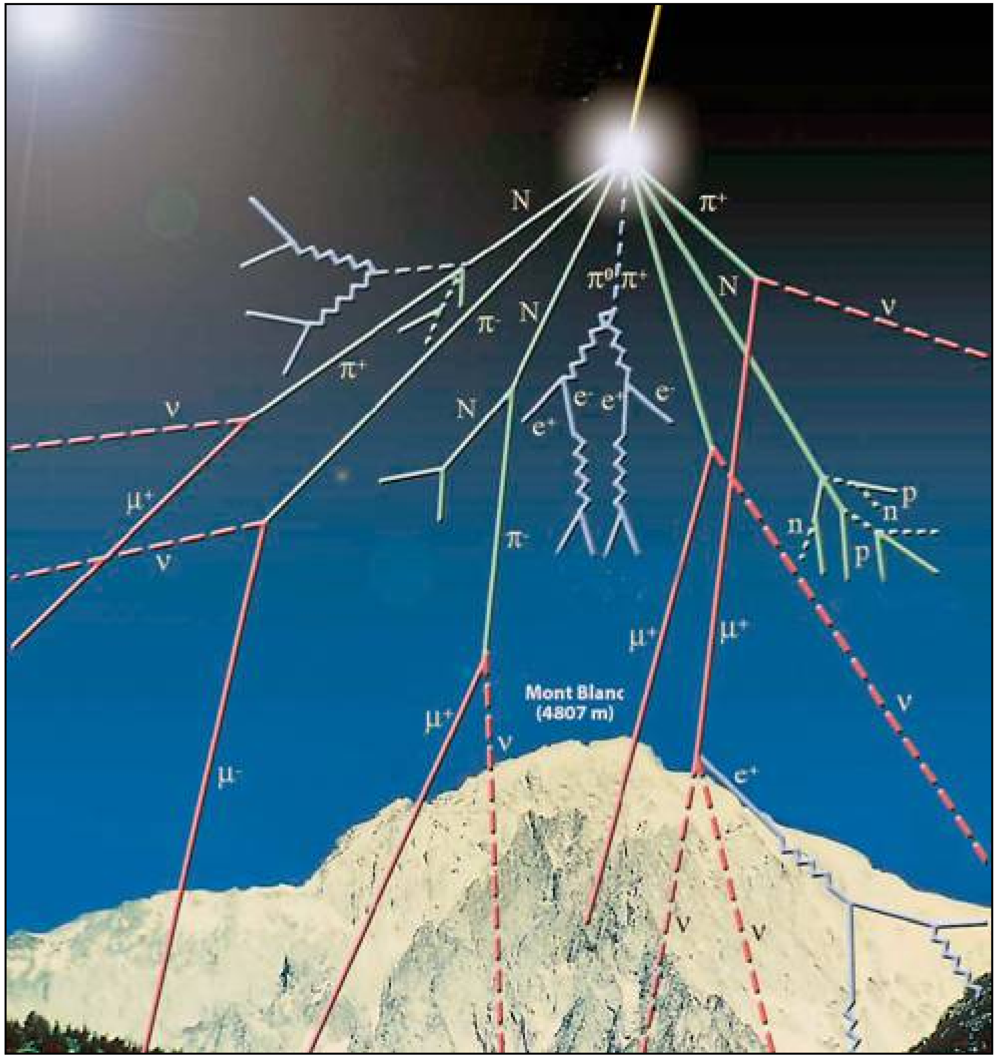
Contents

- **the early days of CR radio detection**
- the revival of CR radio detection
  - experiments
  - theory
  - results
- the future of CR radio detection



Extensive air showers

- cosmic rays interact with nuclei in the atmosphere
- cascade of secondary particles evolves
  - grows up to billions of particles before it declines again
  - depth of shower maximum (X_{max}) carries information about primary mass
- hadronic interactions at extremely high energies
  - Monte Carlo simulations
  - considerable model uncertainties

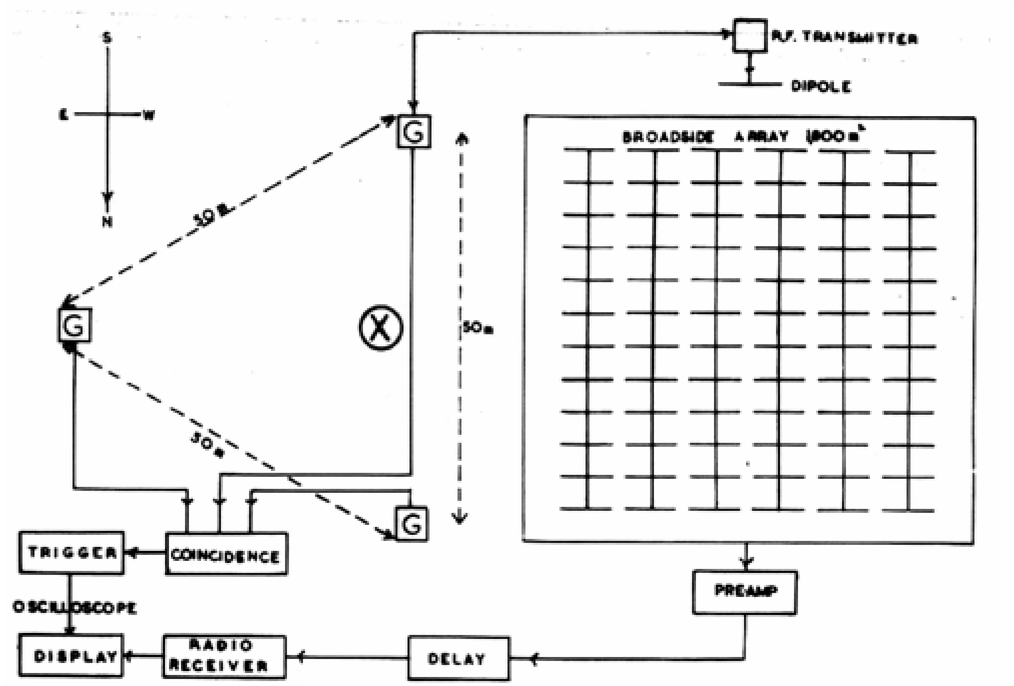


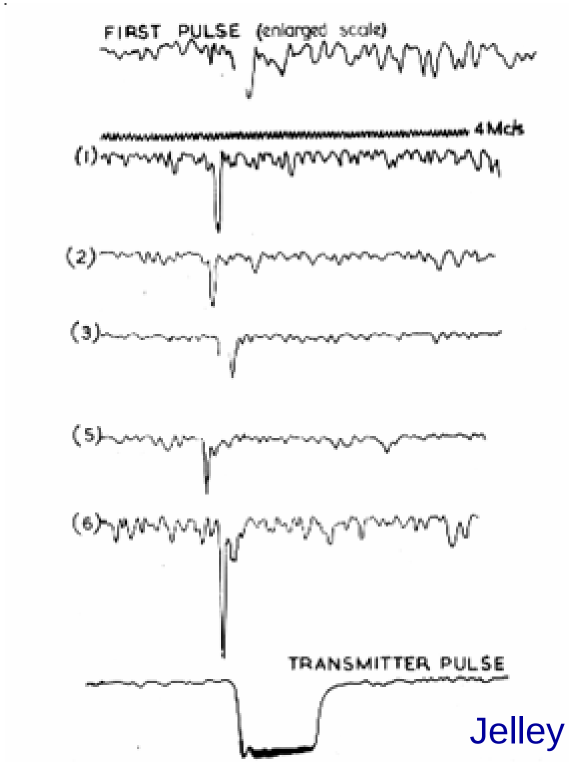
The beginning of CR radio detection

- **1941: Blackett and Lovell try to detect ionisation trails of cosmic ray air showers with radar techniques**
- **1958: Jelley proposes that Cherenkov radio emission from air showers might be detectable at GHz frequencies, but signals are predicted to be very small**
- **1962: Askaryan proposes *coherent* radio Cherenkov emission from a charge excess in air showers at MHz frequencies**
- **1964: Jelley et al. set up an experiment at Jodrell Bank**

The Jodrell Bank experiment

- **array of dipoles with 10° FWHM beam width**
- **operation at 44 MHz with 2.75 MHz bandwidth**
  - **BBC TV channel, turned off from midnight to 9 a.m.**
- **Geiger counter coincidence triggers photograph of oscilloscope traces**





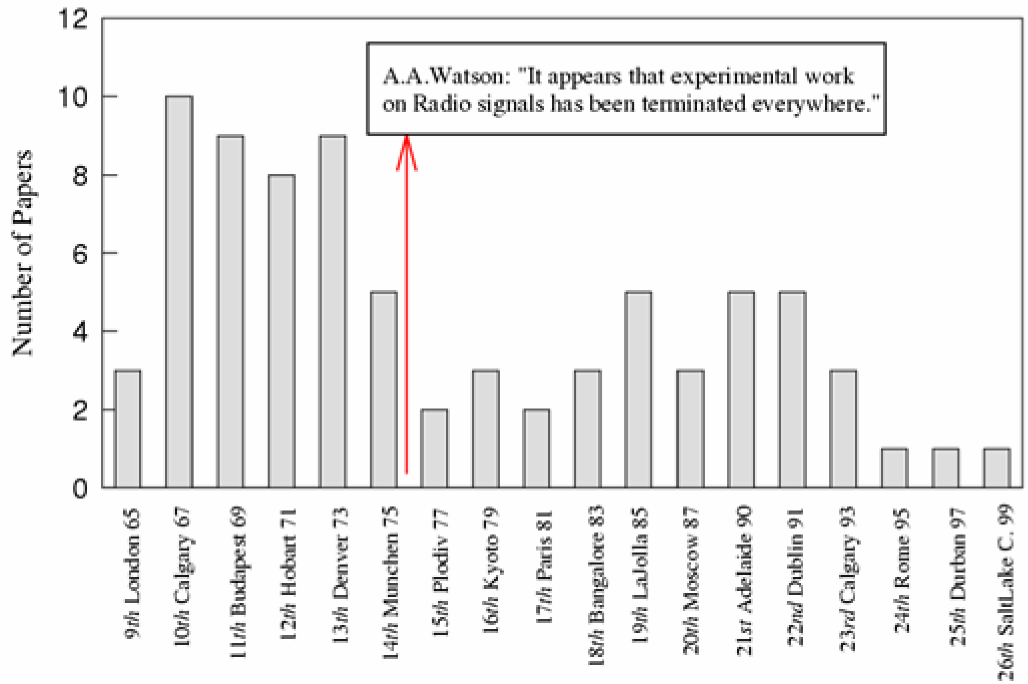
Jelley et al., Nature 1965

A flurry of activity

- interpretation of the emission mechanism
  - radio Cherenkov from charge excess (“Askaryan mechanism”)
  - geomagnetic separation of secondary electrons and positrons
  - other mechanisms soon excluded (transition radiation, …)
- many following experiments
  - lower and higher frequency observations
  - measurements towards specific directions w.r.t. geomagnetic field
  - polarisation measurements – support geomagnetic effect!
- groups active in the UK, Ireland, Italy, Russia, Canada
  - problems in pinning down the absolute strength of the emission, differences of order of magnitude between different groups

