Radio detection of air showers

Frank G. Schröder

Karlsruhe Institute of Technology (KIT), Institut für Kernphysik, Karlsruhe, Germany

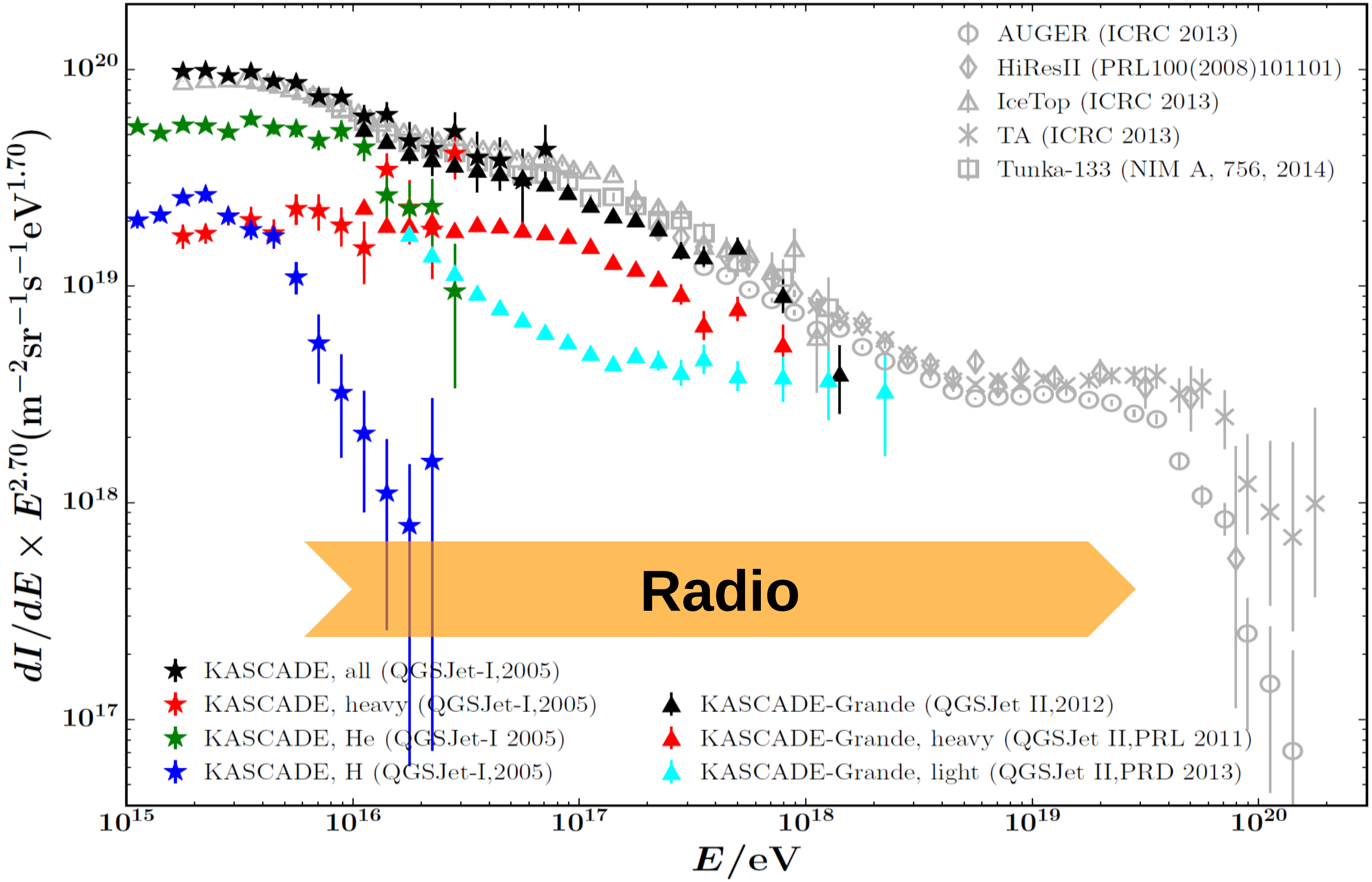
Content

- Radio emission by air showers
  - Mechanism(s)
  - Signal properties
  - Simulations
- Overview on selected experiments
  - evidence for models of radio emission
  - air-shower direction and energy
  - techniques: calibration, interferometry
- Methods for cosmic-ray composition

frank.schroeder@kit.edu
Institut für Kernphysik (IKP)

Energy range for radio detection

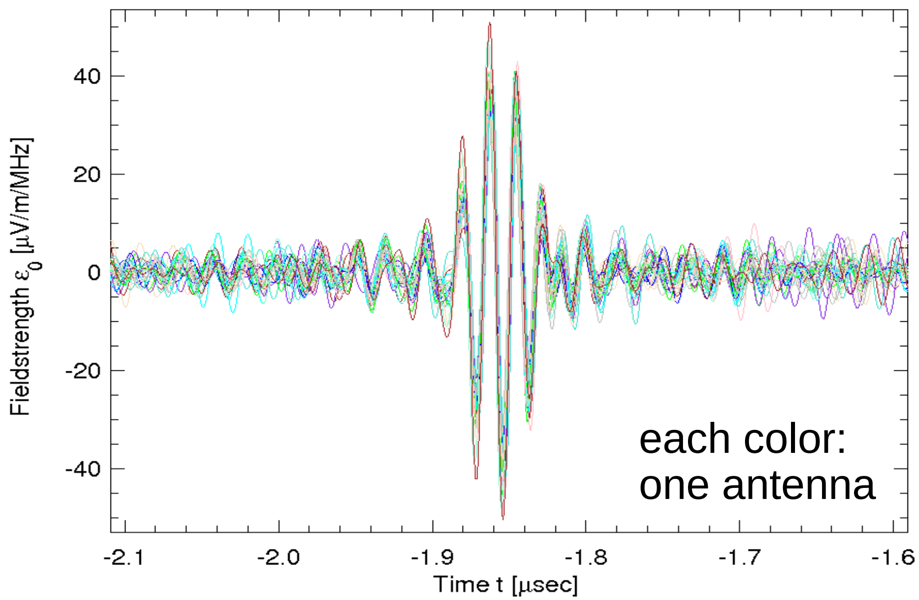
- Range of assumed galactic – extragalactic transition



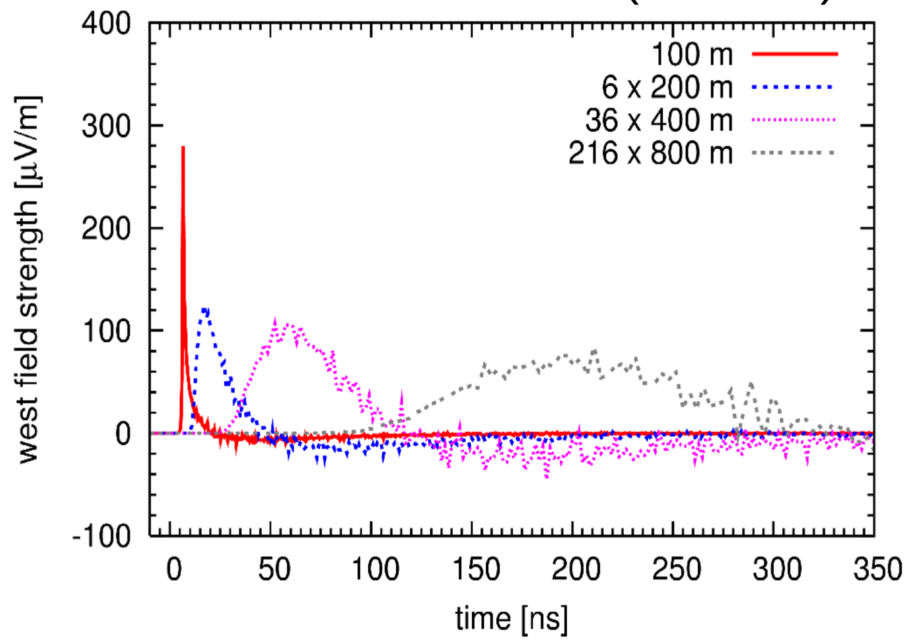
Radio pulses emitted by air showers

- Amplified emission due to coherence
  - Thickness of shower pancake ~ wave lengths ~ meter
  - Typical measurement bandwidth: 30 – 80 MHz

LOPES measurement (band-limited)



CoREAS simulation (full band)