Loss of interest

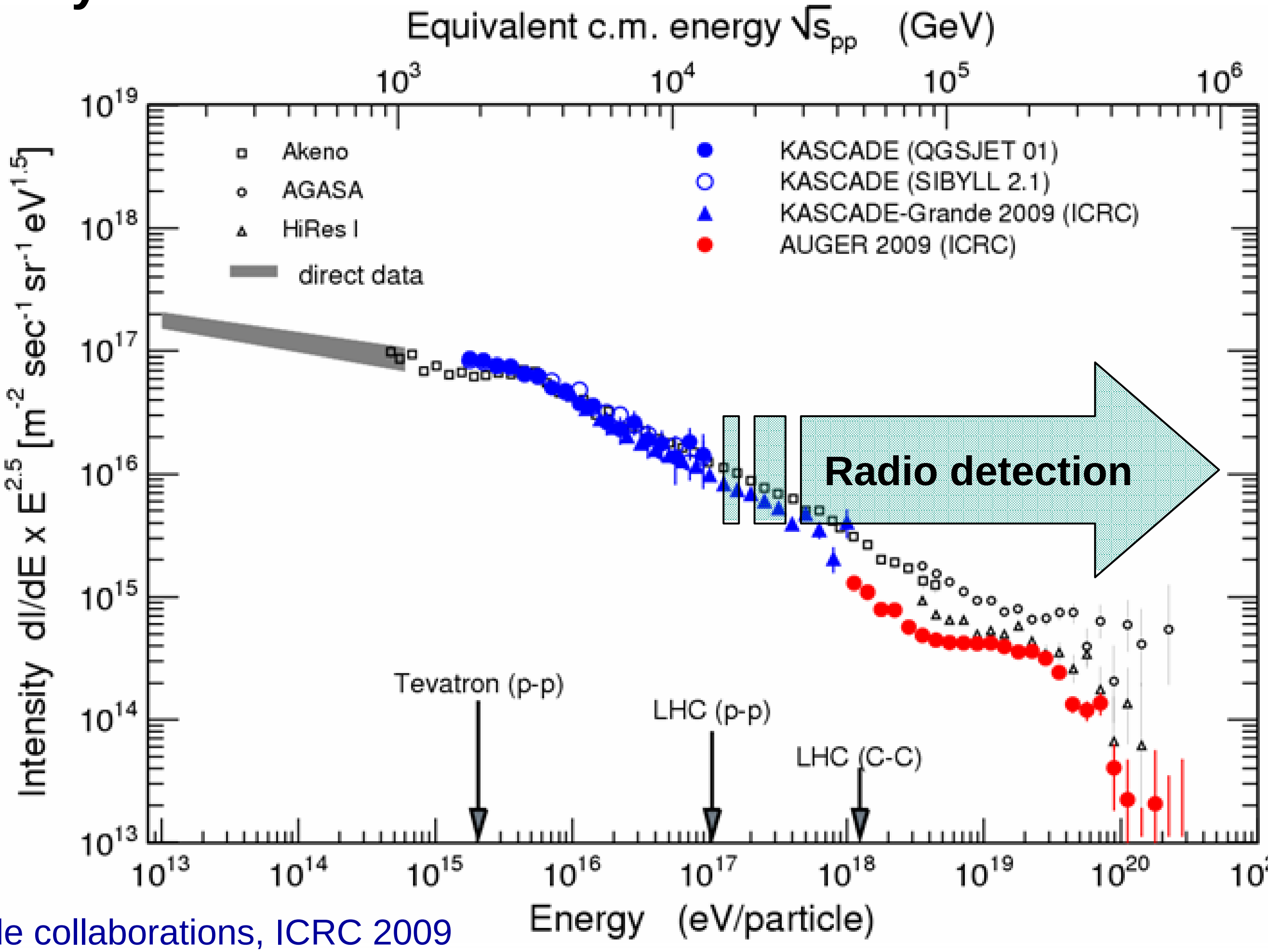
- work ceased almost completely in 1970s
  - technical difficulties
    - few antennas
    - limited bandwidth
    - pure analogue technology
    - increasing RFI
  - interpretation problems
    - dependence on electric fields in atmosphere?
  - success of other techniques



T.C. Weekes, RADHEP 2000

Cosmic ray measurements

- many open questions, especially about origin of ultra-high energy cosmic rays
- detection techniques
  - direct measure-ments
  - surface particle detectors
  - air fluores-cence measure-ments
  - radio detection



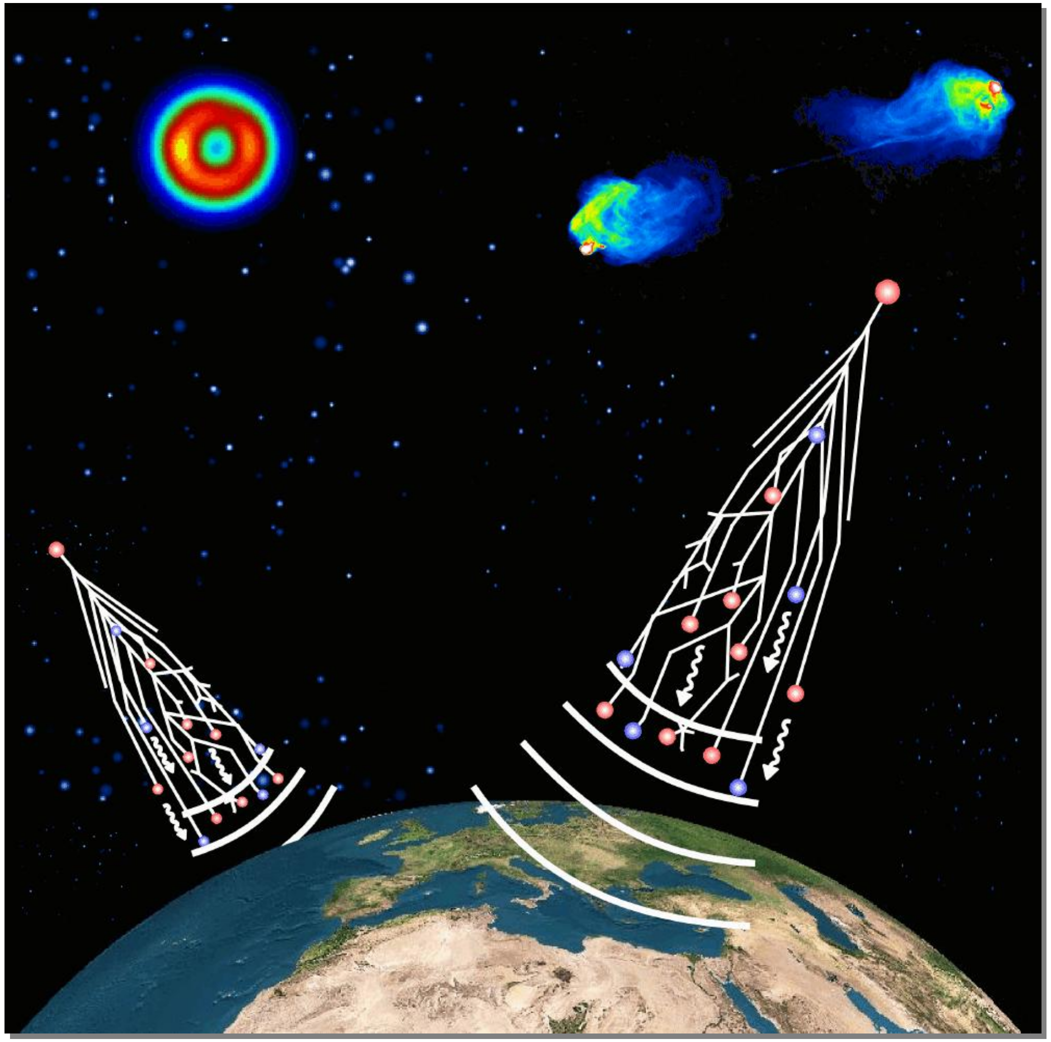
Auger and KASCADE-Grande collaborations, ICRC 2009

Revived interest in radio detection

- today's possibilities in digital signal processing make radio detection of CRs attractive once again
- merits of cosmic ray radio detection
  - complementary to particle detectors
  - 100% duty cycle (cf. 10-15% of optical fluorescence detectors)
  - high angular resolution (< 0.5° achievable)
  - simple (potentially cheap) detectors
  - also applicable to very inclined (e.g. neutrino-induced) air showers
- new projects started in last few years
  - LOPES experiment in Karlsruhe, Germany
  - CODALEMA experiment in Nançay, France
  - Auger radio detection activities, AERA

Contents

- the early days of CR radio detection
- **the revival of CR radio detection**
  - **experiments**
  - theory
  - results
- the future of CR radio detection



A new generation of experiments

- LOPES (Karlsruhe, Germany)
  - 30 channels
  - 40-80 MHz
  - triggered by KASCADE-Grande experiment
- CODALEMA (Nançay, France)
  - 24 channels
  - (usually) 24-82 MHz
  - triggered by array of 17 particle detectors

LOFAR as starting point for LOPES

- LOFAR revives long-wavelength astronomy at ~30-240 MHz
- fully digital interferometer
  - full sky coverage
  - high angular resolution
  - “parallel beams”
  - buffering makes it *ideal for detecting transient sources*
- idea to reattempt radio detection of cosmic rays with modern technology

LOPES – “LOFAR Prototype Station”

Karlsruhe Institute of Technology

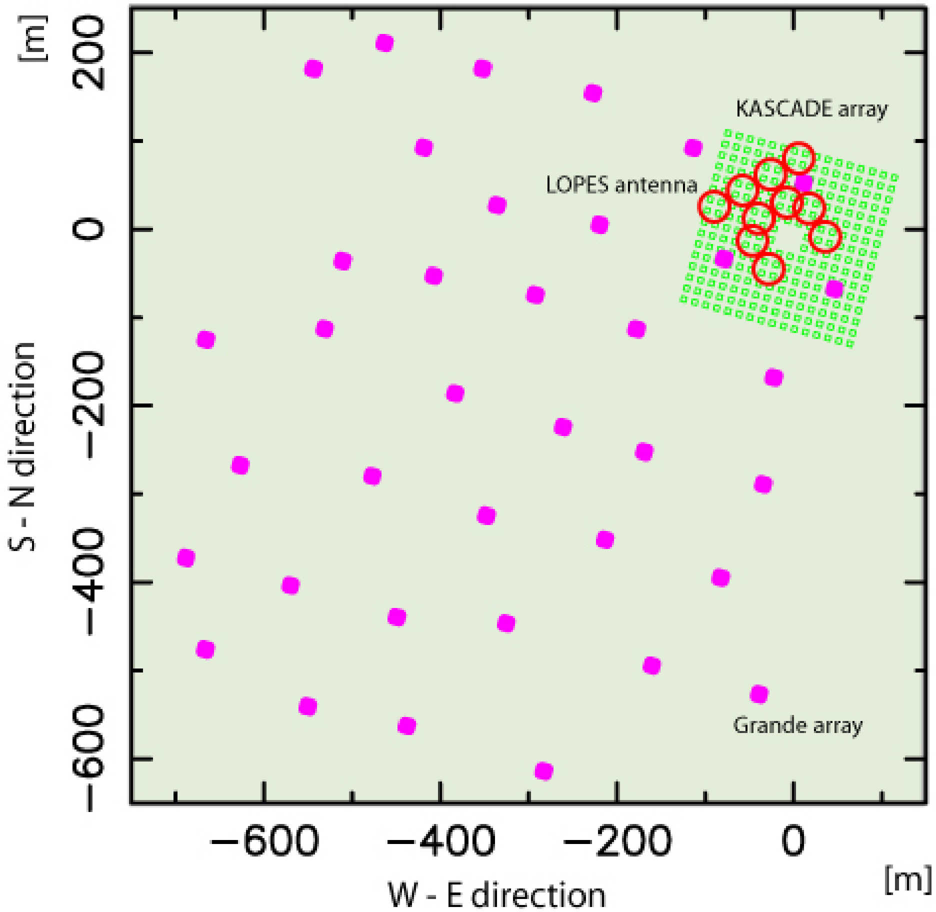
- **based on LOFAR hardware**
- **integrated with KASCADE-Grande experiment in Karlsruhe**
  - **provides trigger**
  - **provides air shower geometry**
  - **provides per-event air shower parameters for study of radio emission systematics**
- **goals of LOPES:**
  - **deliver “proof of principle”**
  - **study radio emission physics up to ~ 10^{18} eV**
  - **develop and optimise technique for large scale application at ultra-high energies**

LOPES and KASCADE-Grande

- located at Forschungszentrum Karlsruhe

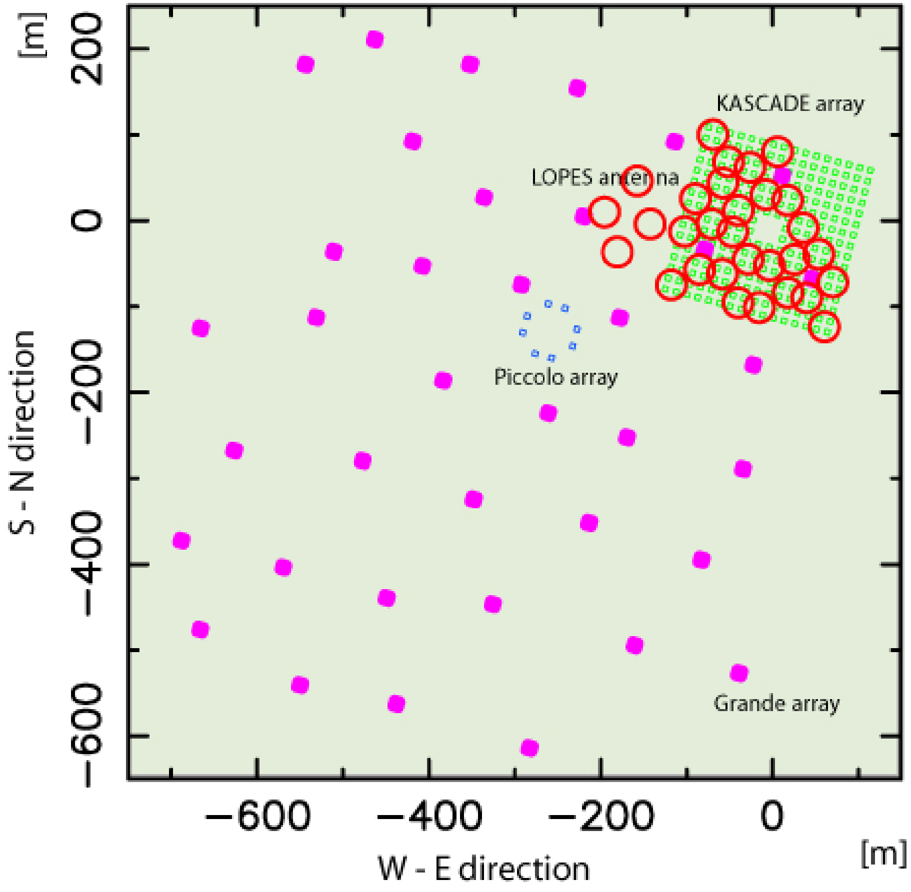
The first phase: LOPES10

- **10 dipole antennas in the KASCADE-array**
  - **measuring at 40-80 MHz**
  - **east-west polarized**
  - **triggered by KASCADE above ~10^{16} eV**
- **gathered 7 months of data in 2004**



The second phase: LOPES30

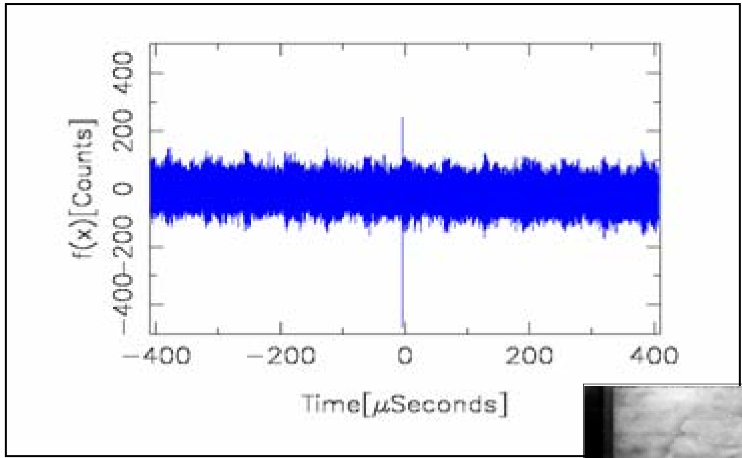
- extension to 30 antennas with longer baselines
  - better sensitivity
  - better angular resolution
  - per-event measurement of lateral profile
- absolute calibration with a reference source
  - absolute field-strengths unclear since 40 years
- monitoring of environmental conditions
- now dual-polarization measurements
  - 15 EW channels
  - 15 NS channels