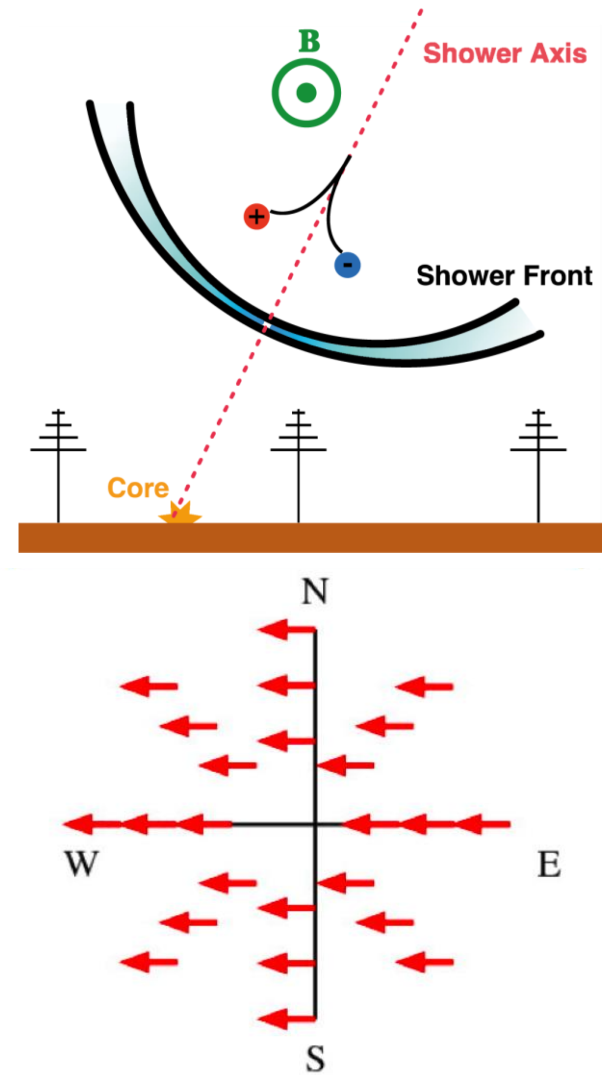


LOPES Collaboration

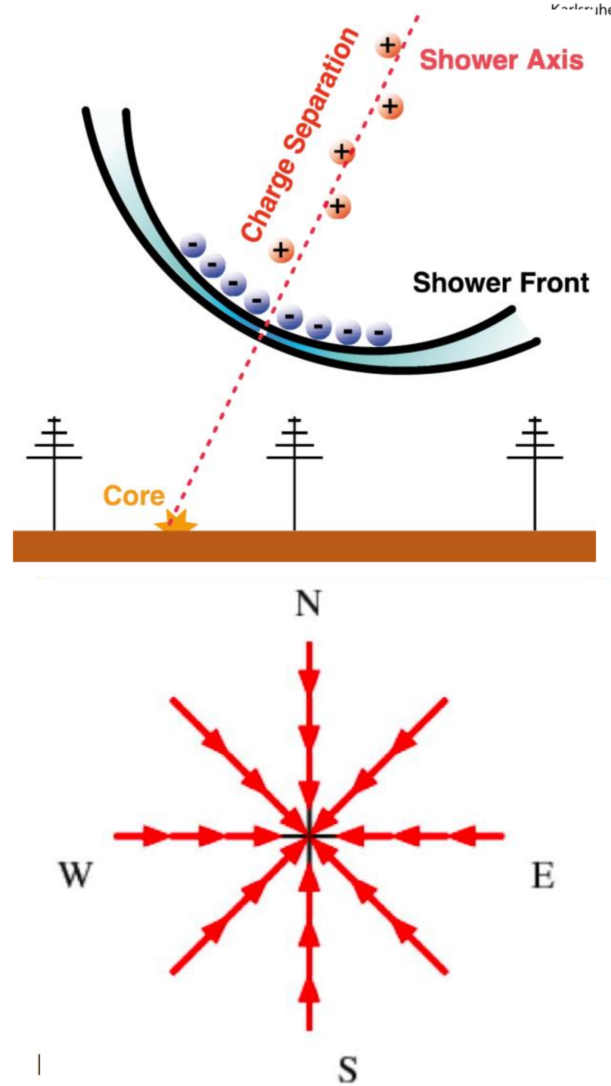
T. Huege et al., ARENA2012

Emission mechanisms

$\dot{\vec{I}}$



Geomagnetic effect ~ 90%

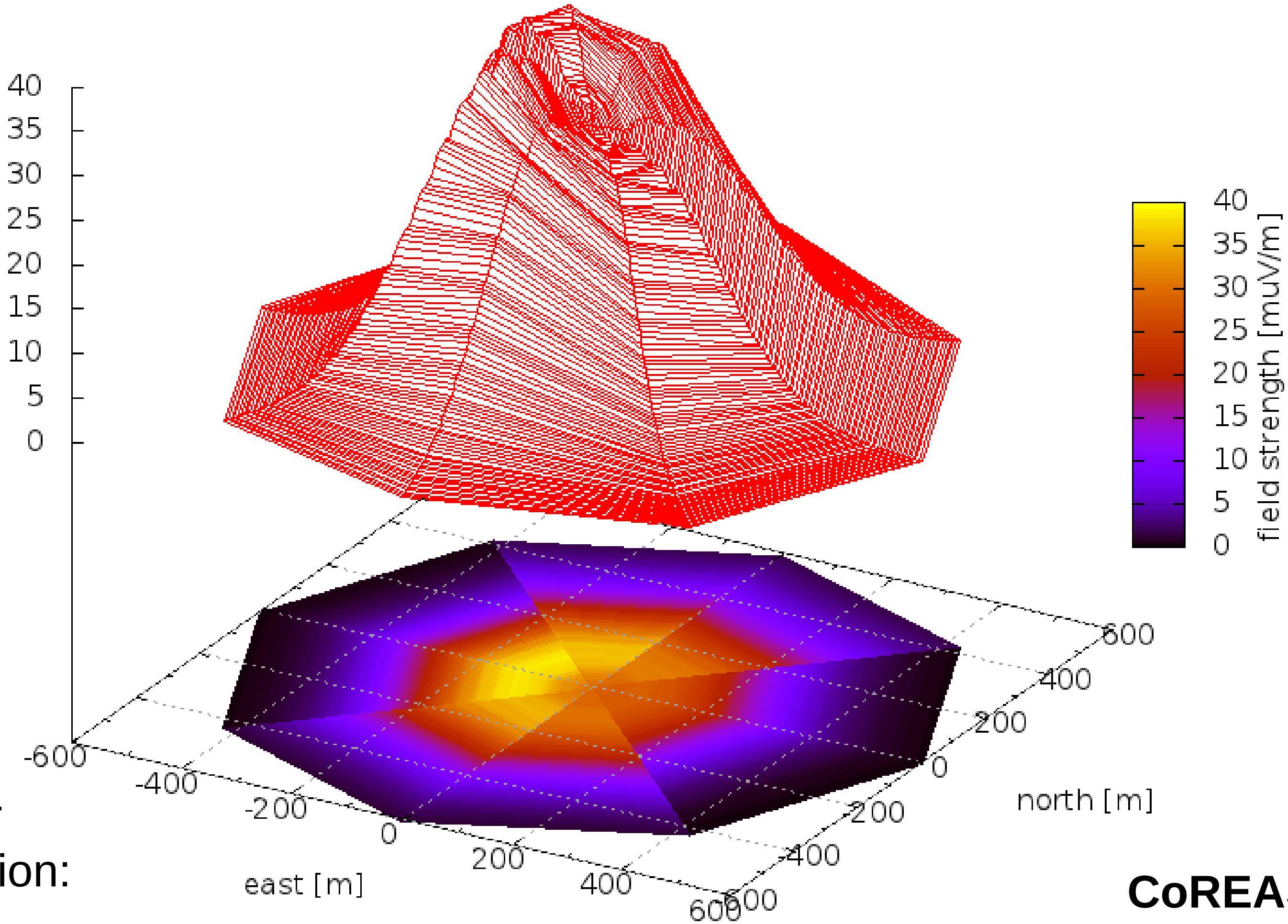


$\dot{q}$

Askaryan effect ~ 10%

diagrams by H. Schoorlemmer and K.D. de Vries

Asymmetric lateral distribution

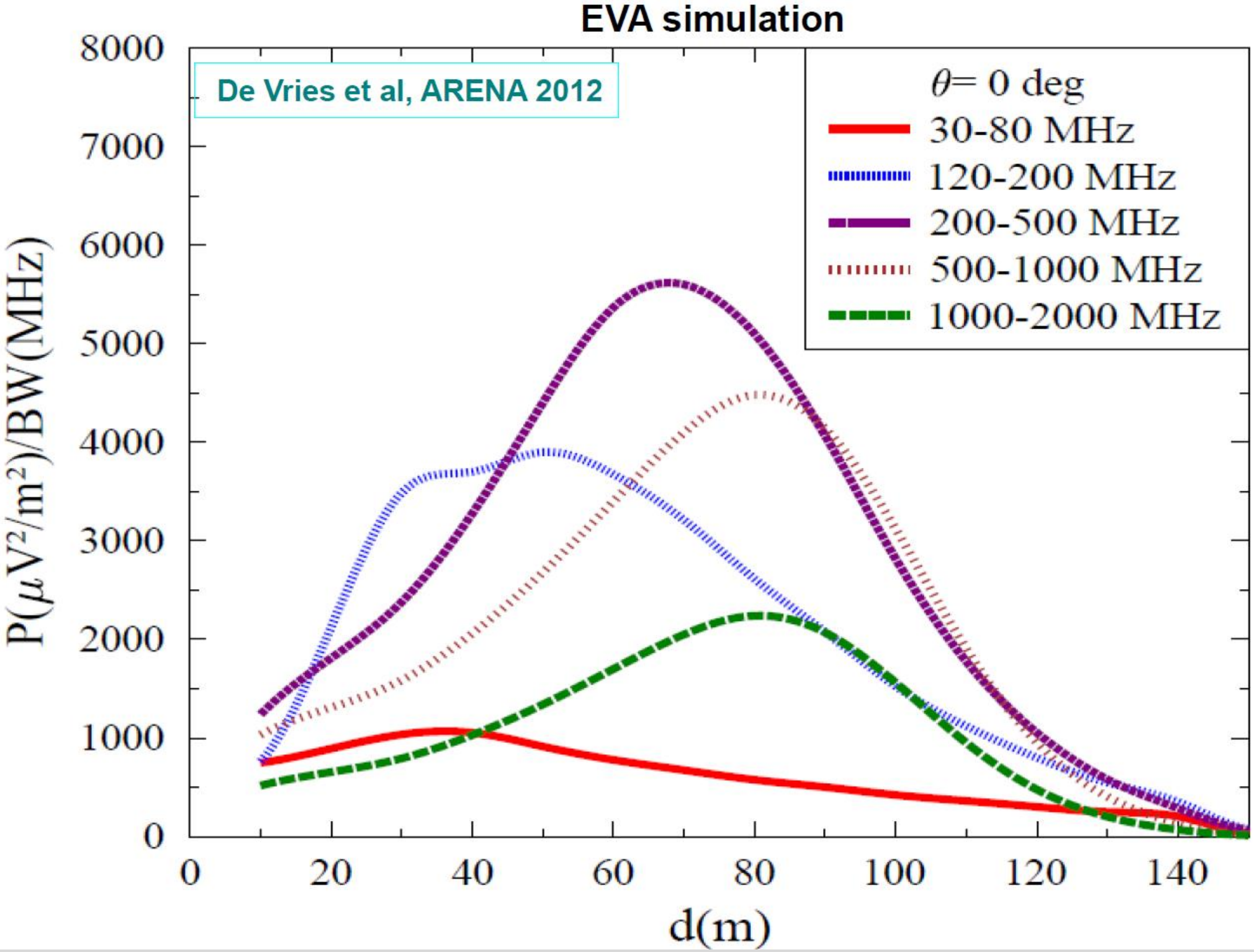


shower inclination: $\theta = 45°$

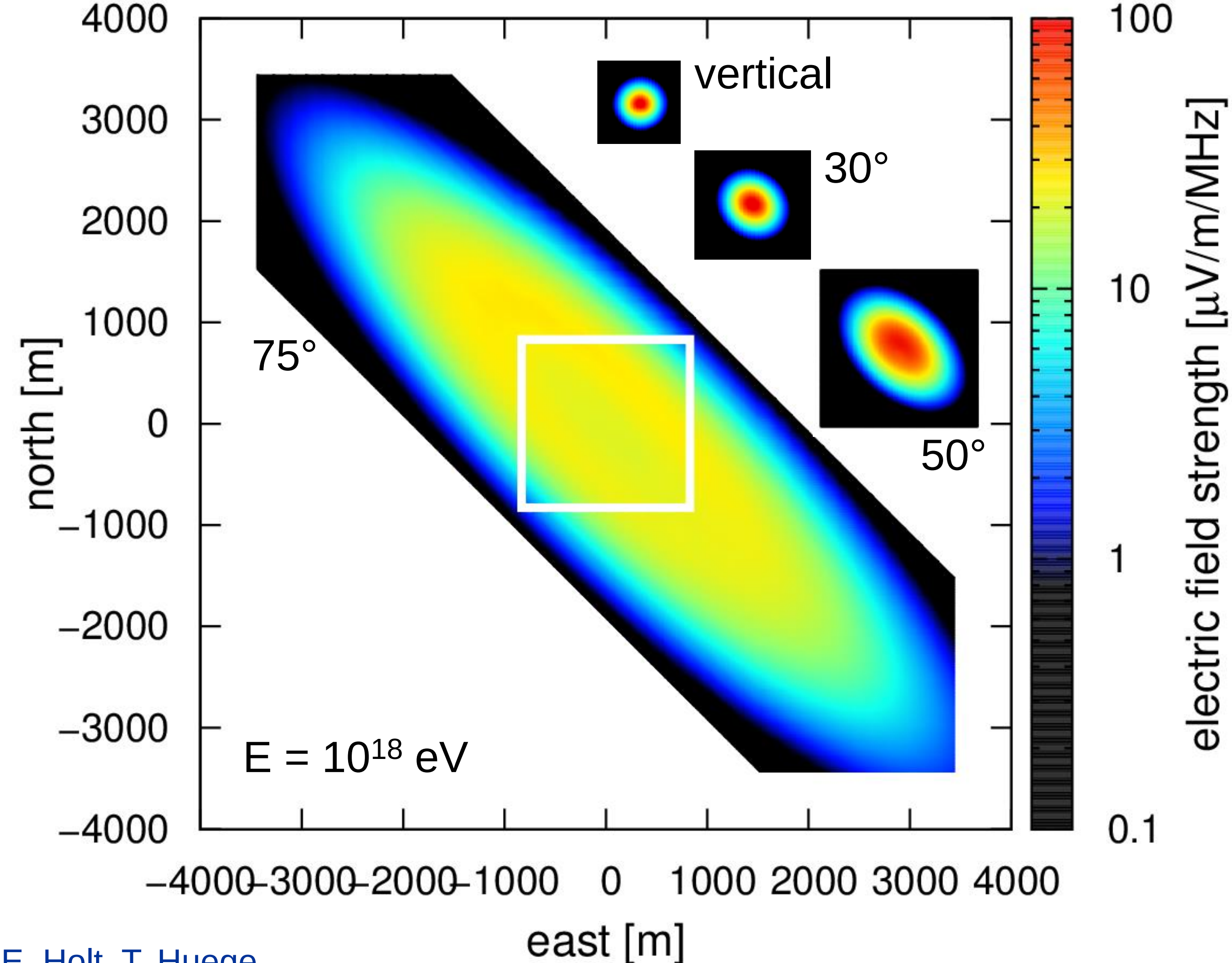
CoREAS simulation for LOPES experiment: 43-74 MHz

T. Huege et al., ARENA2012

Cherenkov ring (predicted by Allan 1971)



Vertical shower require dense arrays

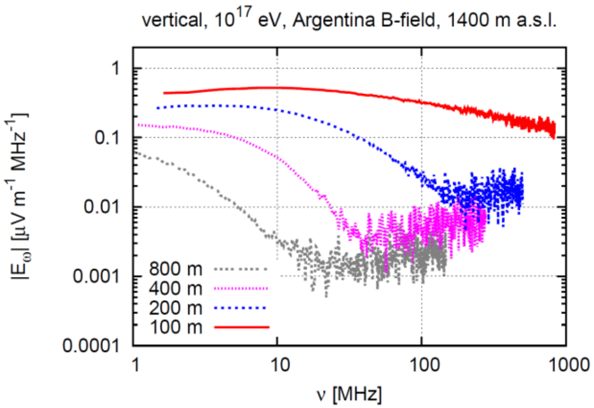


← ~ detection threshold

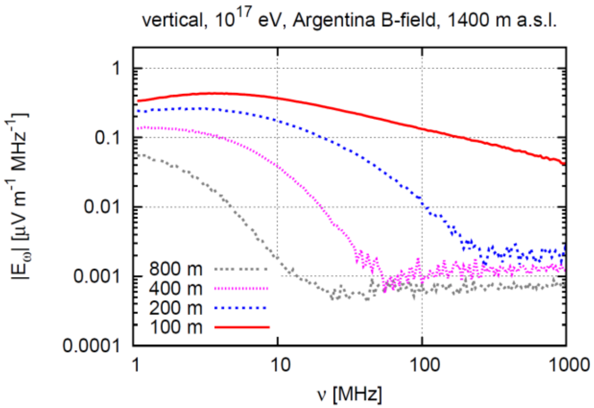
E. Holt, T. Huege

Simulated frequency spectra

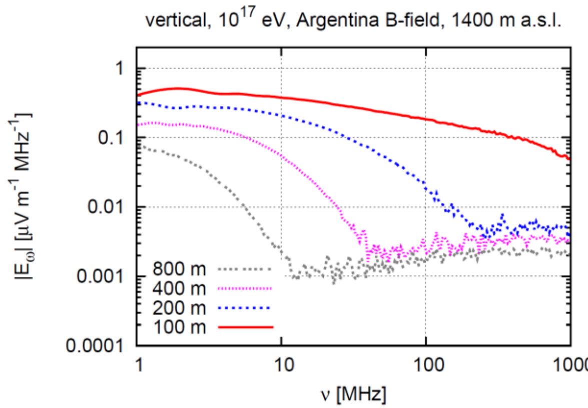
REAS3.1

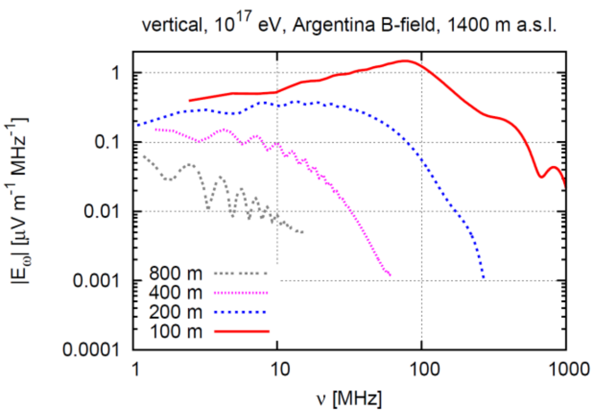


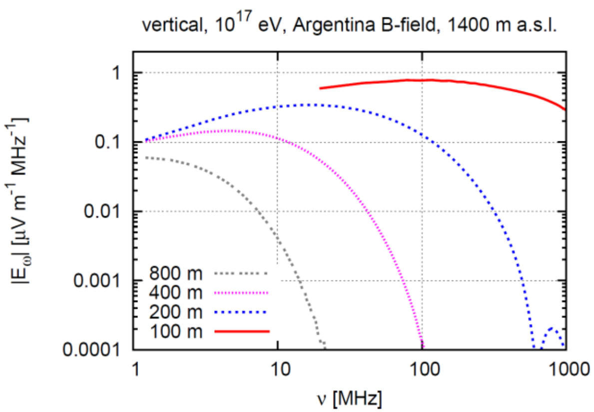
CoREAS

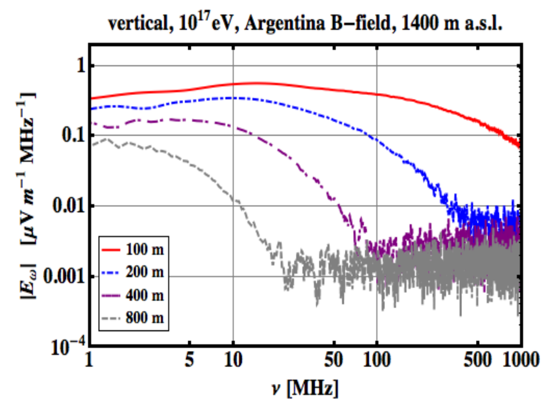


ZHAireS









MGMR

EVA

SELFAS2

vertical 10^{17} eV shower, total field, n=r

T. Huege et al., ARENA2012

Summary of theoretical understanding

- Agreement on qualitative features
  - geomagnetic + Askaryan emission
  - refractive index important: Cherenkov-like ring

- Not yet totally clear:
  - At which frequency Cherenkov radiation becomes non-negligible?
  - Are there other sub-dominant emission mechanisms?
    - transition radiation and bremsstrahlung when shower enters ground
    - contribution of plasma behind shower pancake
  - Role of atmospheric properties, e.g., humidity

- Wish for high-accuracy measurements with SKA
  - Agreement between different models and experiments on 10% level

frank.schroeder@kit.edu
Institut für Kernphysik (IKP)

Experiments (personal selection)