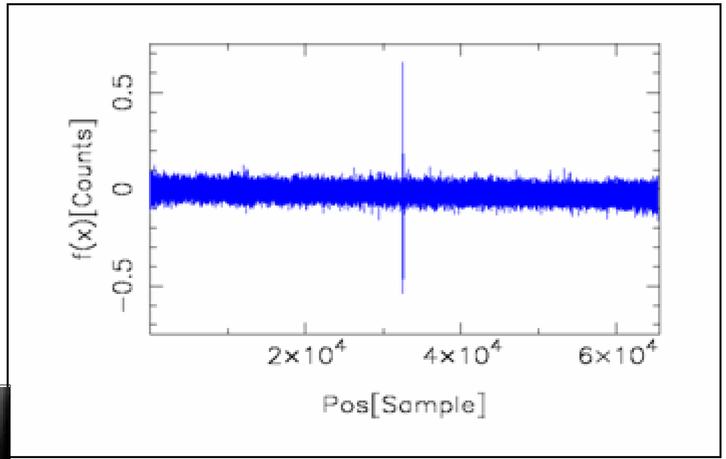
LOPES analysis: Digital RFI Suppression

- **narrow-band noise can be filtered digitally**

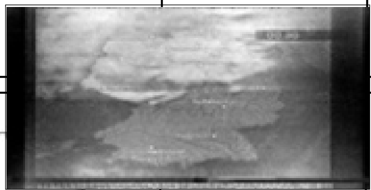
raw data

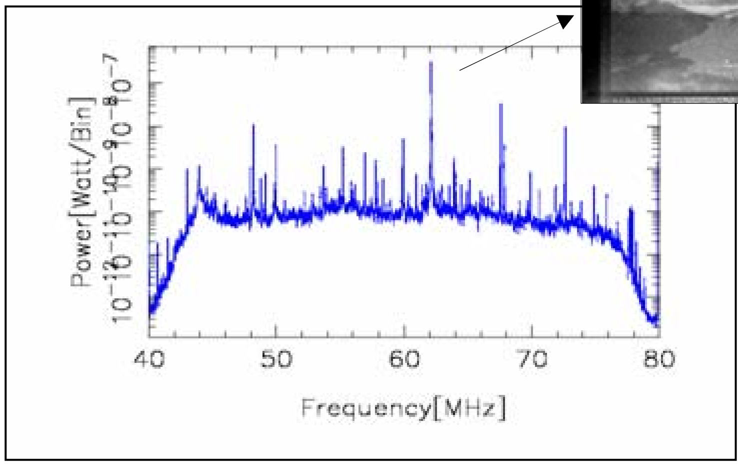


digitally filtered

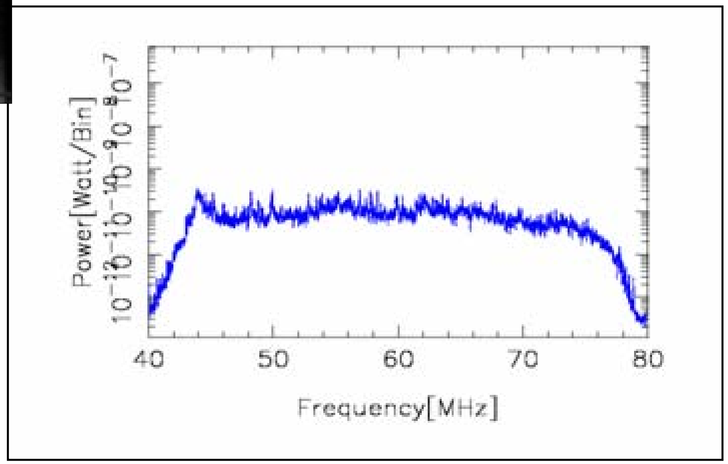


time series



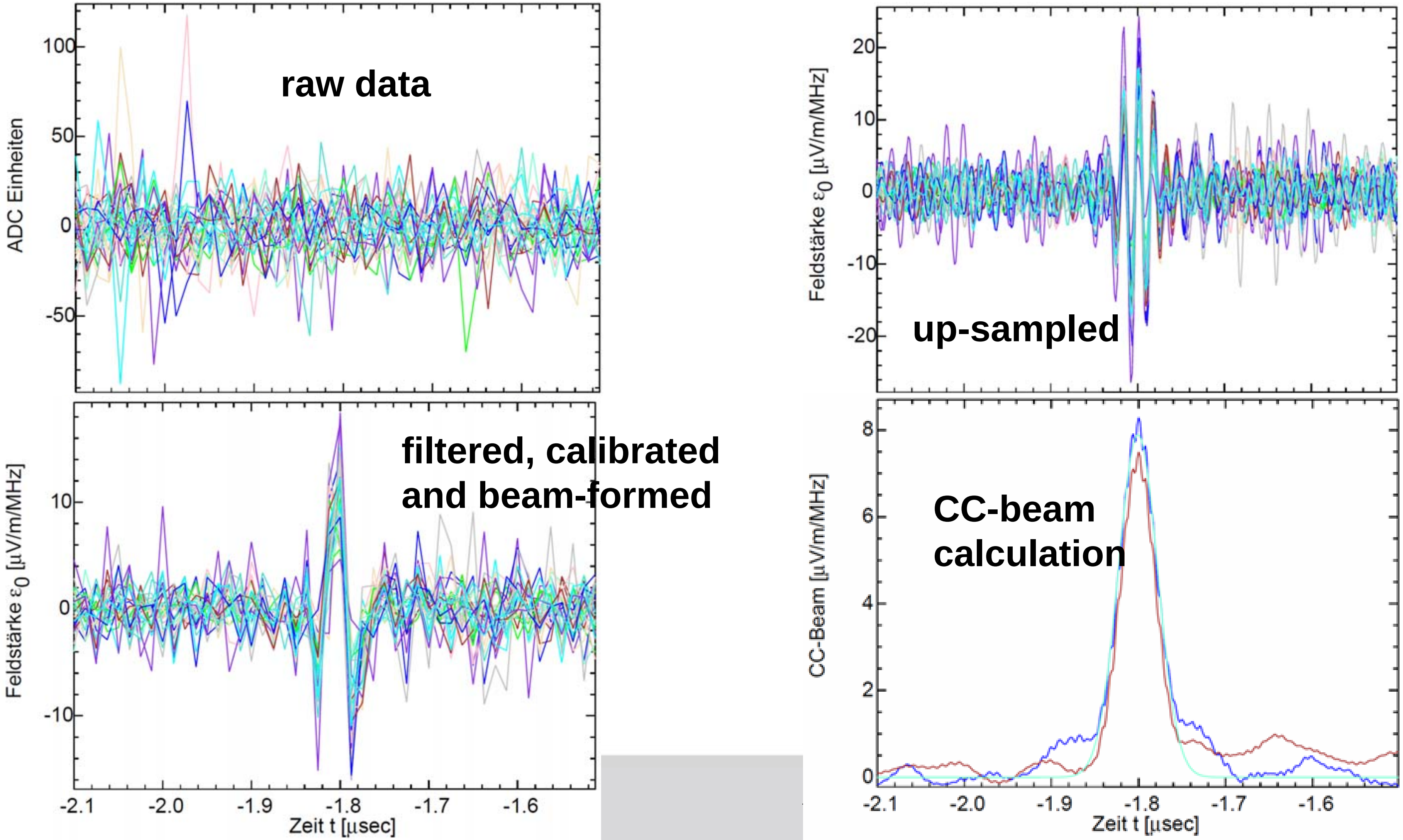


frequency spectrum



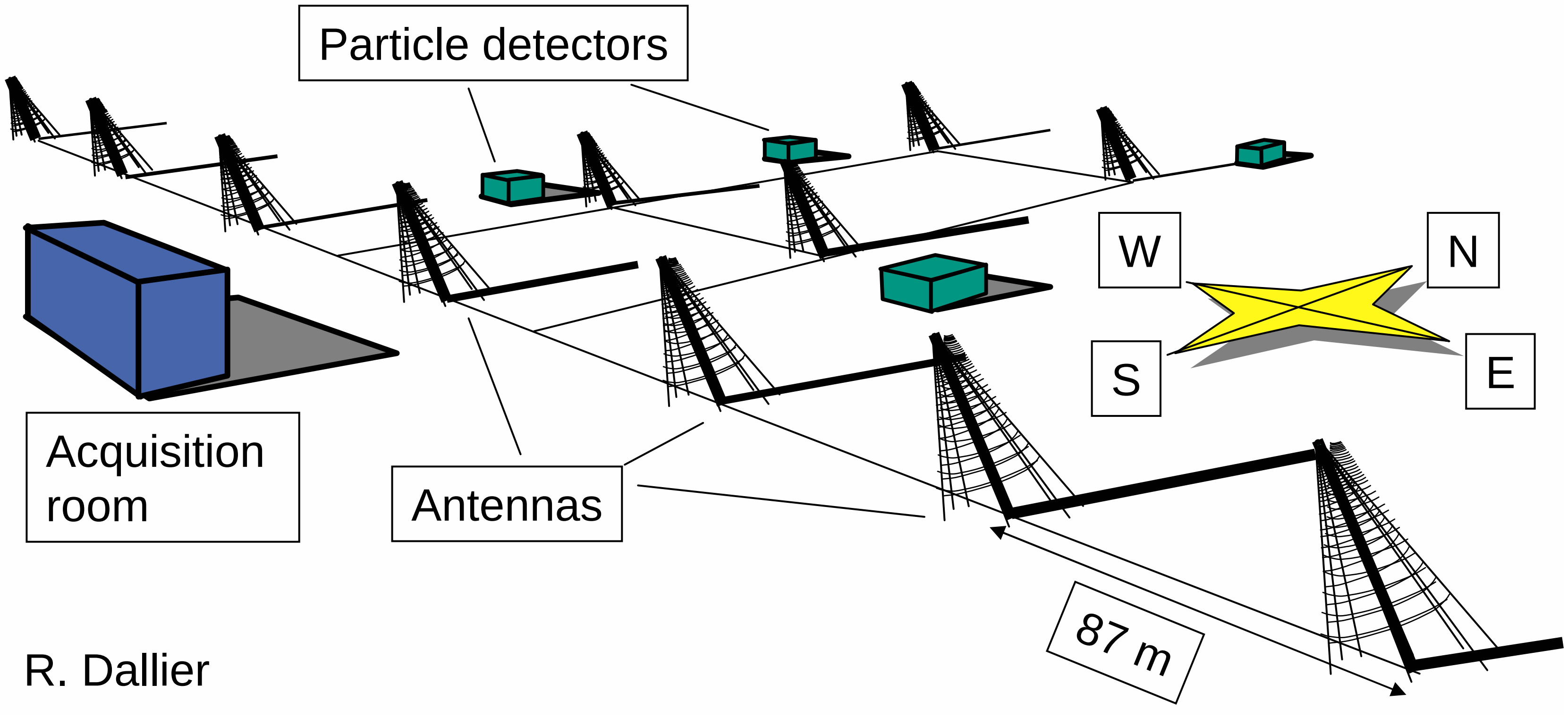
LOPES analysis: Digital interferometry

- **LOPES antennas are read out after KASCADE-trigger**
- **KASCADE reconstructs event and provides air shower geometry as starting point for the “beam forming”**



The early CODALEMA experiment

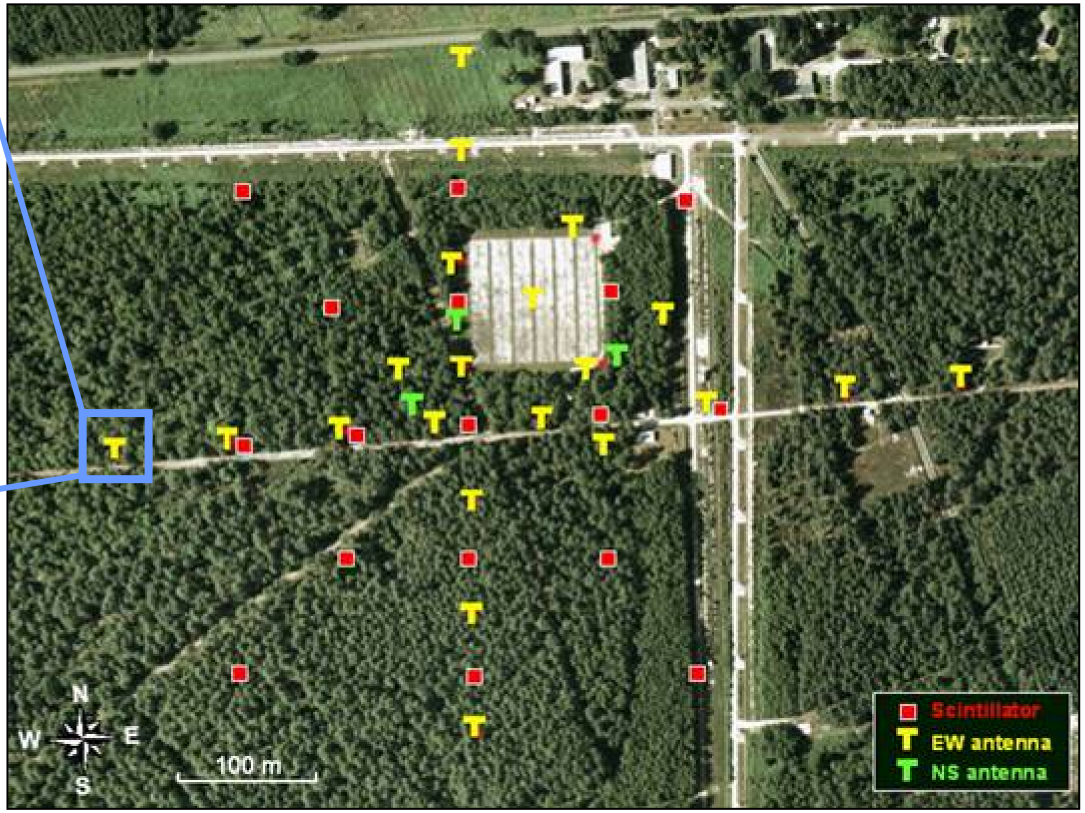
- used existing radioastronomical instrument: Nançay Decametric Array
  - circularly polarised antennas, frequency range 40-70 MHz
- triggered by small number of particle detectors



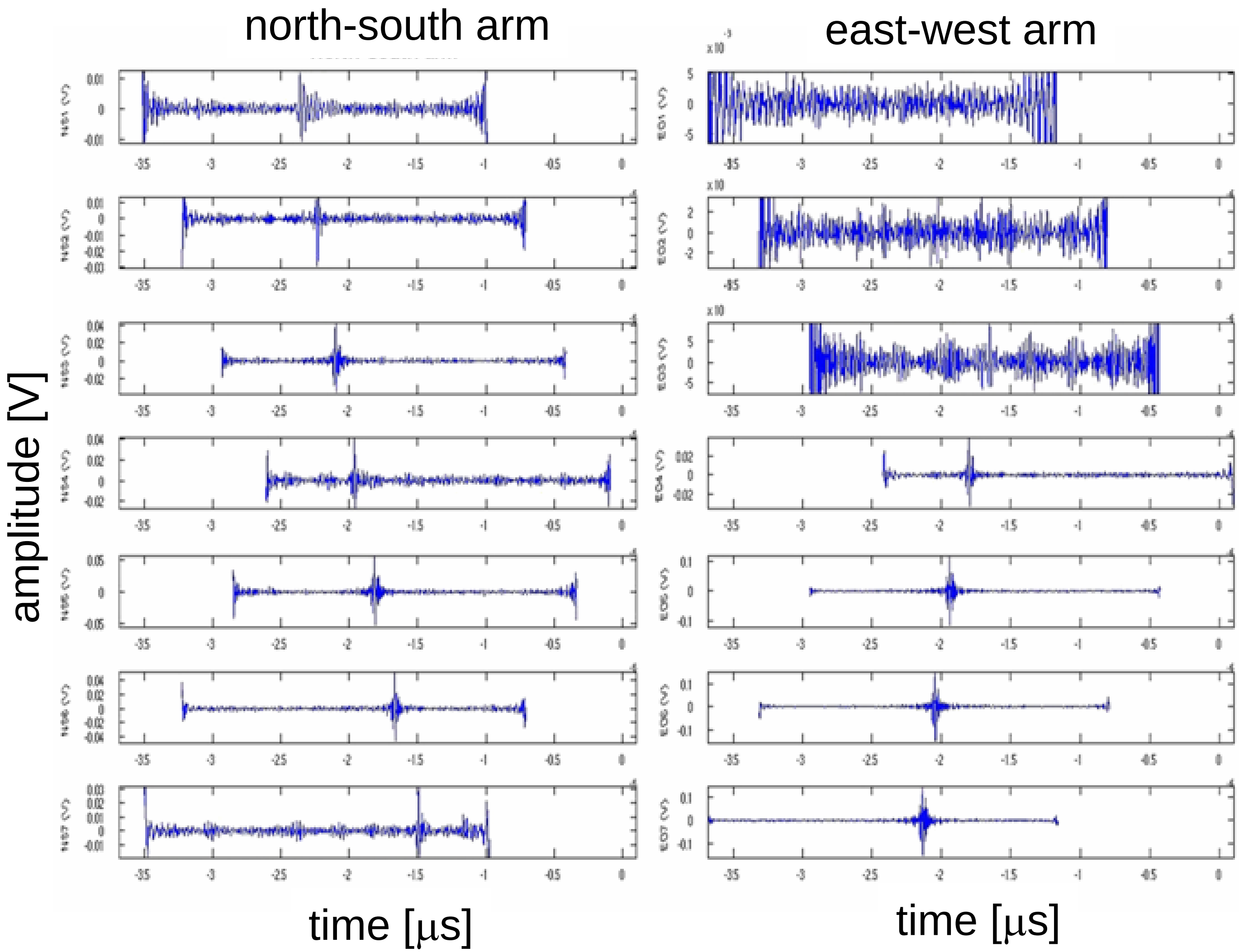
The CODALEMA experiment today

- **array of 24 fat dipole antennas, triggered by 17 scintillators**
  - **21 measuring east-west polarisation**
  - **3 measuring north-south polarisation**
  - **recording at 1-200 MHz, but analysis usually in 24-82 MHz band**

P. Lautridou et al. (CODALEMA coll.), ARENA 2008



CODALEMA analysis

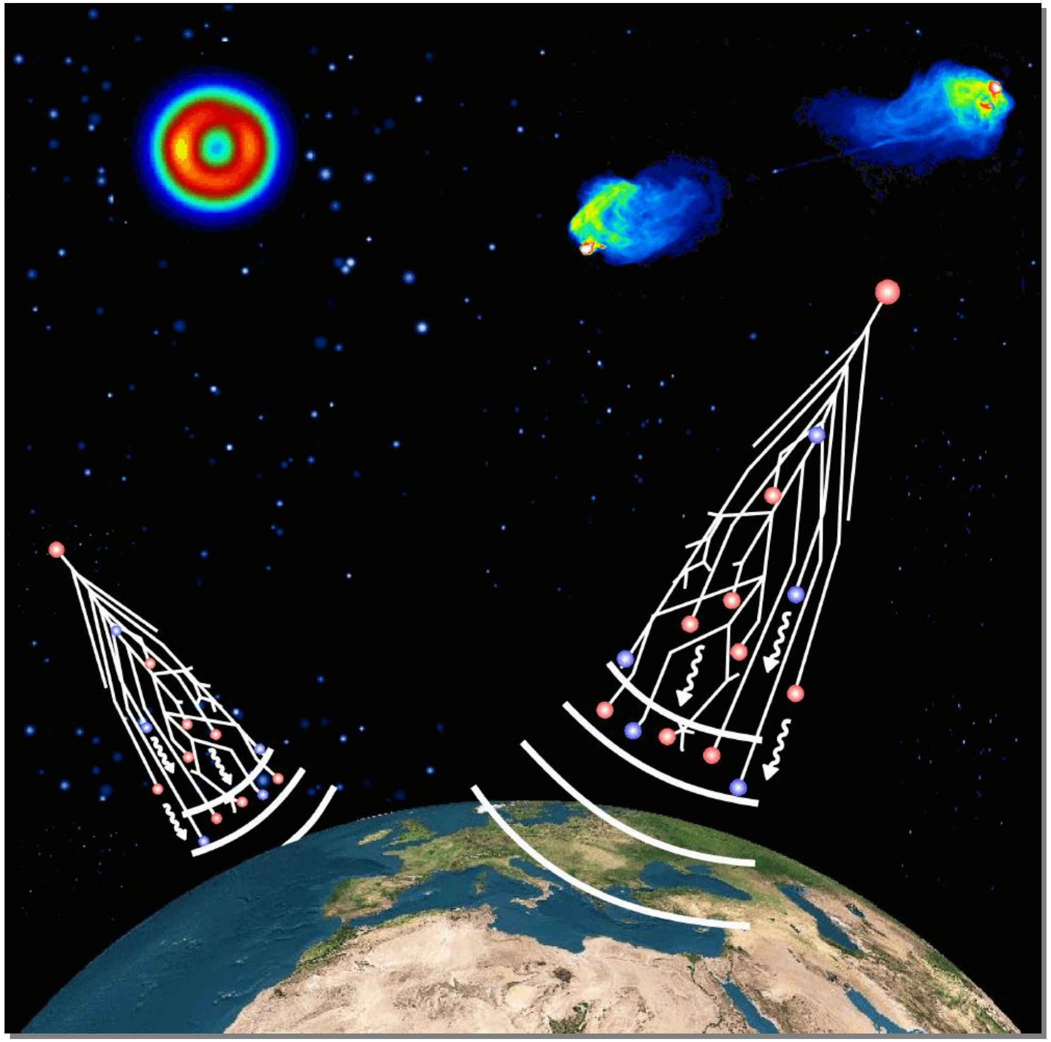


- digital filtering to 24-82 MHz band
- analyse individual channels (no inter-ferometry)
- direction from peak timings

P. Lautridou et al (CODALEMA coll.), ARENA 2008

Contents

- the early days of CR radio detection
- the revival of CR radio detection
  - experiments
  - theory
  - results
- the future of CR radio detection

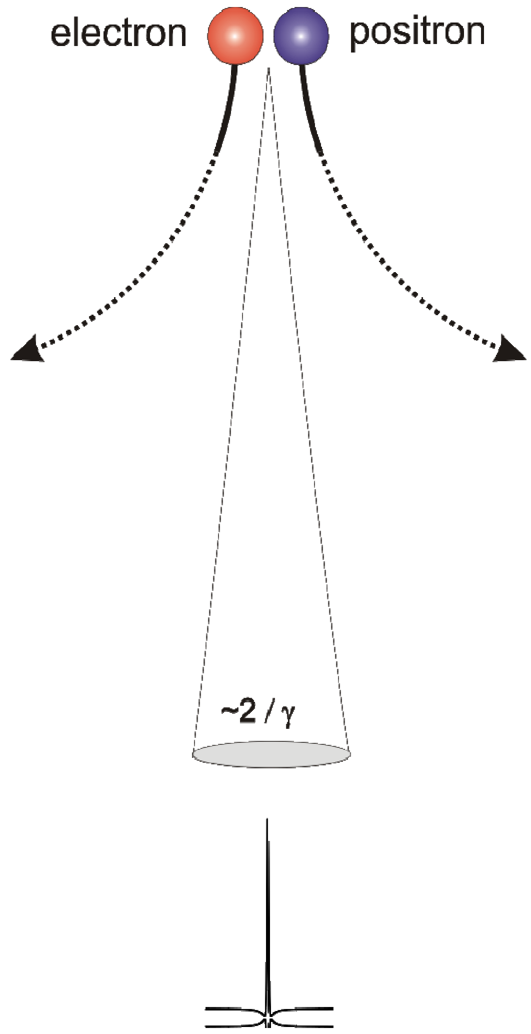


Emission mechanisms

- coherent Cherenkov emission („Askaryan mechanism")
  - 10-20% charge excess of e^- in air showers leads to Cherenkov radiation
  - negligible in air, but important in dense media (neutrino detection in antarctic ice, lunar regolith, …)
- geomagnetic mechanism
  - deflection of secondary e^+ and e^- in geomagnetic field
  - found to be dominant already in historical experiments (polarisation, north-south asymmetries in event rates)
  - can be described macroscopically („transverse currents") or microscopically („geosynchrotron emission")
  - several modelling attempts, will only mention the two most prominent here: REAS2 and MGMR