- Several "historic" experiments using analog electronics
  - Discovery of almost all known qualitative features
- Revival of the field using digital techniques
  - CODALEMA, France
  - LOPES, Germany
- Second generation
  - GHz experiments, e.g., CROME
  - Tunka-Rex, Siberia
  - AERA, Argentina
  - LOFAR, The Netherlands

Geomagnetic field comparison

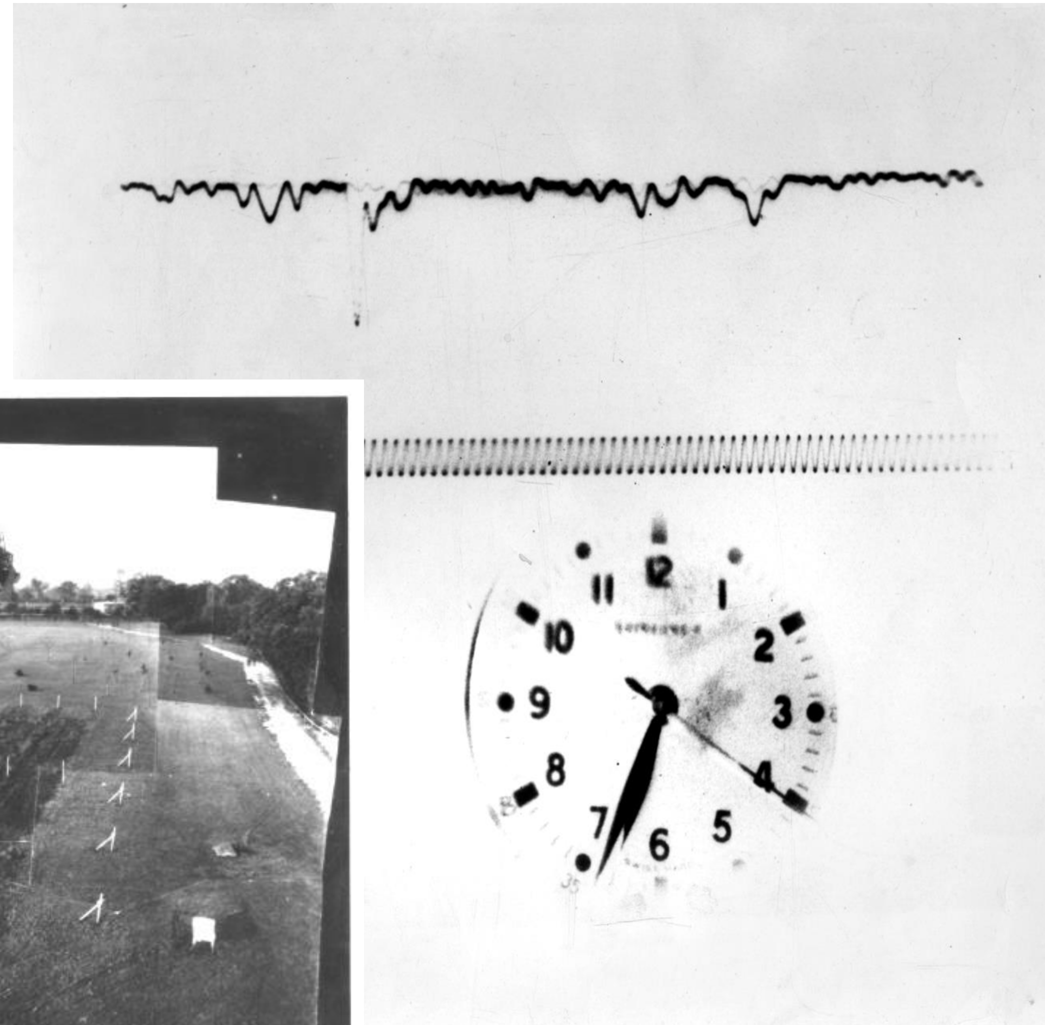
Experiment	Location	Height	B-Field	Inclination
LOPES	**Germany, Karlsruhe**	110 m	48.3 µT	64°
Tunka	**Siberia, ~ Irkutsk**	675 m	60.3 µT	71°
AERA	**Argentina, Malargüe**	1400 m	24.2 µT	- 36°
LOFAR	**Netherlands**	0 m	49.3 µT	68°
ASKAP	**Australia**	370 m	55.6 µT	- 60°
MeerKAT	**South Africa**	?	26.5 µT	- 65°

Source: IGRF (GFZ Potsdam)

- Radio signal at ASKAP should be comparable to LOFAR

frank.schroeder@kit.edu
Institut für Kernphysik (IKP)

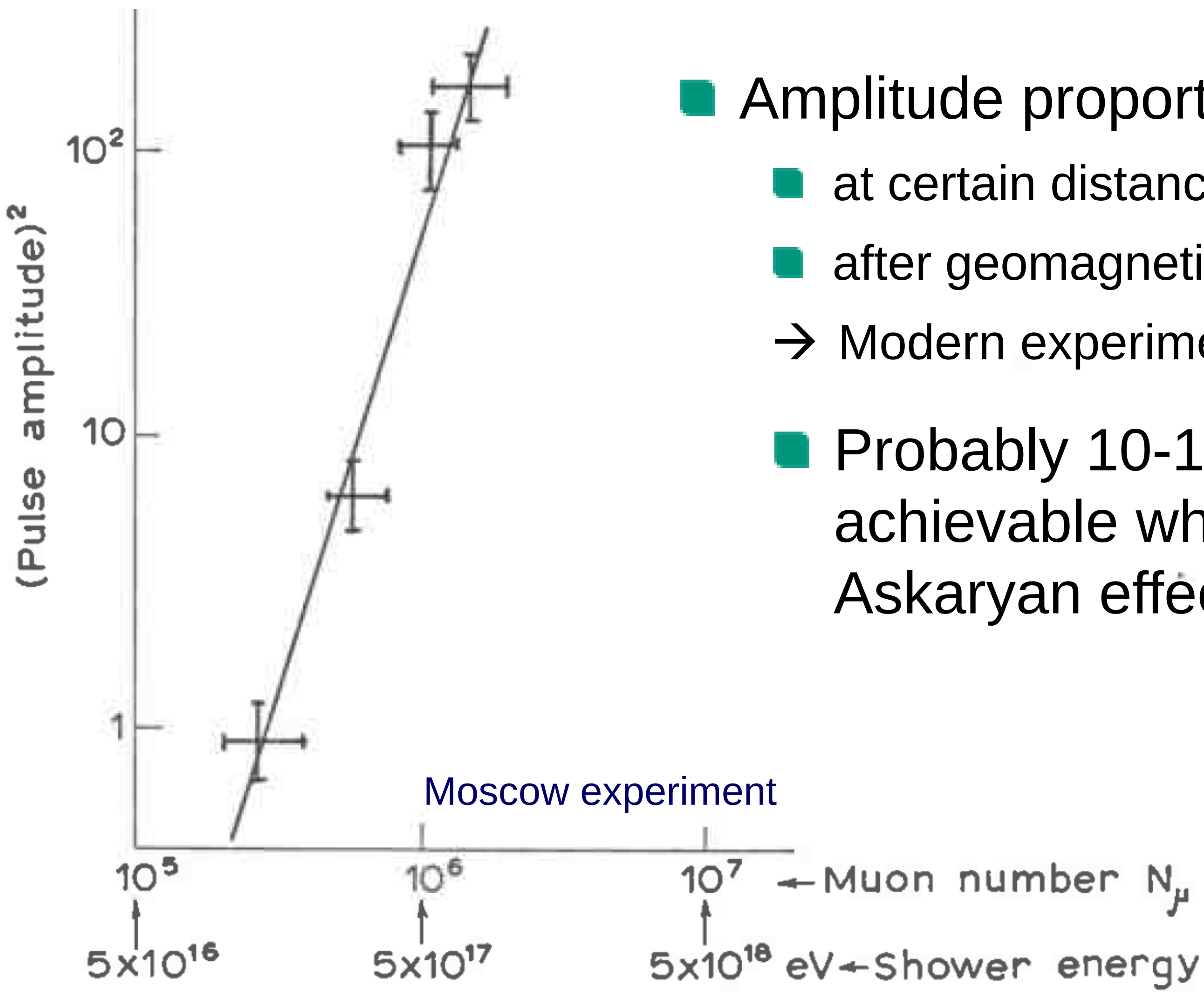
Distant in time, but close in space: first detection



Jelley et al Nature 1965
R. A. Porter MSc Thesis 1967,

Correlation of amplitude with energy

Karlsruhe Institute of Technology

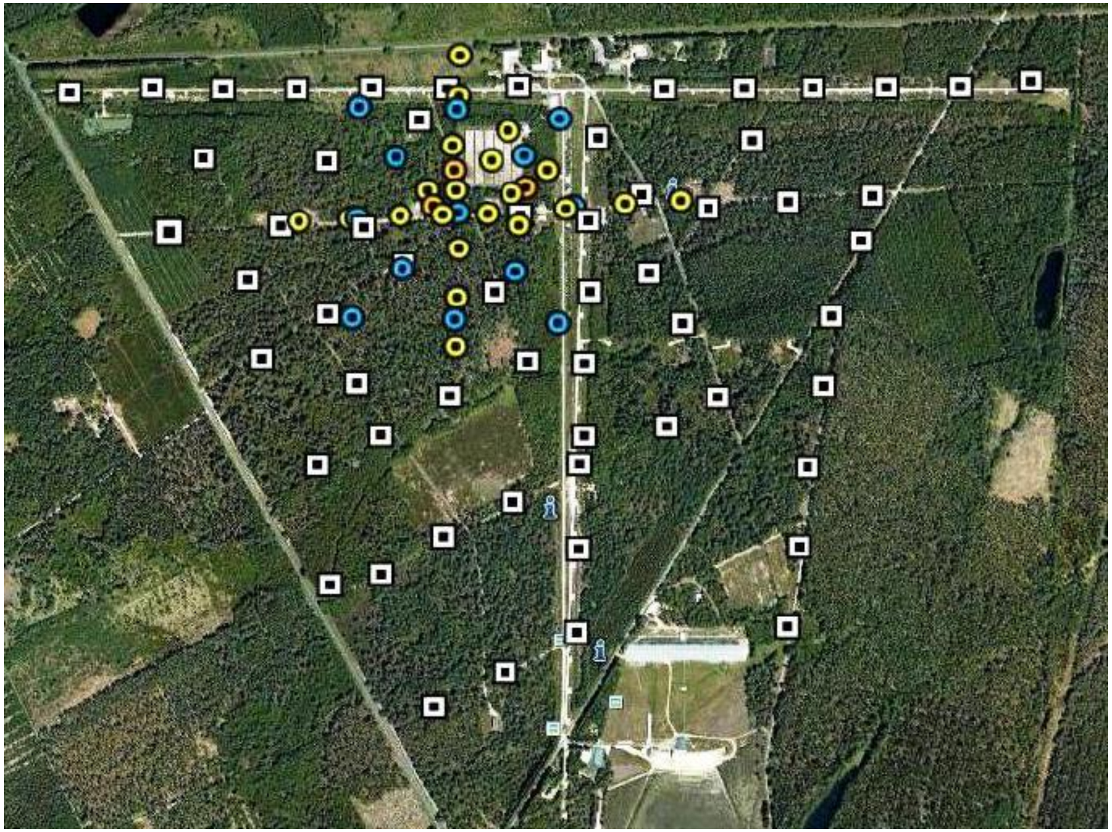


- Amplitude proportional to energy
  - at certain distance
  - after geomagnetic correction
  - → Modern experiments: precision < 20%
- Probably 10-15 % precision achievable when including Askaryan effect

Vernov et al. (1968),
from Allan review (1971)

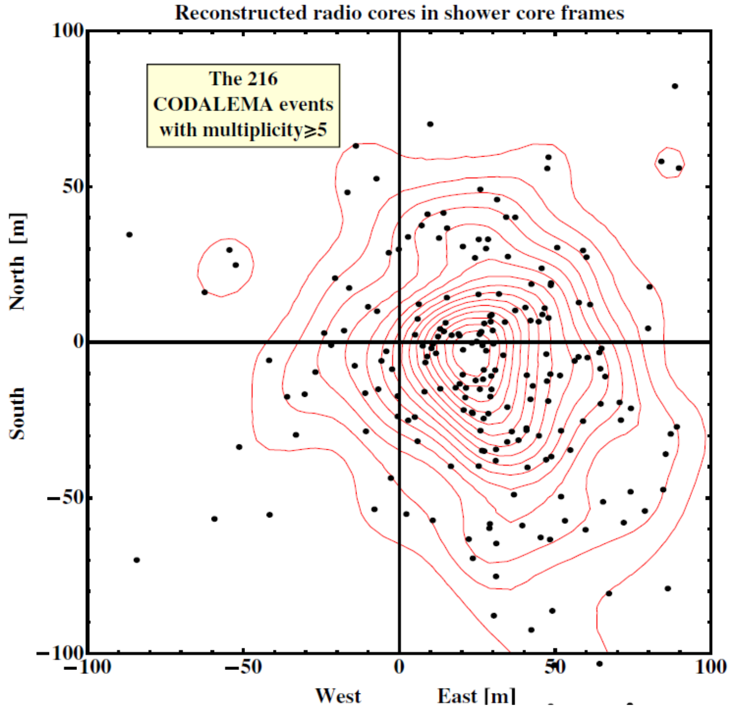
CODALEMA

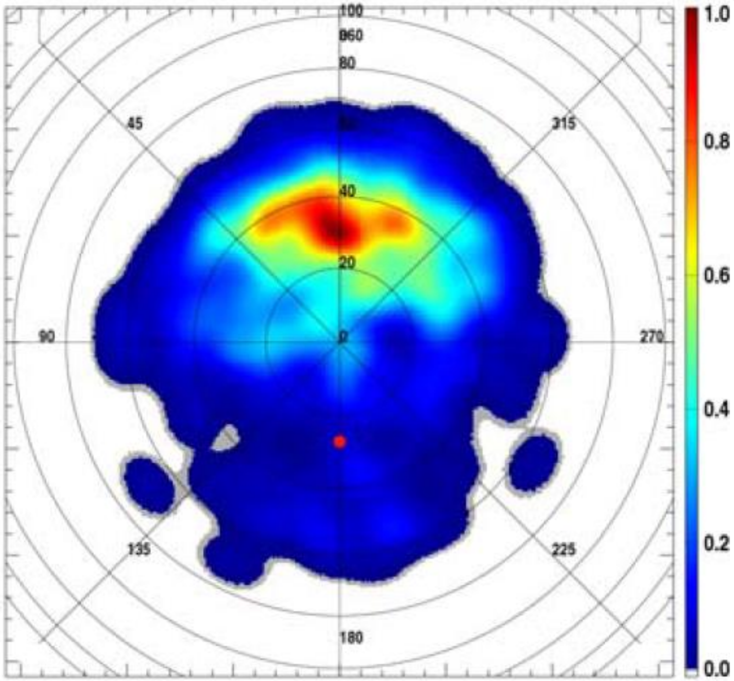
- Several configurations since 2003, close to Nancy, France
  - now: self-triggering stations (30-80 MHz) + particle detectors

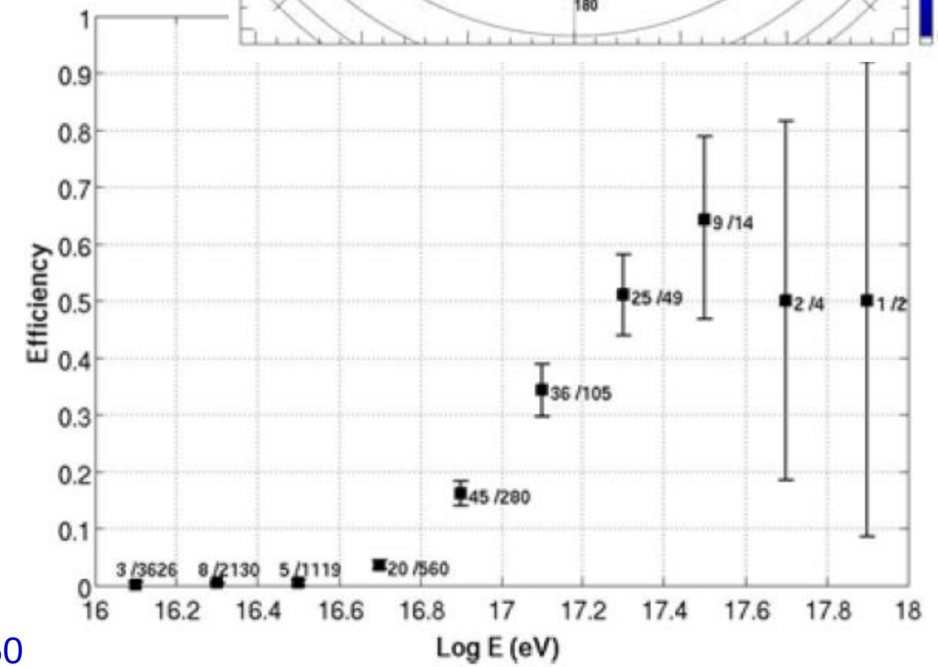


Evidence for emission mechanisms

- Geomagnetic angle determines efficiency
- Core shift due to Askaryan effect

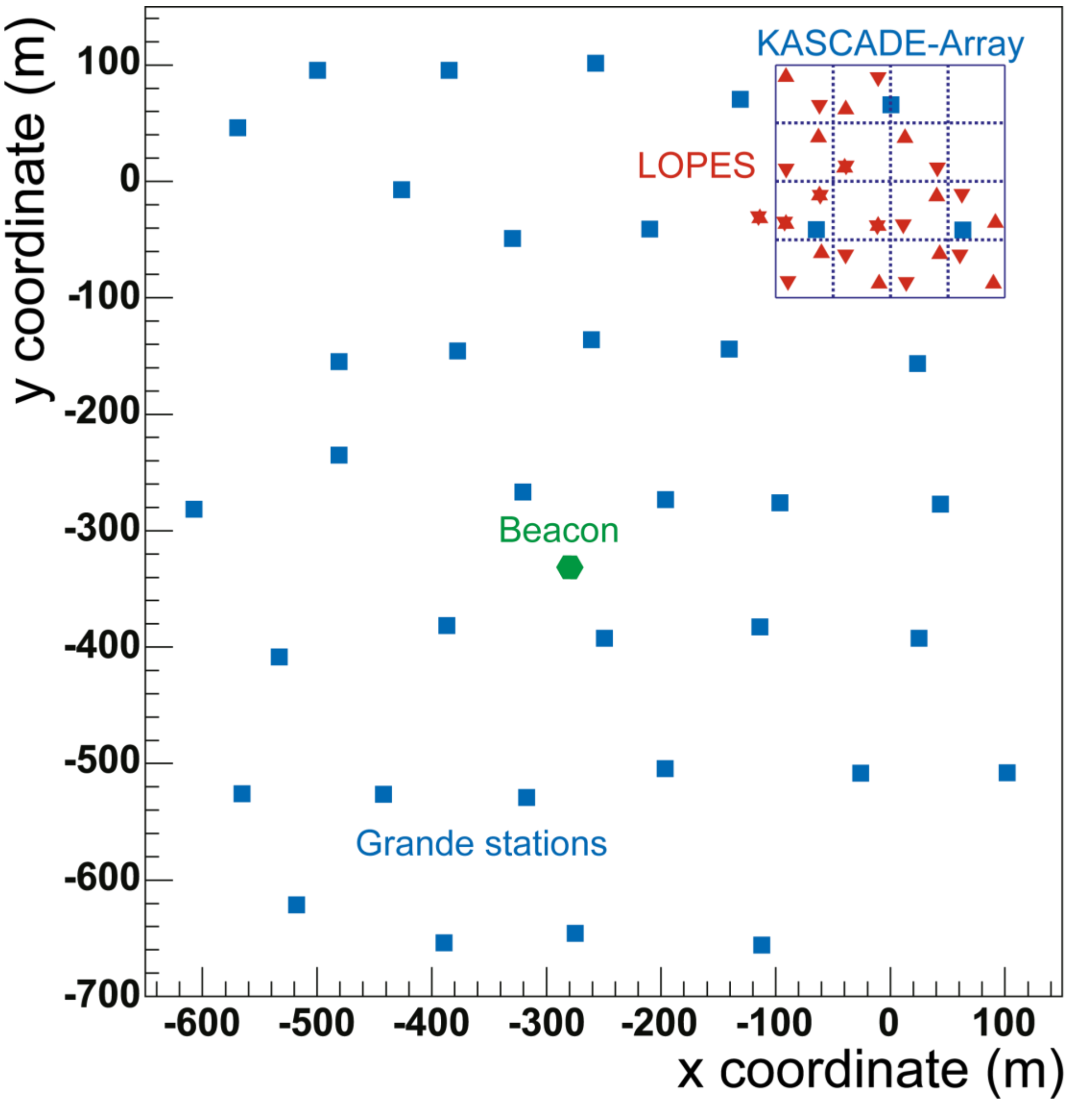






CODALEMA, Astropp. 31 (2009) 192 and 69 (2015) 50

LOPES (also since 2003, was at KIT)

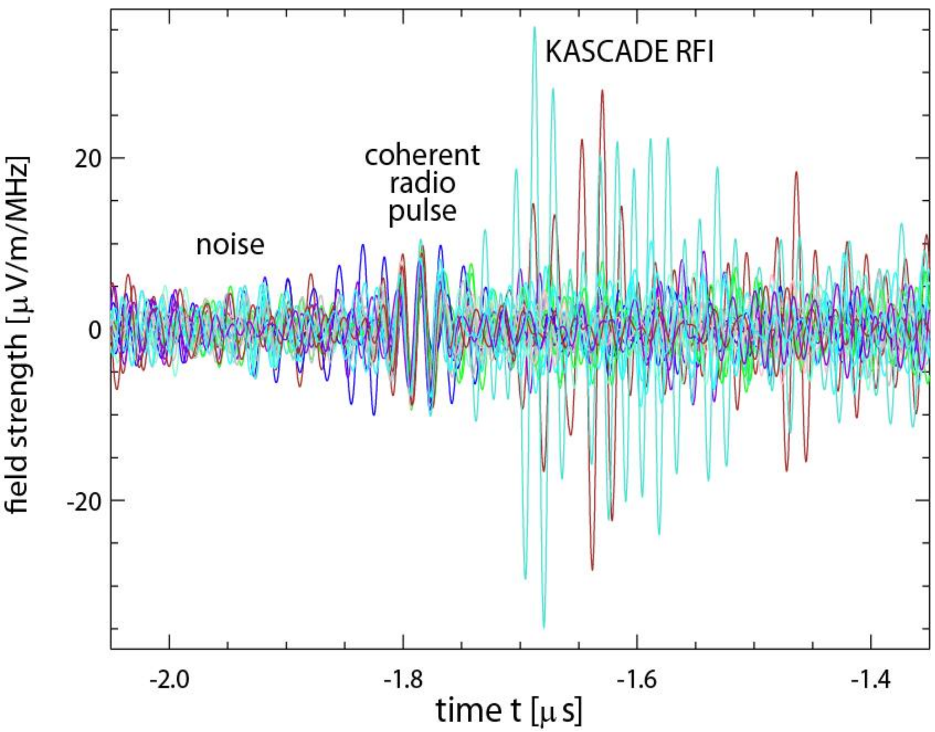


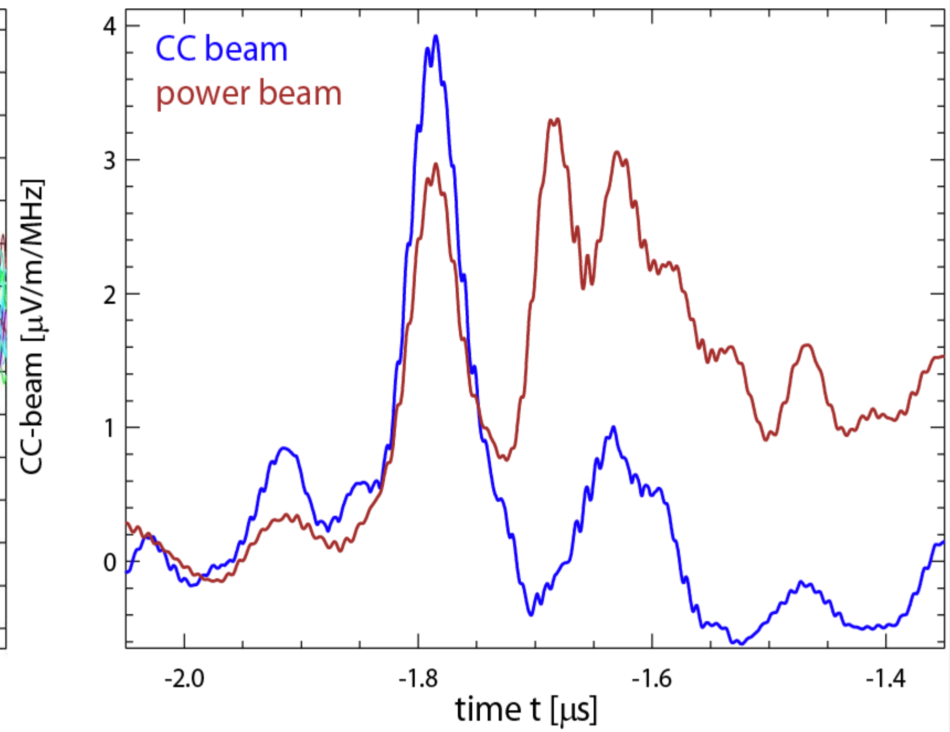
- 30 dipole antennas
  - 40 – 80 MHz
  - **east-west** / north-south
- Trigger by KASCADE

frank.schroeder@kit.edu
Institut für Kernphysik (IKP)

Cross-correlation beamforming

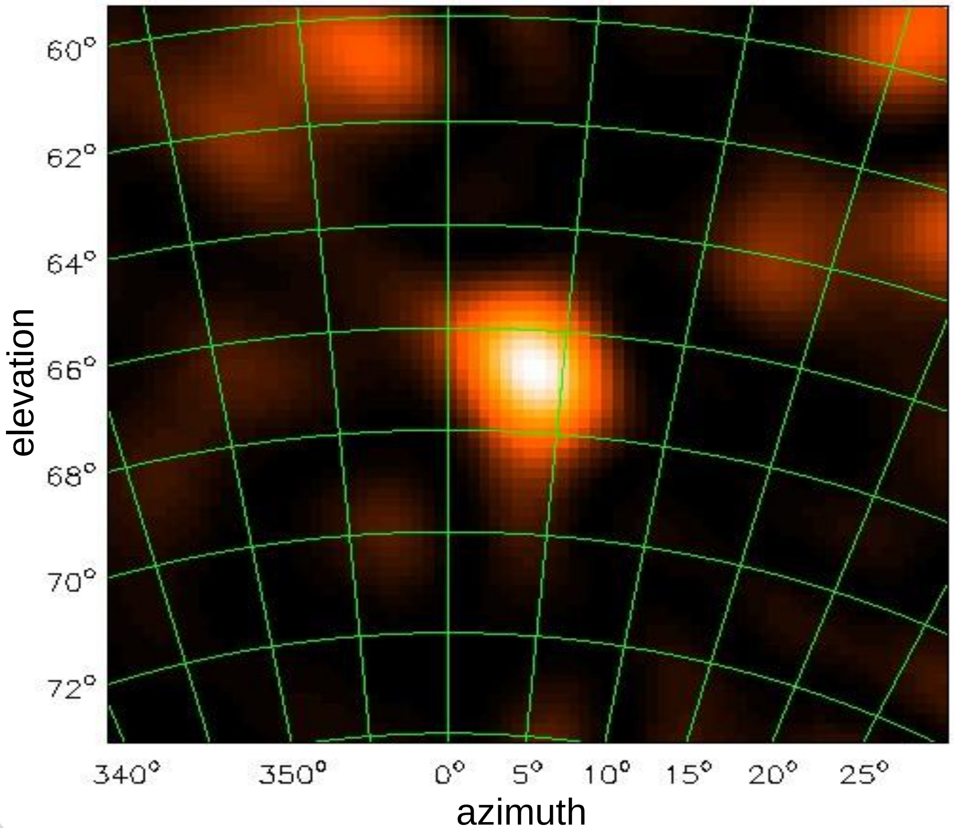
- Digital Interferometry: only air shower pulse correlated in all antennas, when looking in the arrival direction

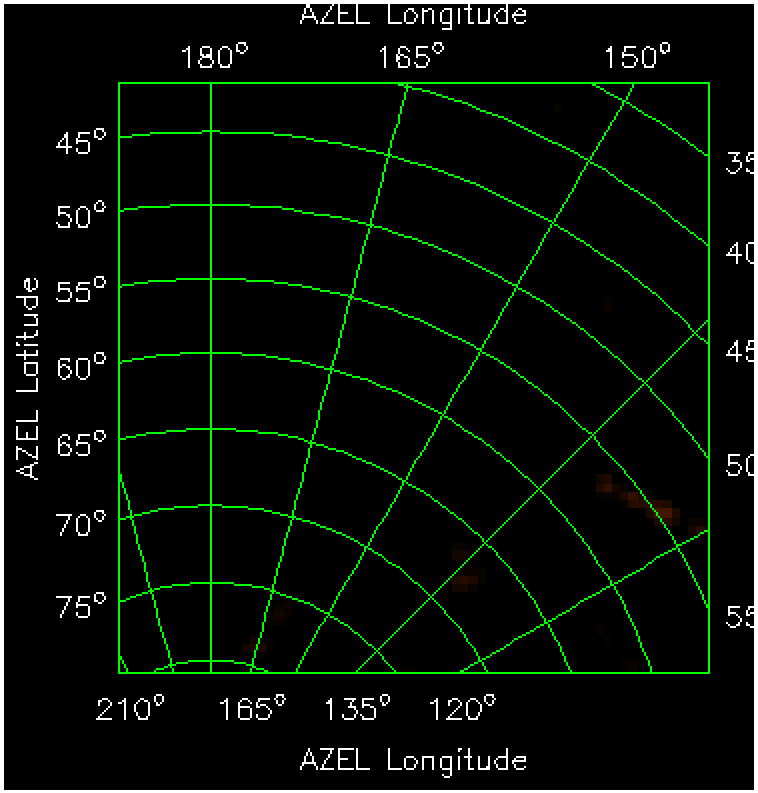




Interferometric Visualization

- Air shower radio pulse = flash for a few 10 ns
- Direction precision < 0.7°
- But is real imaging of the shower possible?