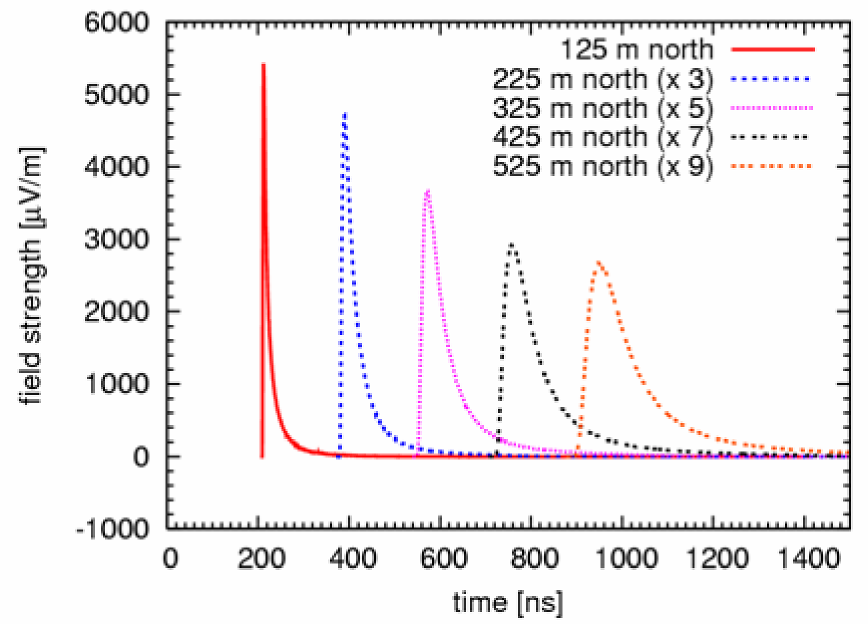
Geosynchrotron radio emission

- **historical studies**
  - **geomagnetic mechanisms dominant**
  - **works not detailed enough**
- **new approach to description of geomagnetic emission mechanism**
  Falcke & Gorham, Astrop. Phys. 2003
  - **electron-positron pairs gyrate in the Earth's magnetic field: radio pulses**
  - **coherent emission at low frequencies**
- **first step: analytical calculations**
  Huege & Falcke, Astron. Astrophys. 2003
- **second step (REAS1): Monte Carlo simulations using parametrised showers**
  Huege & Falcke, Astron. Astrophys. 2005
  Huege & Falcke, Astrop. Phys. 2005
- **current stage (REAS2): Monte Carlo simulations based on realistic air showers derived with CORSIKA**
  Huege, Ulrich, Engel, Astrop. Phys. 2007

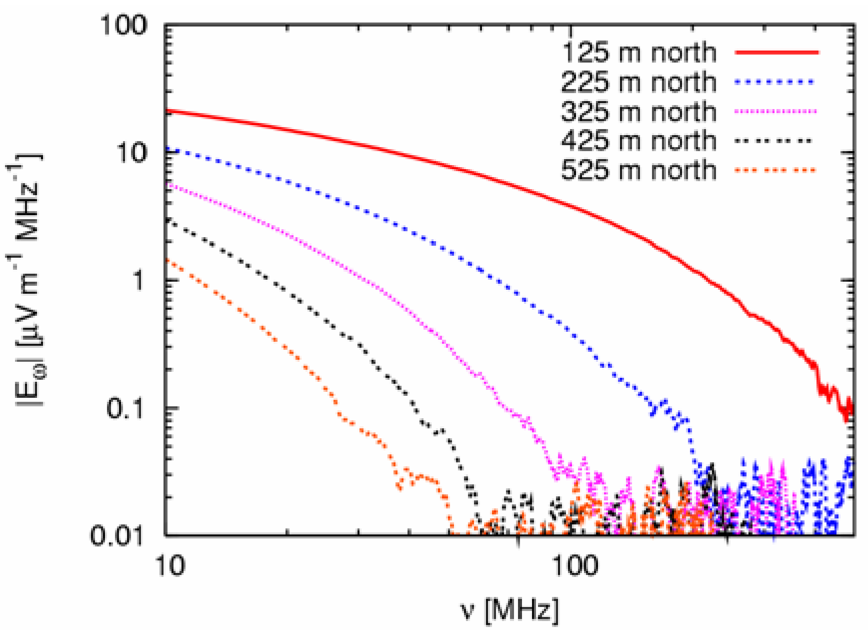


REAS2 simulations of EAS radio emission

10^{17} eV vertical, pulses



10^{17} eV vertical, spectra

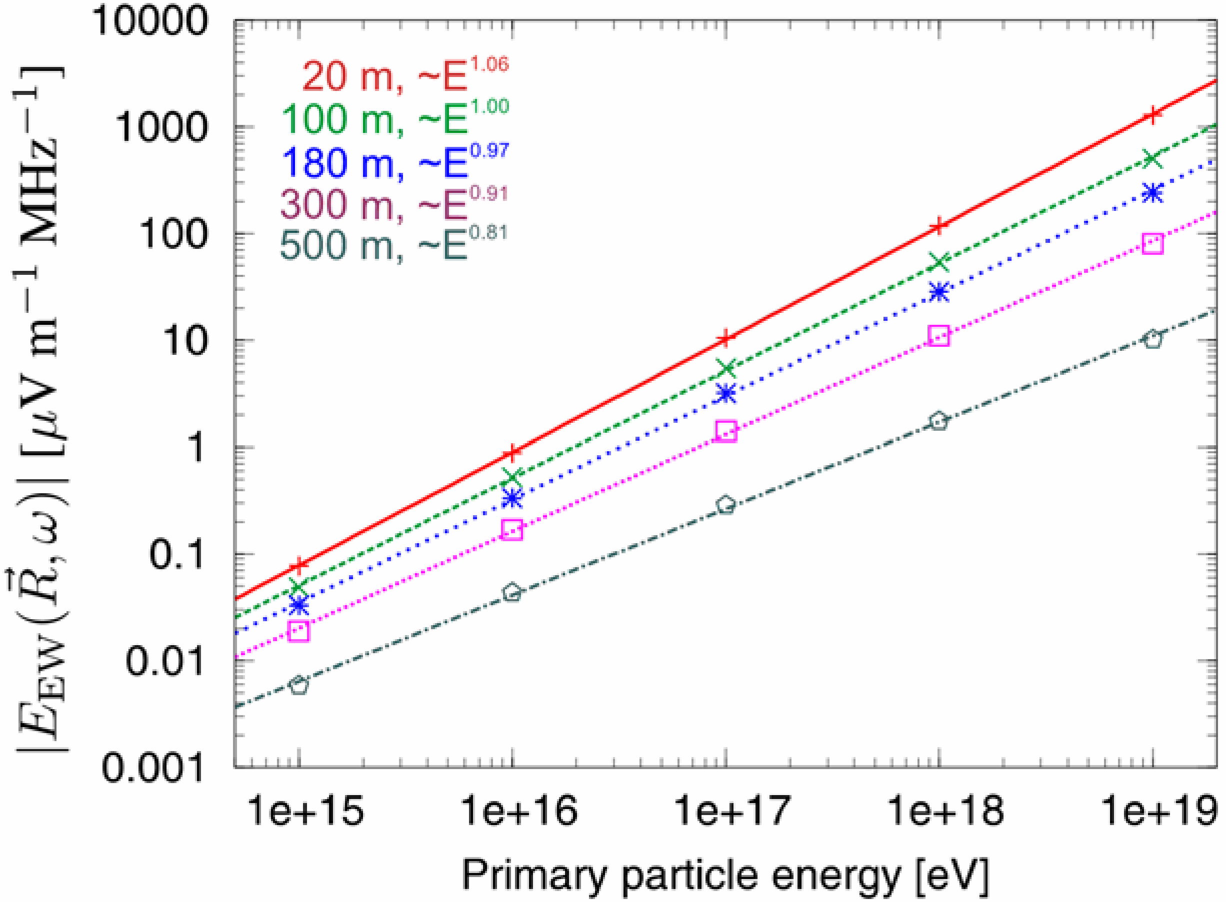


- **radio pulses of a few tens of nanosecond length**
- **steeply falling lateral distribution of pulse amplitudes**
- **steeply falling frequency spectra**

T. Huege

REAS: Coherent emission

Vertical shower, 10 MHz



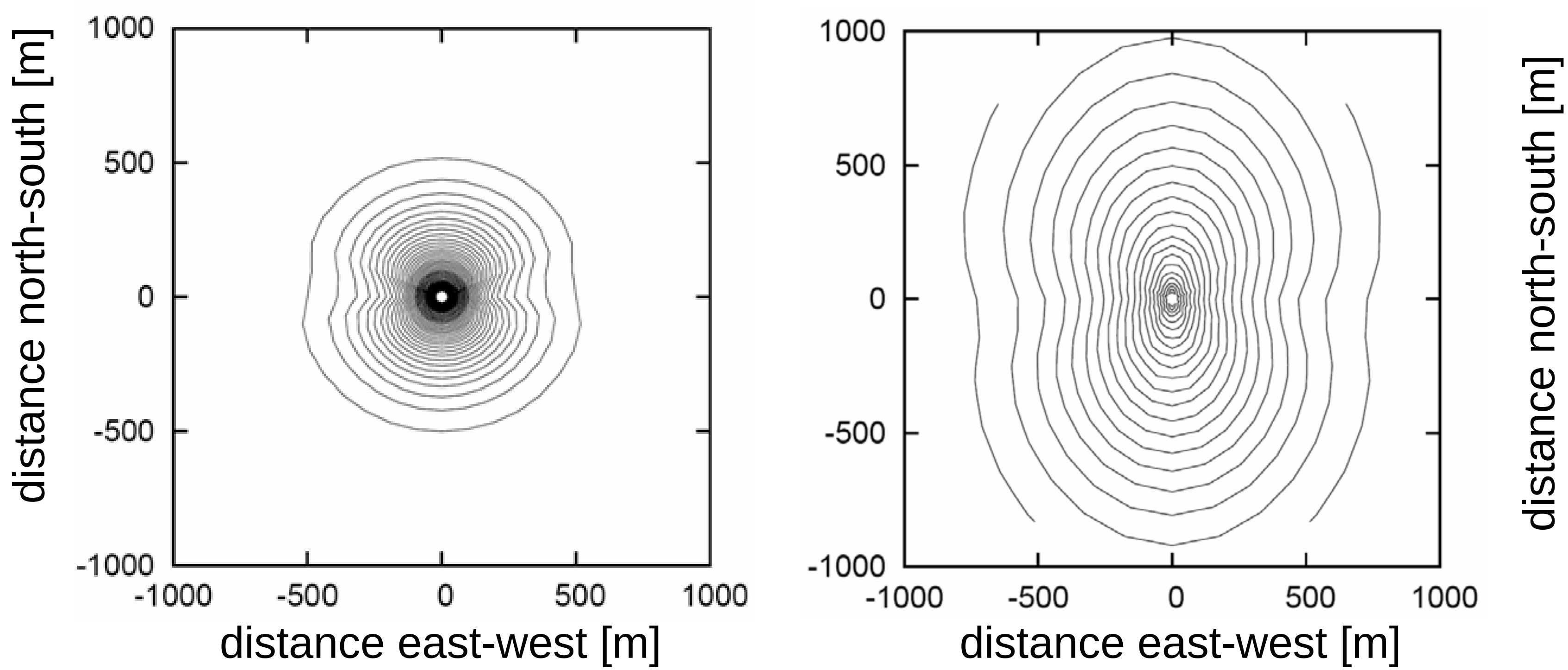
- **E-field scales approx. linearly with primary particle energy**
- **coherent signal**
- **X_{max} effects influence slope**

Huege & Falcke, Astrop. Phys. 2005

REAS: Vertical vs. inclined showers

Vertical 10^{17} eV shower

45° inclined 10^{17} eV shower

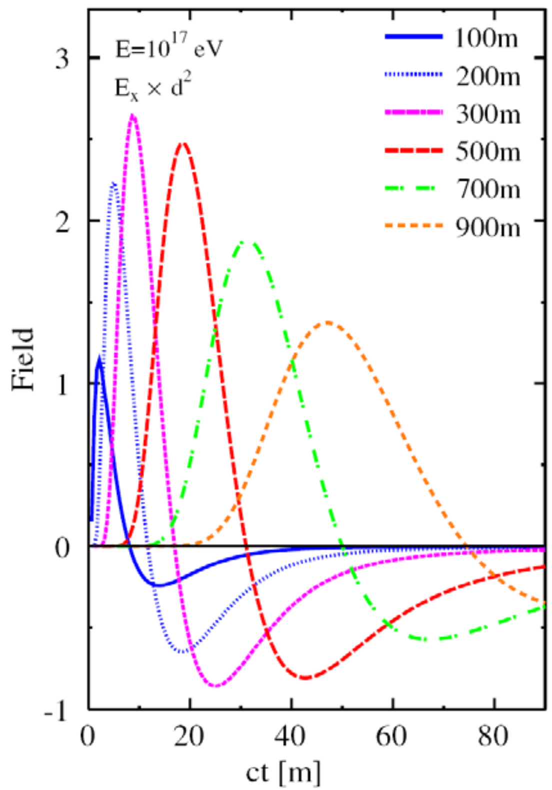


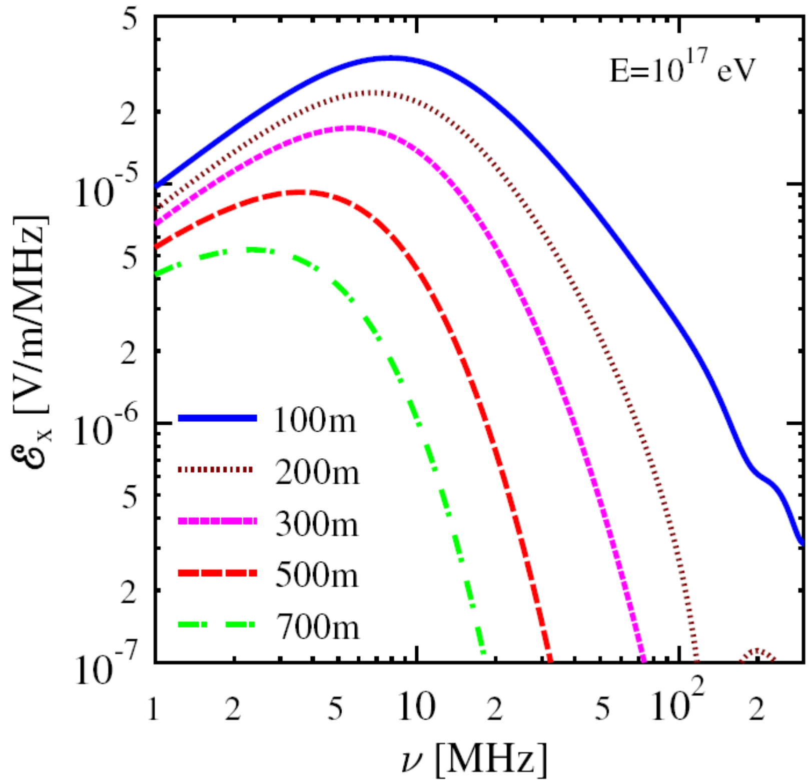
- **broader emission footprint allows better detection**
  - **projection along shower axis**
  - **flatter lateral distribution as X_{max} recedes from observer**

Huege & Falcke, Astrop. Phys. 2005

Macroscopic Geomagnetic Radiation Model

- **transverse current approach with simplified air shower model**
- **macroscopic description in the time-domain**
  - **relates pulse features to longitudinal shower evolution**
- **characteristic bipolar pulses from charge variation**