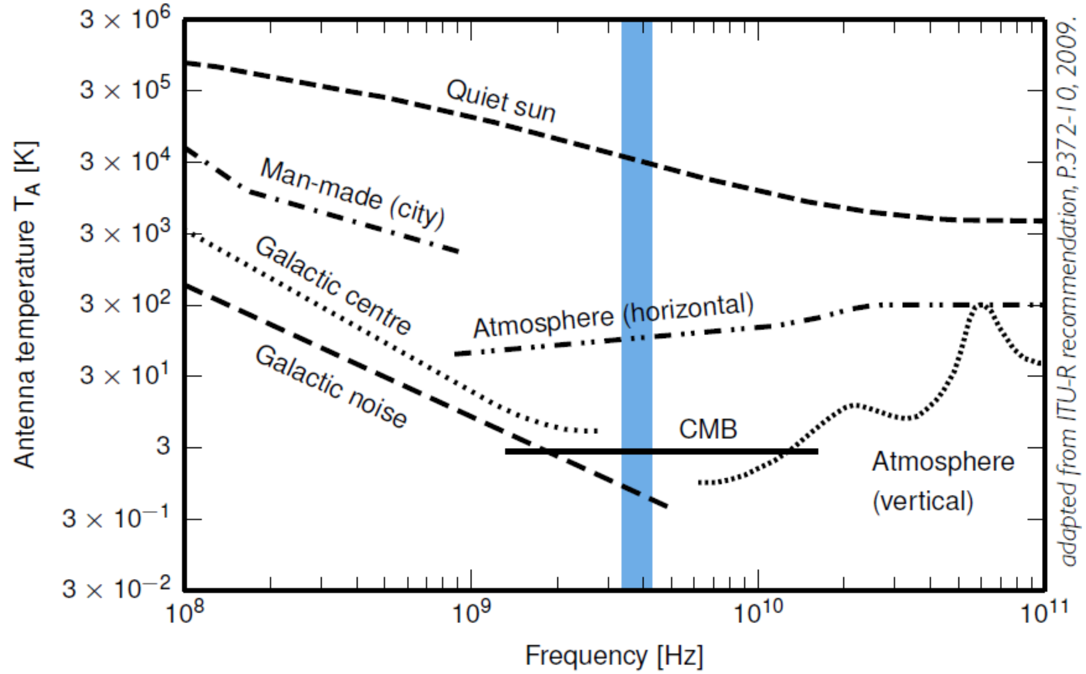


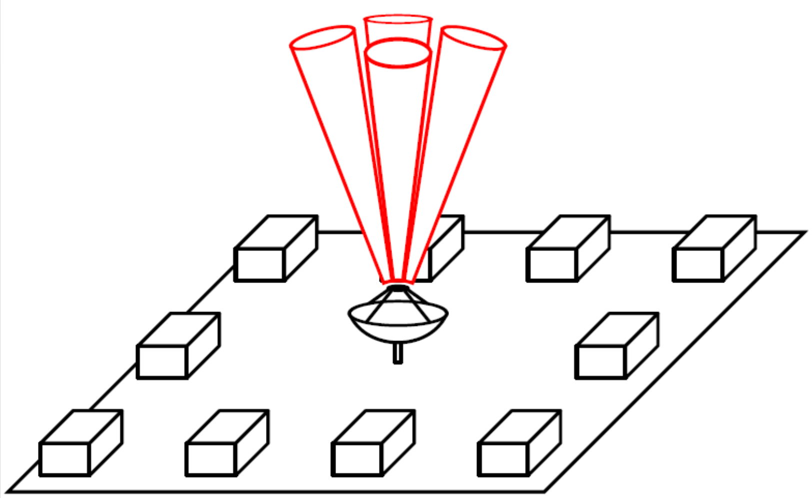


Falcke et al. (LOPES coll.) 2005, Nature

CROME at KIT

- Commercial GHz electronics
- Detection in C band
  - 3.4 -4.2 GHz
- Low noise: T ~ 80 K

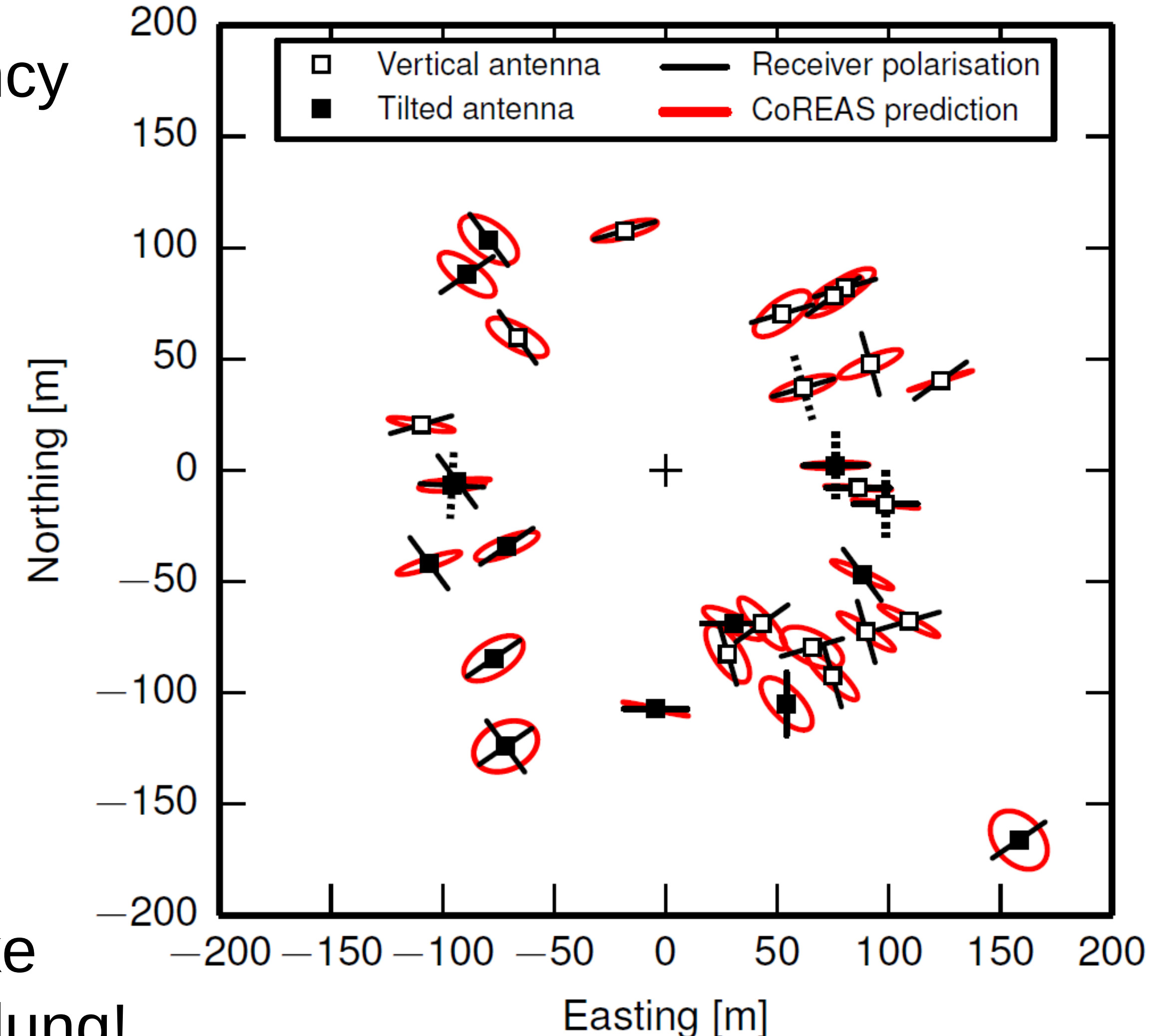




frank.schroeder@kit.edu
Institut für Kernphysik (IKP)

Cherenkov ring seen with CROME

- High detection efficiency on Cherenkov ring at GHz frequencies
- Compatible with CoREAS prediction of geomagnetic and Askaryan emission
- Polarization is not compatible with un-polarized emission, like molecular bremsstrahlung!

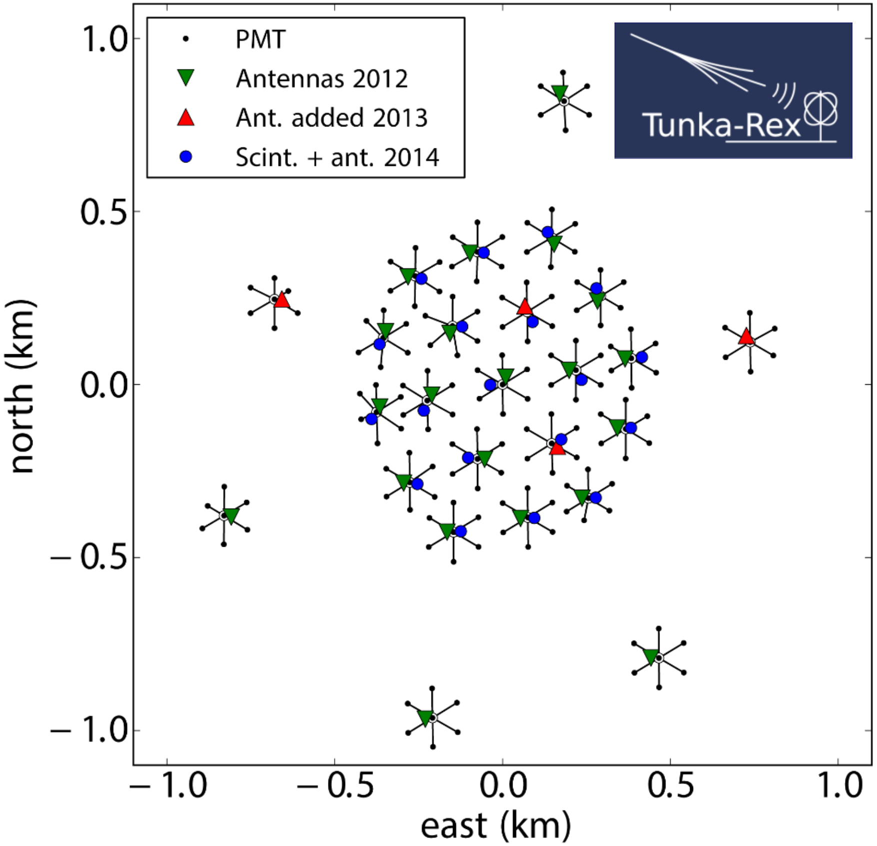


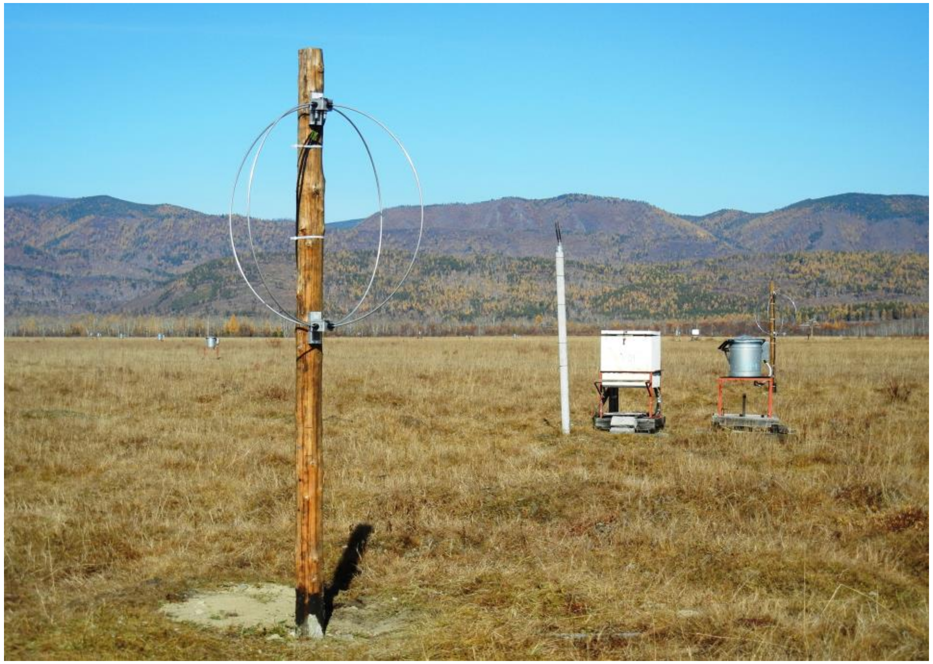
ARENA 2014 and **PRL 113 (2014) 221101**

frank.schroeder@kit.edu
Institut für Kernphysik (IKP)

Tunka-Rex in Siberia close to Lake Baikal

- SALLA antennas, 30 - 80 MHz
- Cross-calibration with co-located air-Cherenkov detector
  - Precision and absolute scale of energy and shower maximum



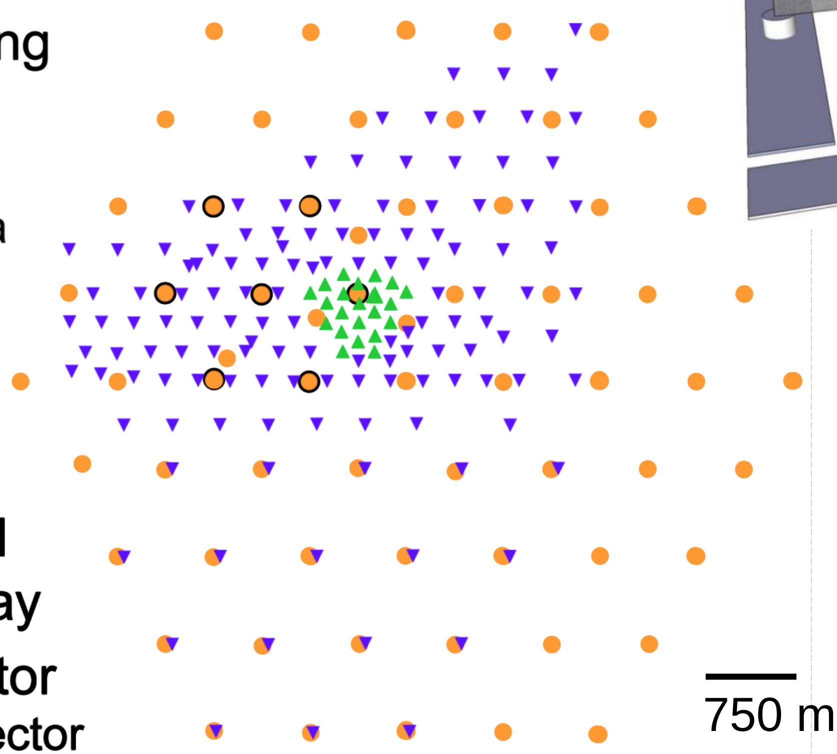


Pierre Auger Observatory

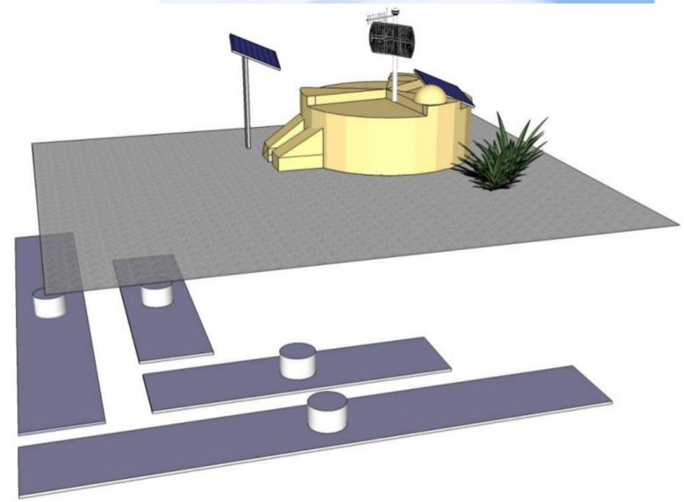
- 20 km² enhancement area for E > 10^{17} eV
  - closer detector spacing (750 m Infill)
  - buried muon detectors
  - 153 autonomous radio stations, 30-80 MH

Auger **E**ngineering **R**adio **A**rray
- ▲ LPDA antenna
- ▼ Butterfly antenna

Auger **M**uon and **I**nfill **G**round **A**rray
- ● **S**urface **D**etector
- ○ with **M**uon **D**etector

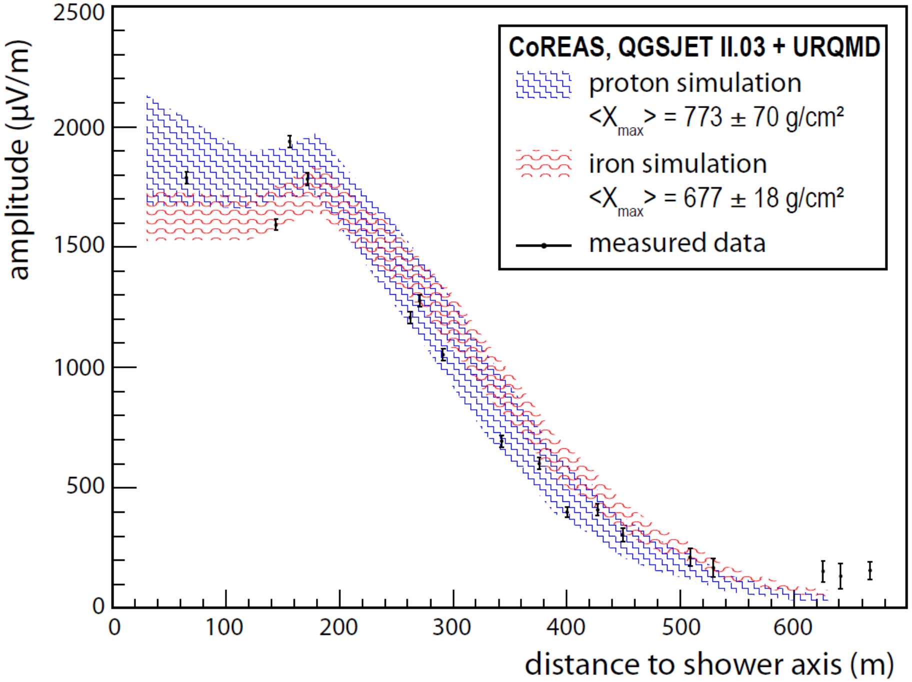


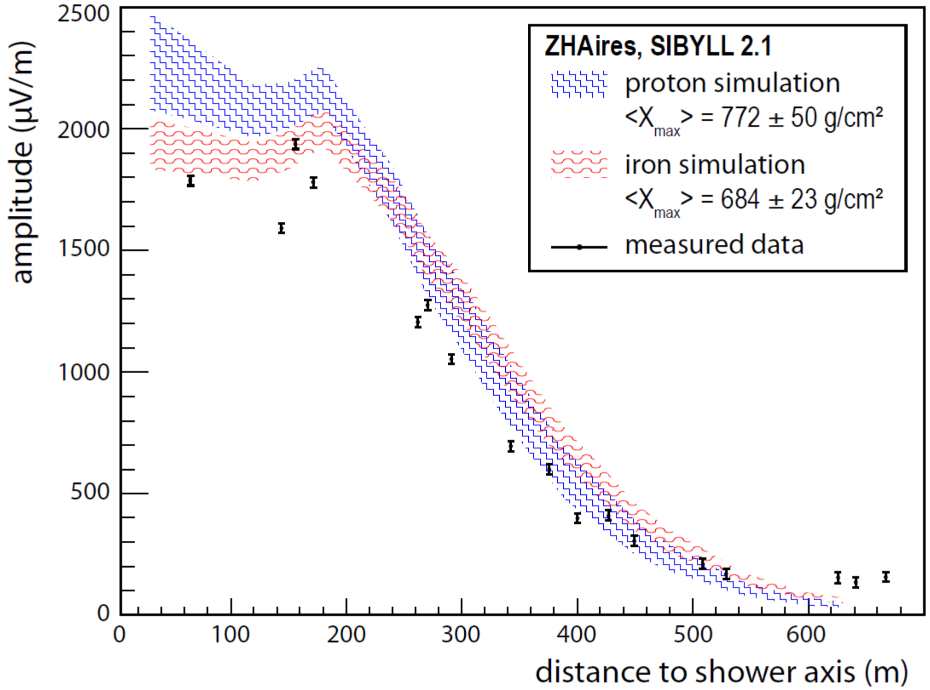
LPDA



Butterfly

Comparing simulations with AERA event

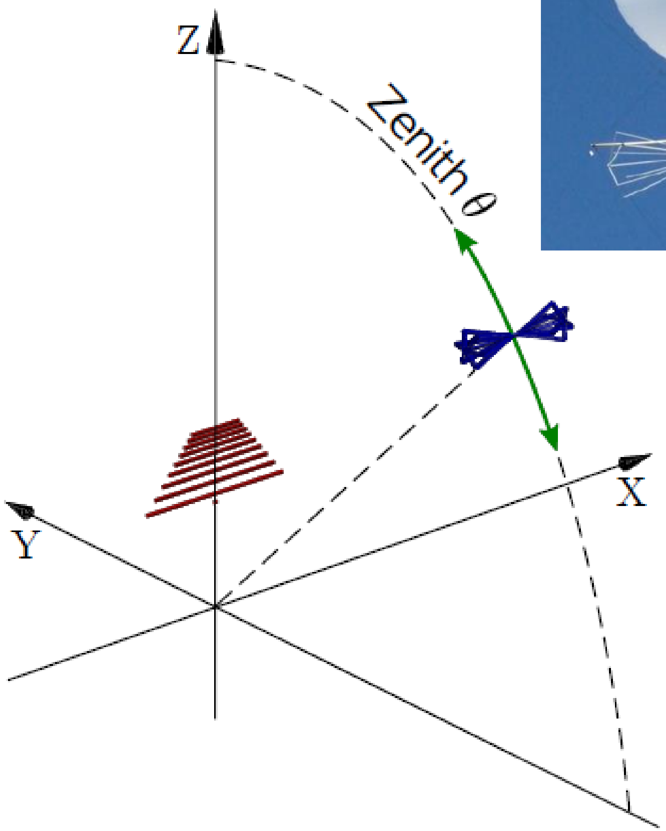


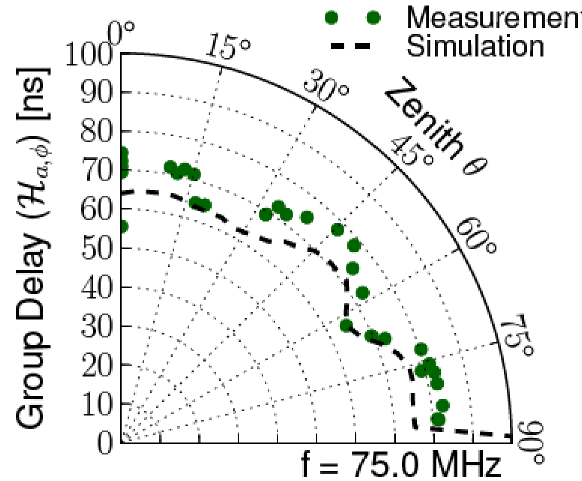


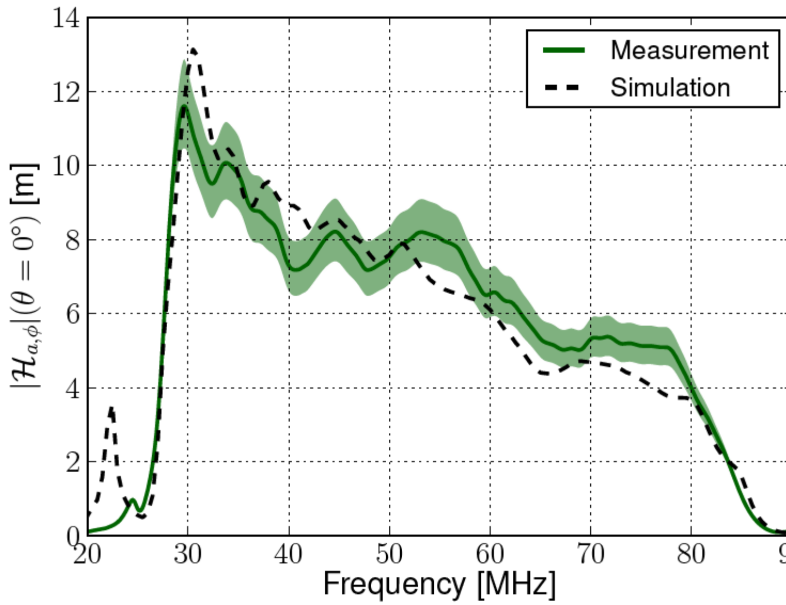
- Example event with calibrated AERA measurements
- CoREAS and ZHAires simulations reproduce shape
  - differences compatible with calibration scale uncertainty?

Pierre Auger Collaboration, ICRC2013, id #899

Antenna calibration





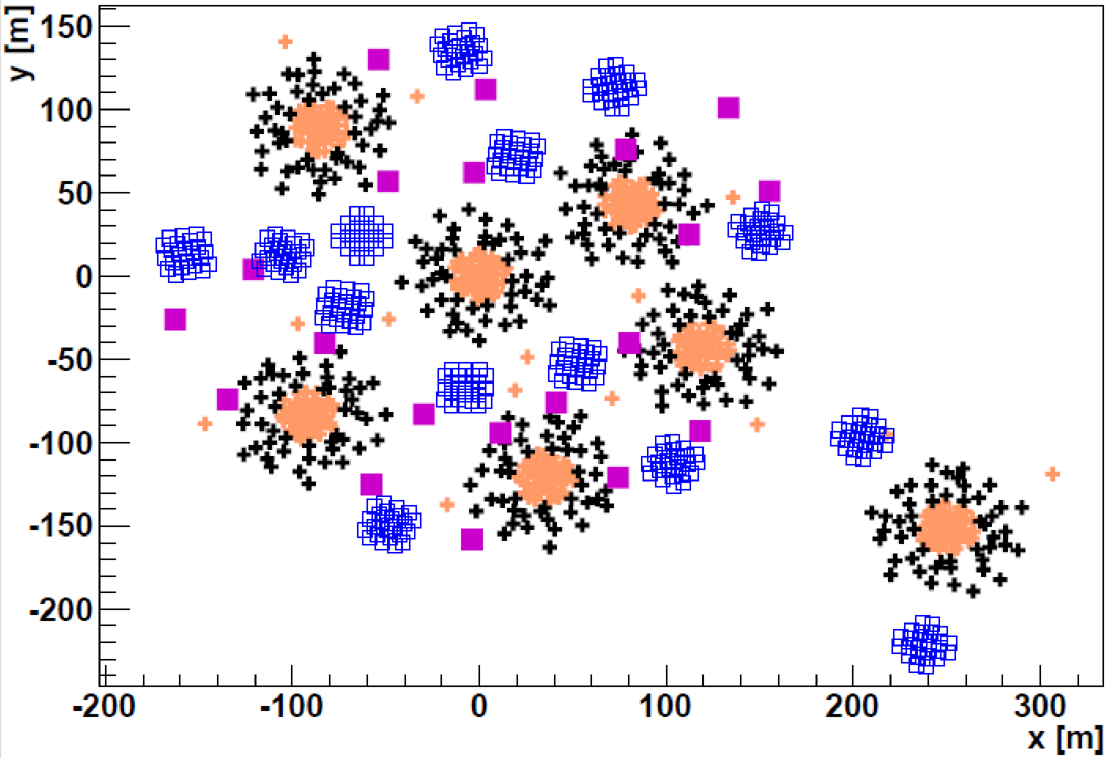


Pierre Auger Coll., JINST 7 (2012) P10011

LOFAR superterp, the Netherlands

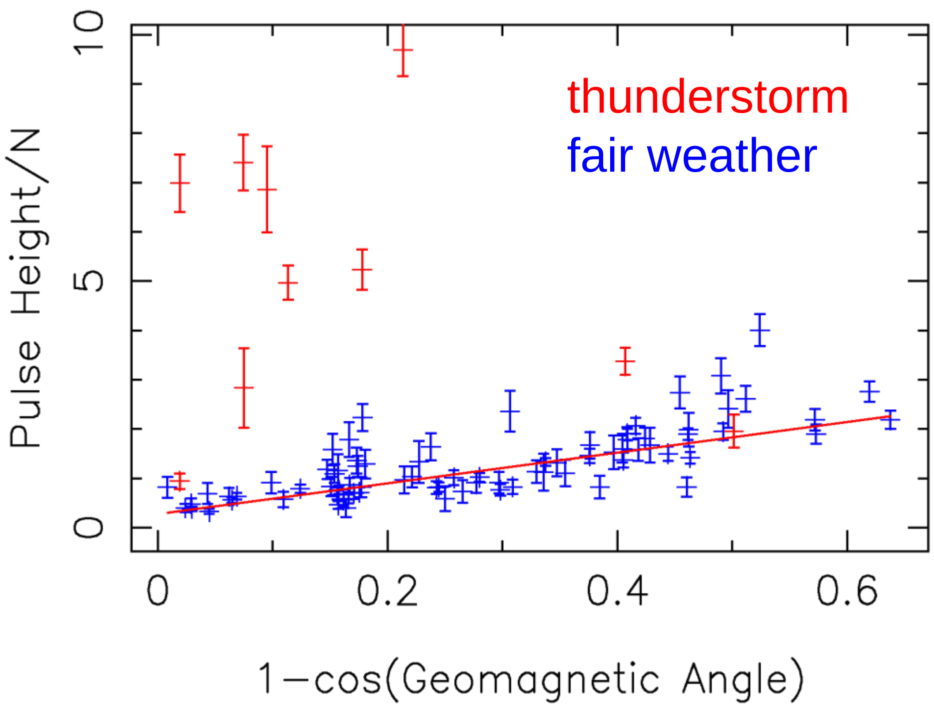
Karlsruhe Institute of Technology

- Several 100 antennas on several 100 m²
  - Low band: 10-90 MHz
  - High band: 110-190 MHz