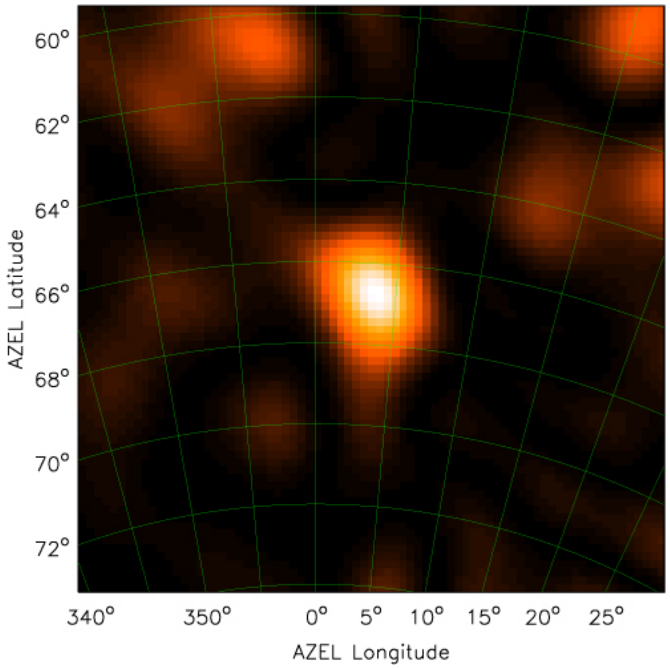


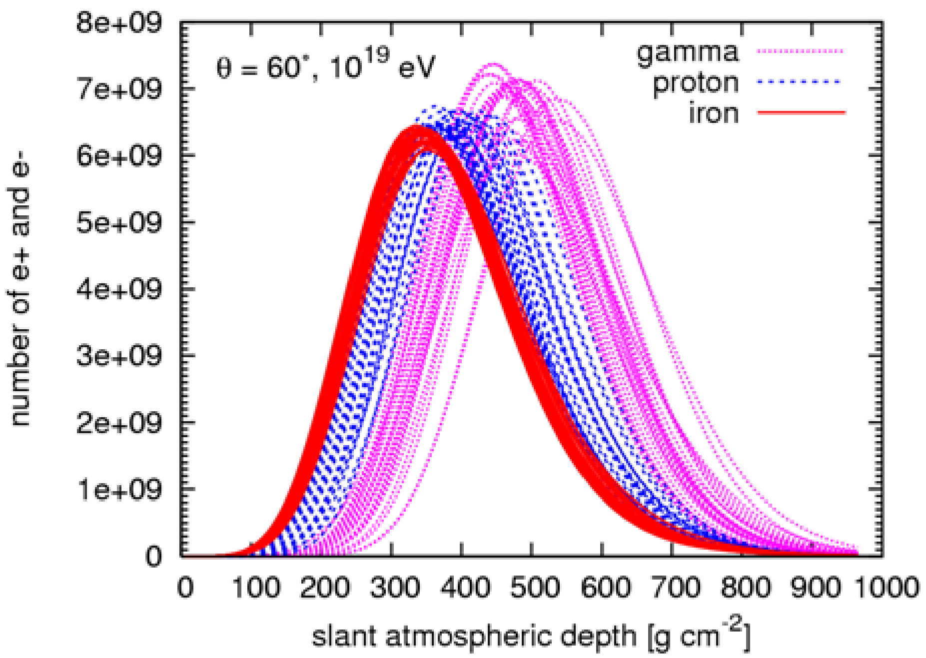


Scholten, Werner, Rusydi, Astrop. Phys. 2008

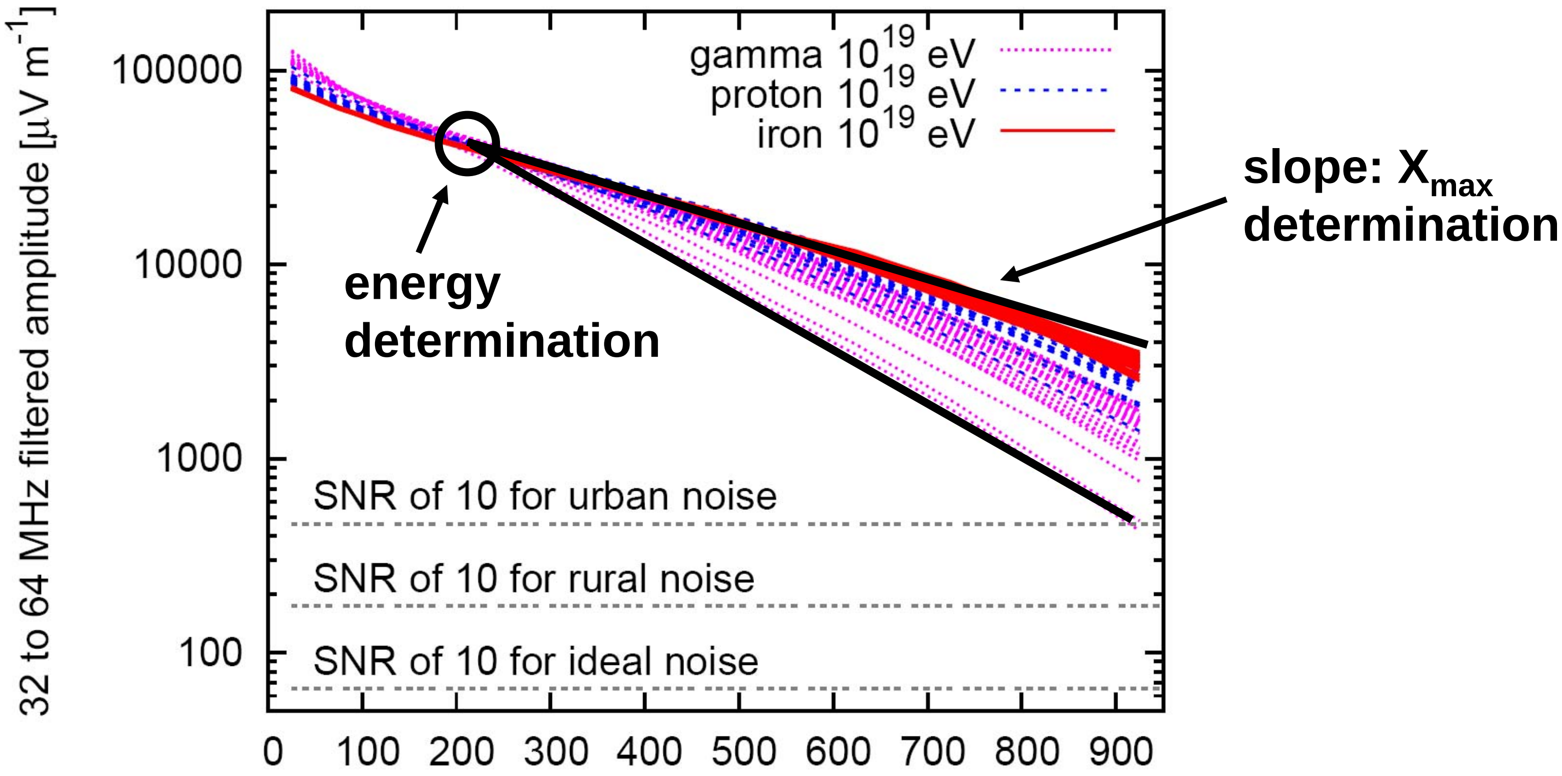
Determination of air shower parameters

- air shower parameters of prime interest are:
  - direction of incoming cosmic ray
  - energy of cosmic ray
  - mass of cosmic ray / depth of air shower maximum
- difficulty: intrinsic shower-to-shower fluctuations





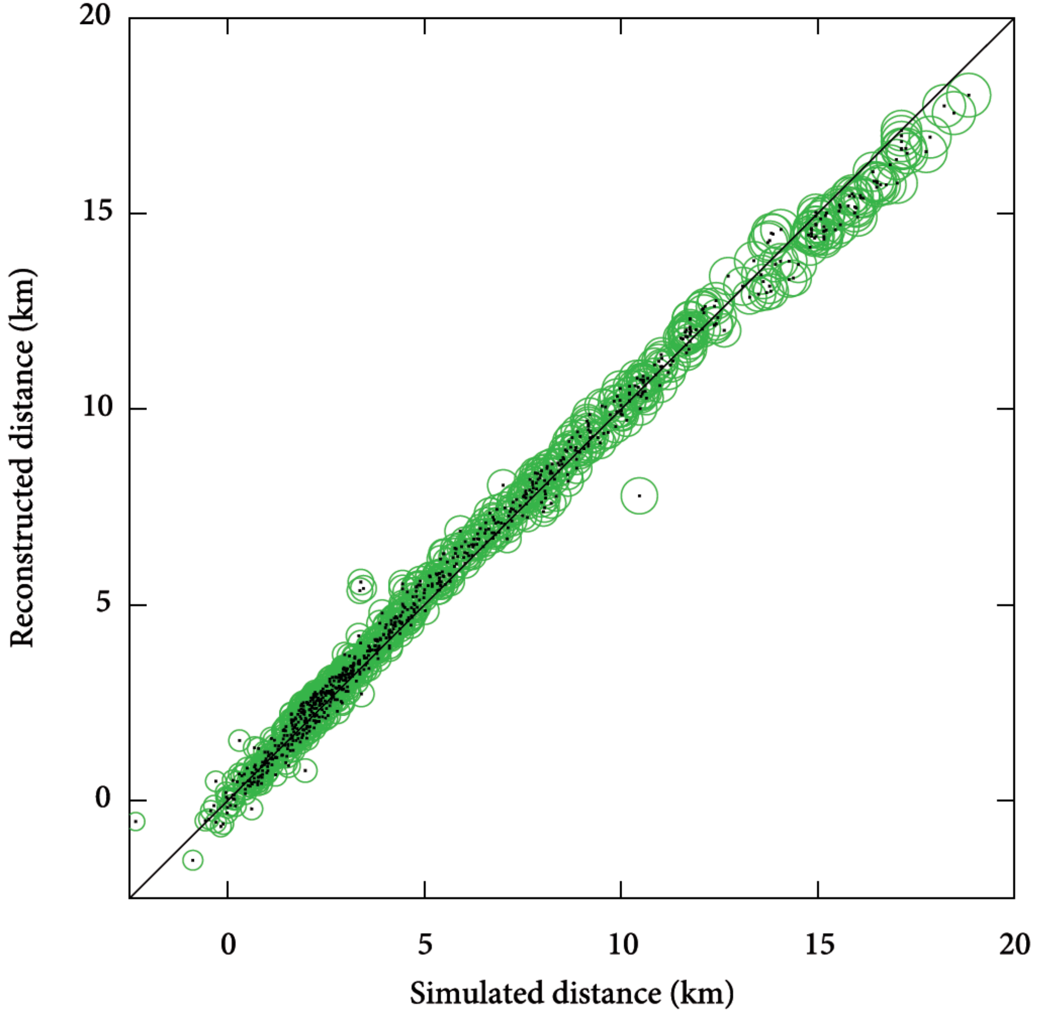
Radio sensitivity on EAS parameters



- **simulation study with REAS2 shows systematics of the lateral distribution of the radio signals**
  - **pivot point close to shower axis**
  - **strong differences from shower to shower at large distances**

Huege, Ulrich, Engel, Astrop. Phys. 2008

X_{max} sensitivity: Curvature

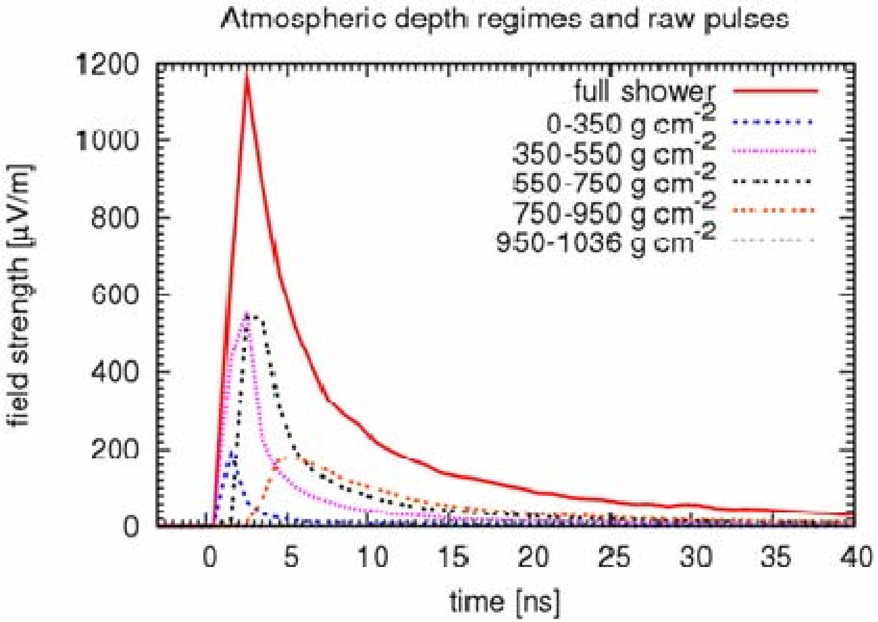


- electromagnetic radio front is no plane wave
- approximation in LOPES: spherical front (point source)
- simulation study based on REAS2: the curvature radius correlates with X_{max}

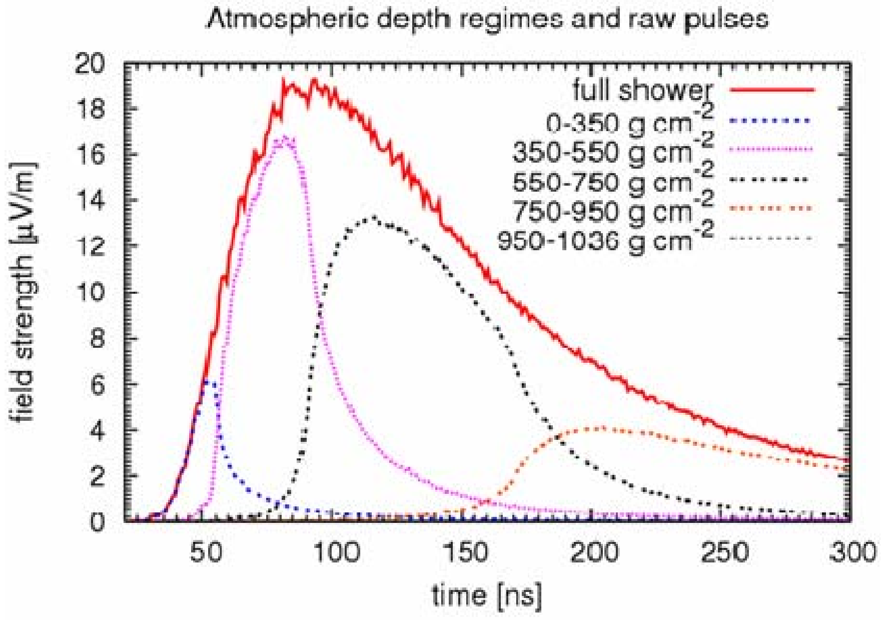
Lafèbre et al., ICRC 2009

Pulse shape dependence shower evolution

75 m north from core



525 m north from core



- **REAS2 simulations show that information on air shower evolution is encoded in the radio pulse shape**
- **an analytical relation of the pulse shape to the air shower evolution is possible at large lateral distances (MGRM model, Gousset et al. approximation)**

Huege, Ulrich, Engel, Astrop. Phys. 2007