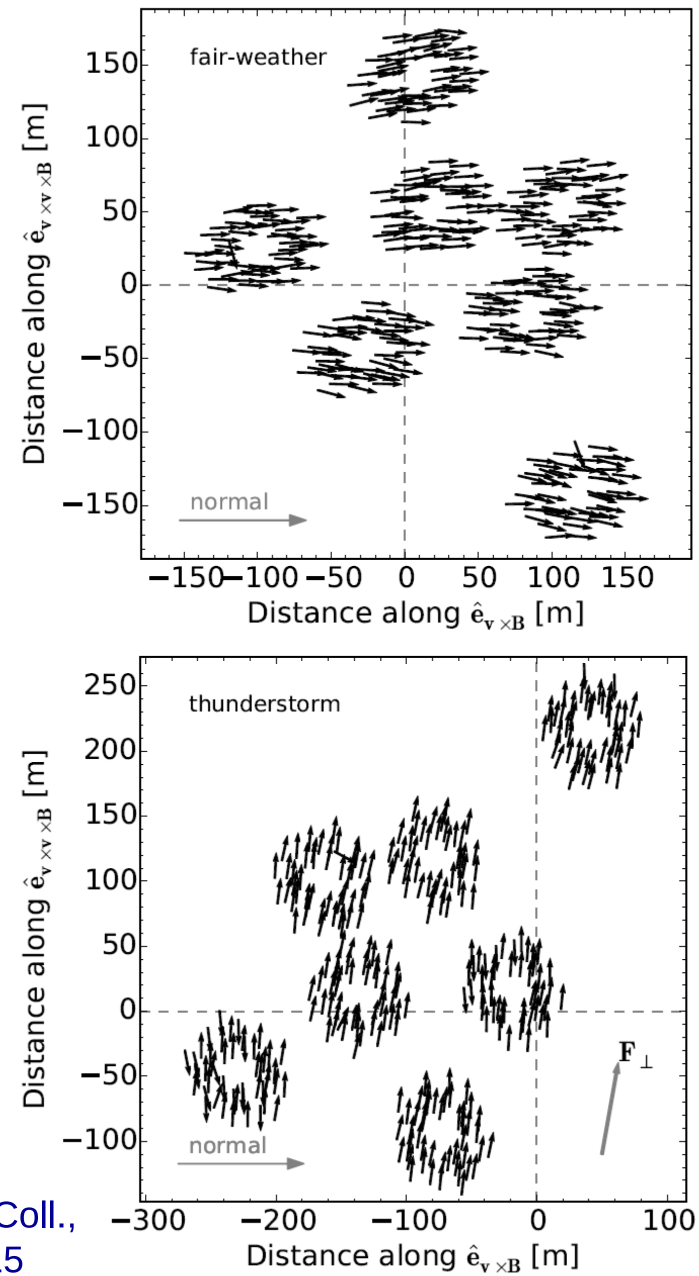


Thunderstorms

- High atmospheric E-fields influence radio emission
  - air-showers could probe atmospheric E-fields



LOPES Coll., A&A 2007



LOFAR Coll., PRL 2015

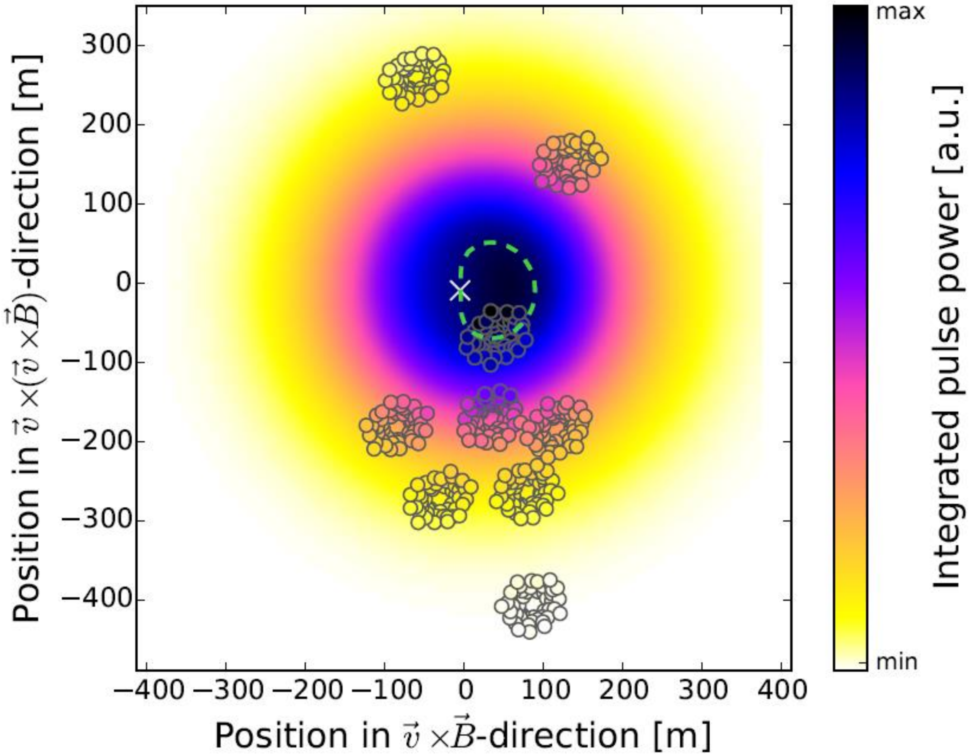
Reconstruction of CR composition

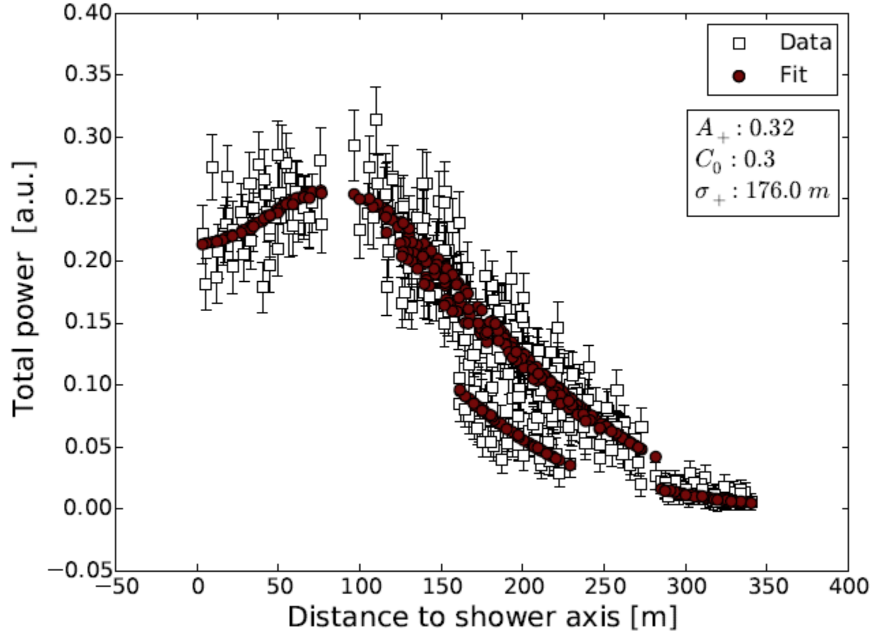
- Shower maximum
  - Lateral distribution
  - Wavefront
  - Frequency spectrum
  - Cherenkov ring
  - Brute-force comparison to simulations

- Radio + Muon detection

Shower maximum via lateral distribution

- Fitting 2-dim asymmetric LDF: slope and width parameters sensitive to shower maximum

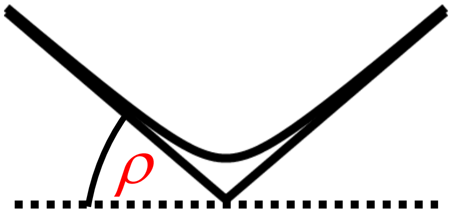




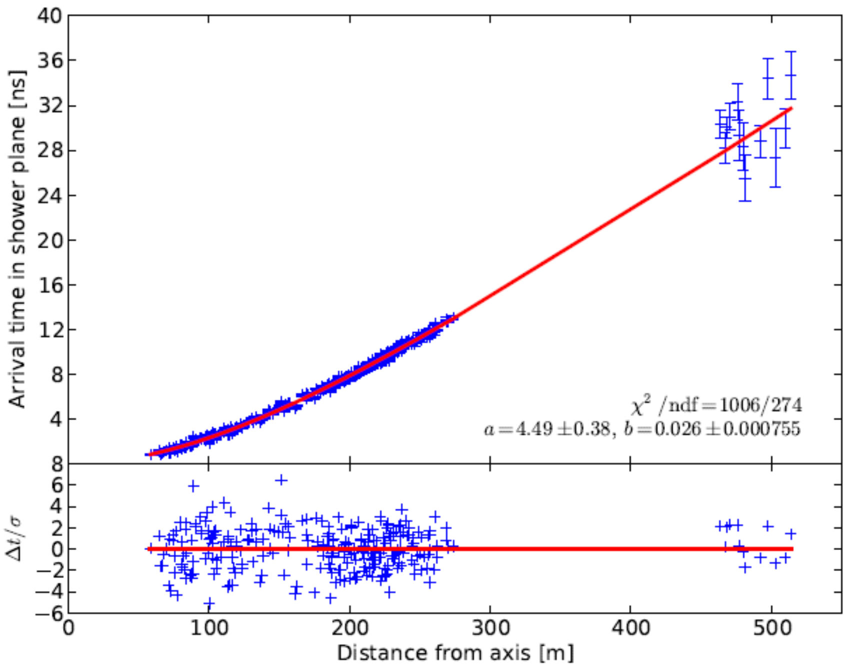
LOFAR Coll, 2014, accepted by JCAP

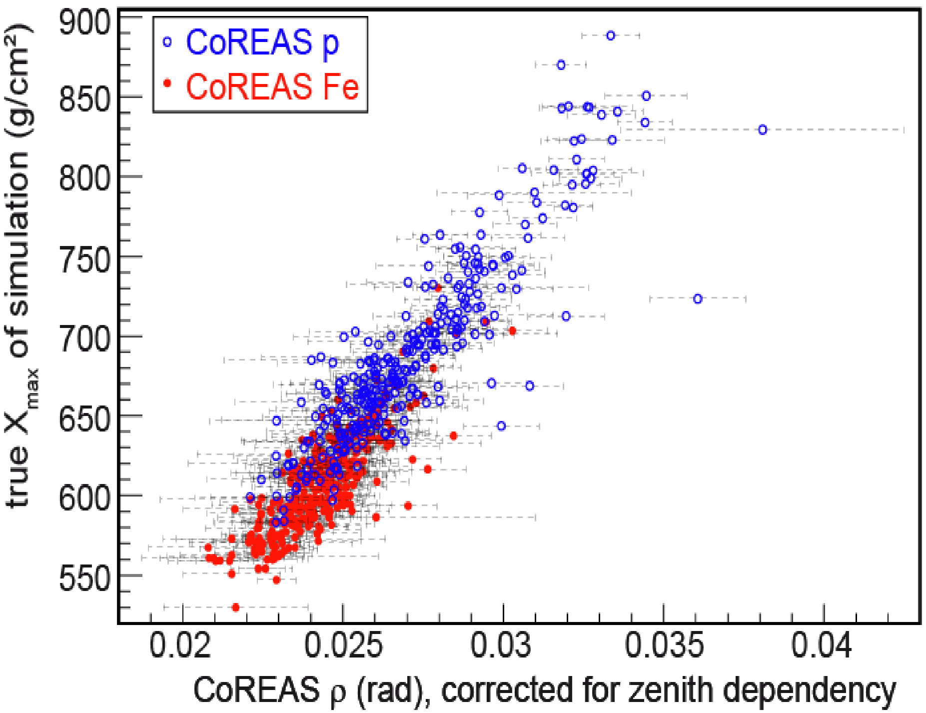
Shower maximum via wavefront

- Radio wavefront has hyperbolic shape
- Cone angle → shower maximum



ca. 1° - 2°

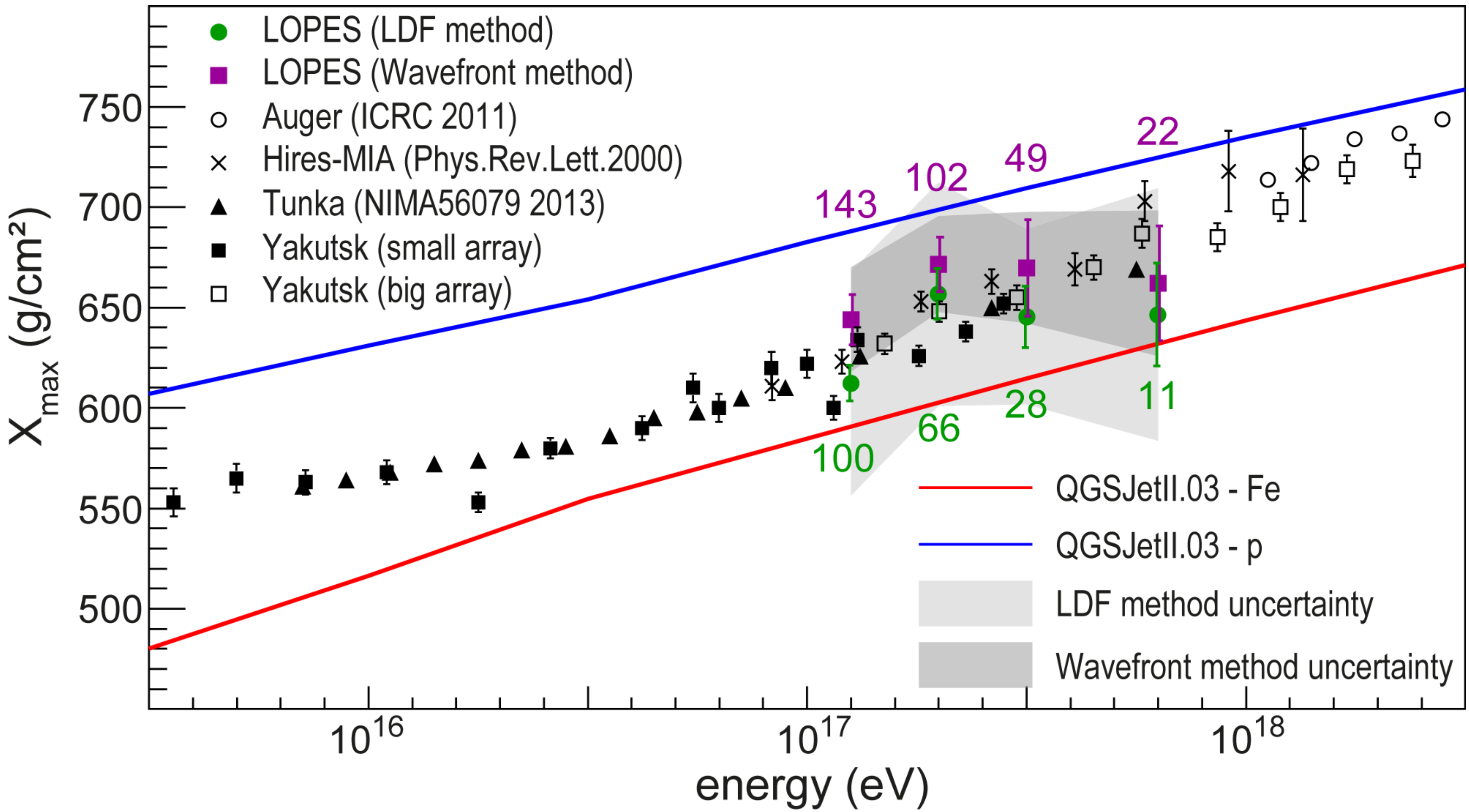




LOFAR Coll, Astropp. 61 (2015) 22

LOPES Coll., JCAP 09 (2014) 025

Radio shower maximum consistent

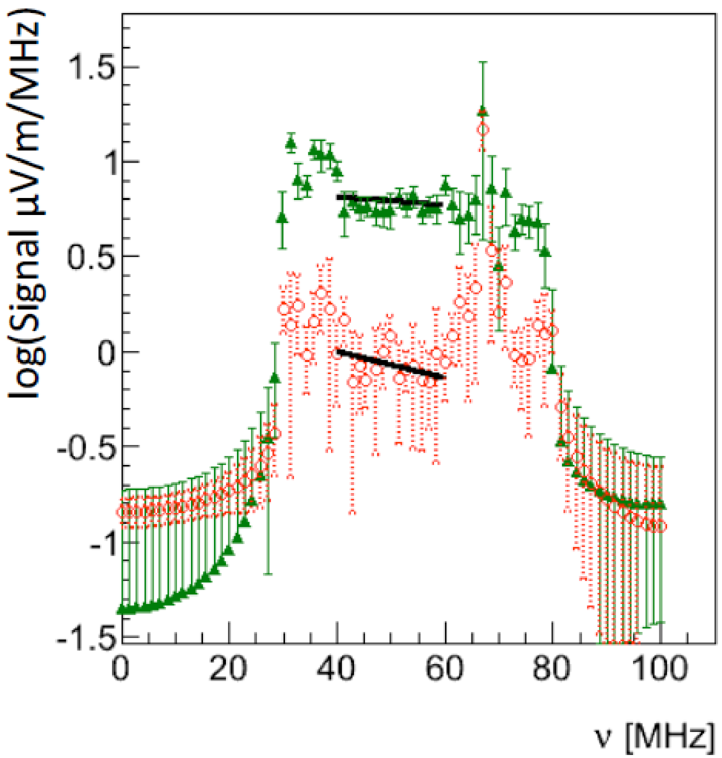


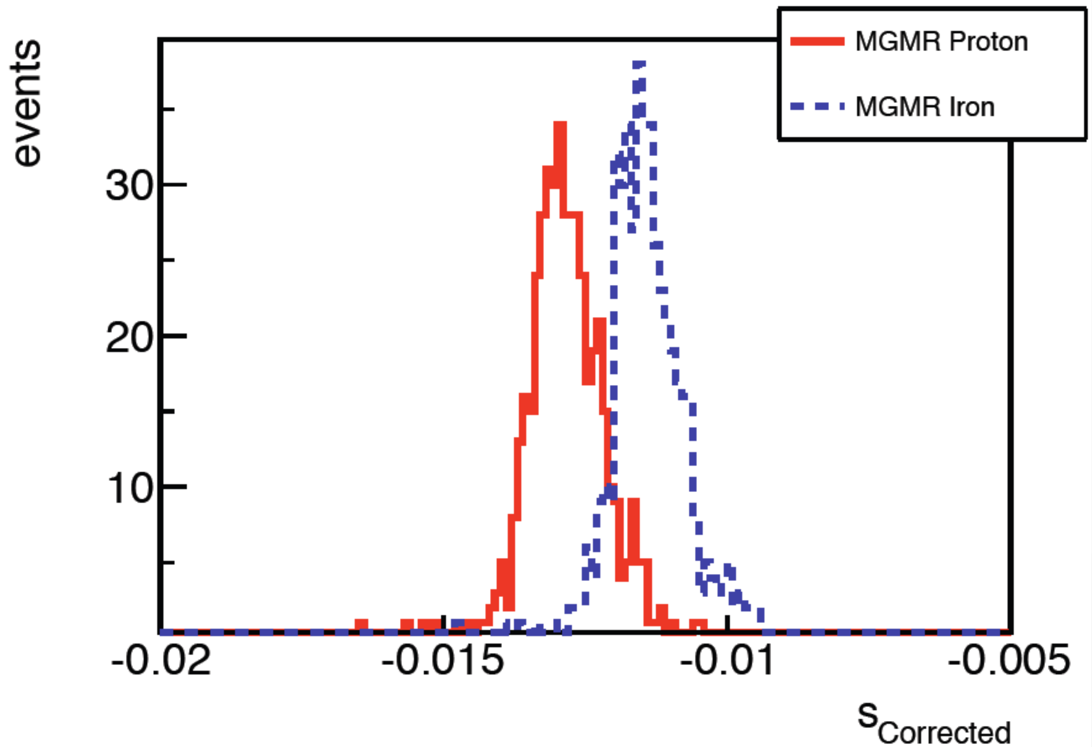
LOPES Coll., ECRS 2014

Slope of frequency spectrum

- Frequency spectrum sensitive to shower maximum
- Hard to measure at AERA, but probably easier at SKA

Fitting range: 40 to 60 MHz

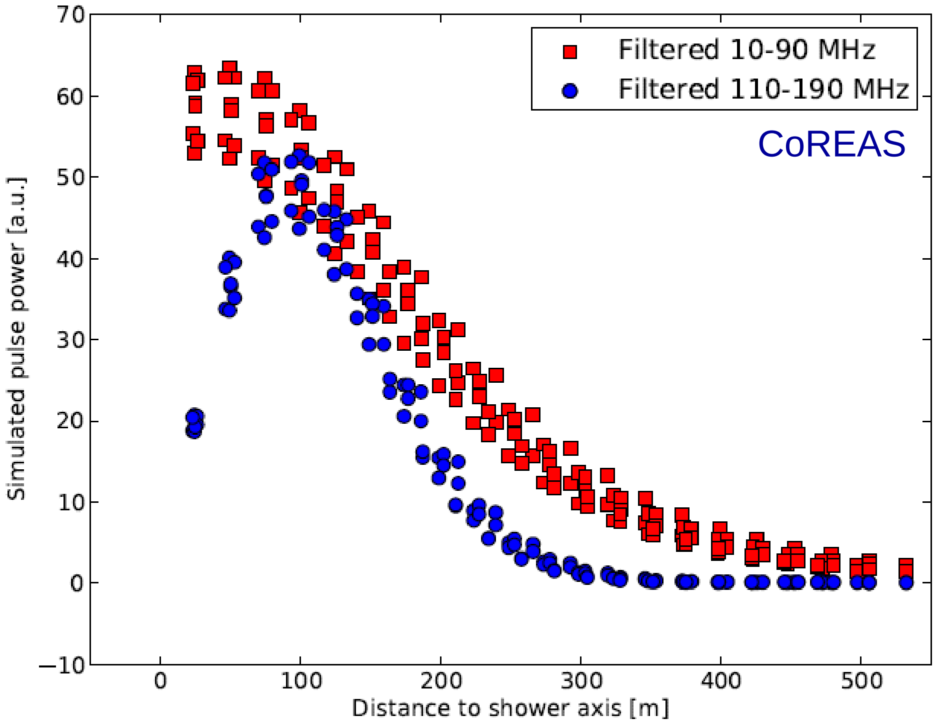


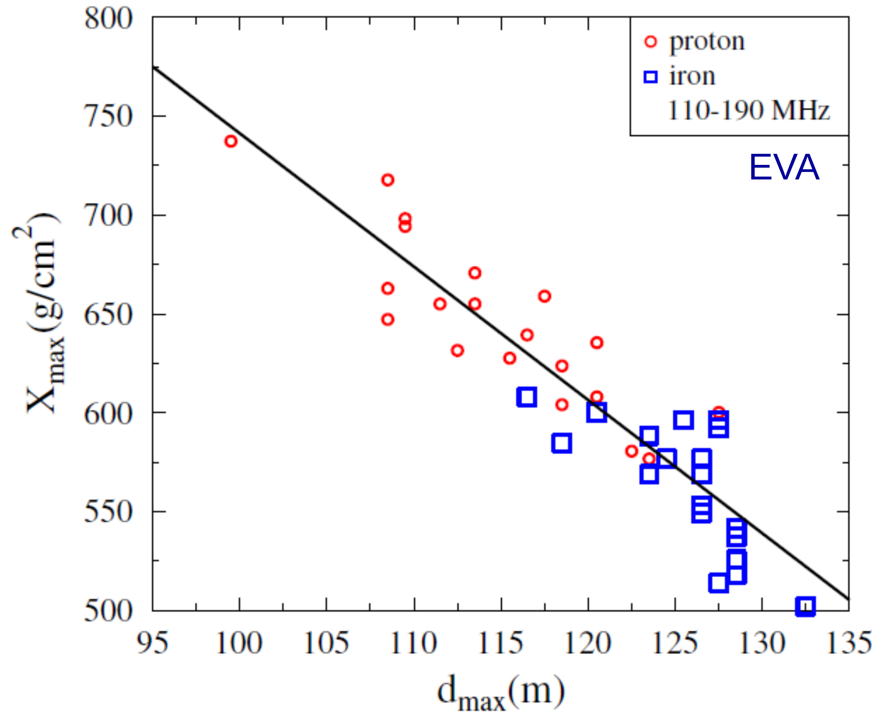


Pierre Auger Coll., ARENA 2012

Cherenkov Ring at LOFAR

- Diameter of Cherenkov ring at higher frequencies seems to be very sensitive to shower maximum
  - dense array required for sufficient precision → SKA?

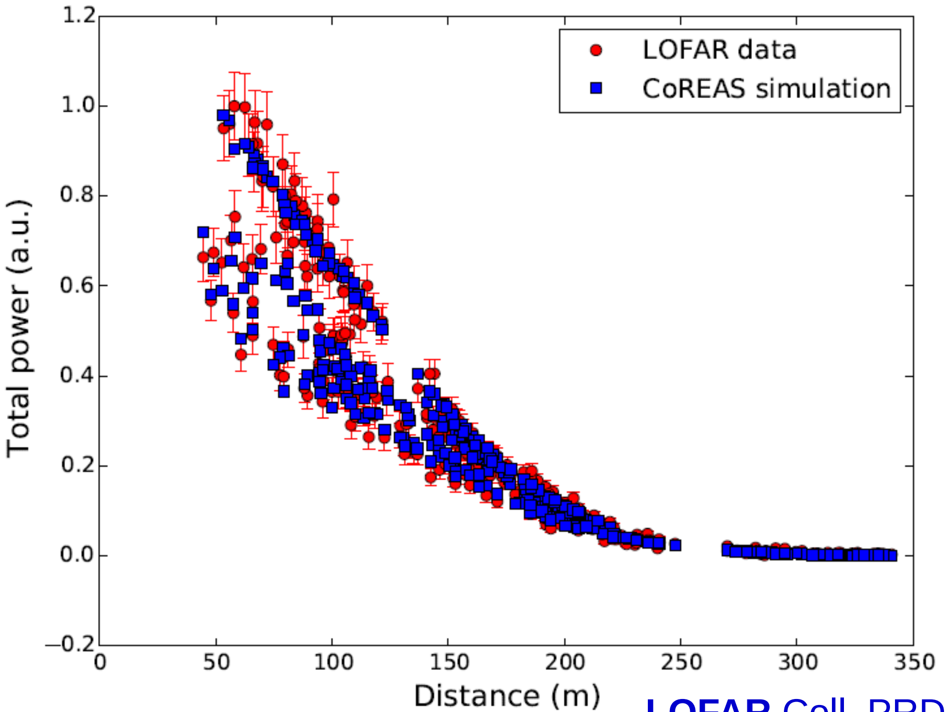


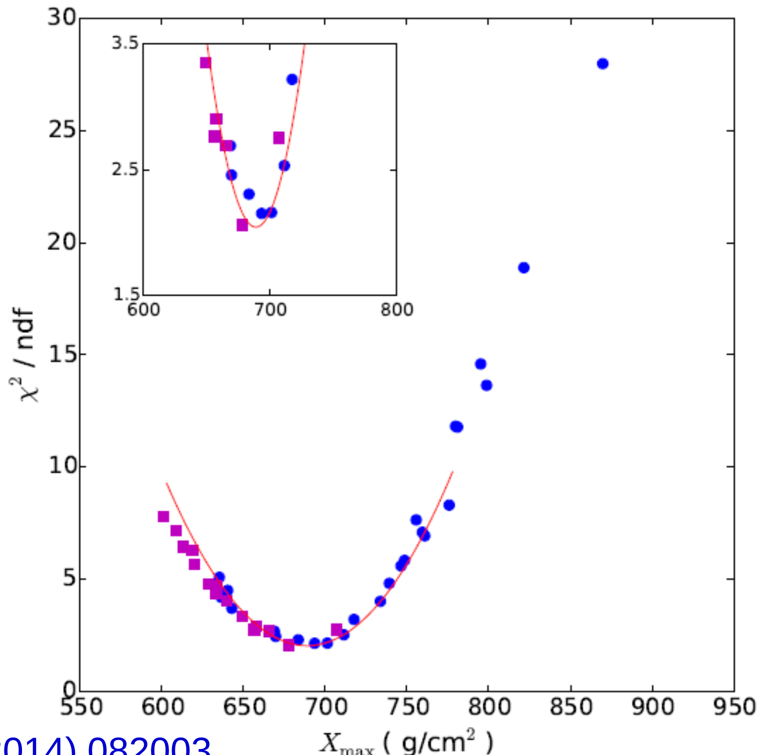


LOFAR Coll, Astropp. 65 (2015) 11

X_{max} with brute-force simulations

- Pick the one of many simulations describing data best
  - very high precision < 20 g/cm²
  - all systematic effects known?
  - Why χ^2/NDF systematically larger than 1?



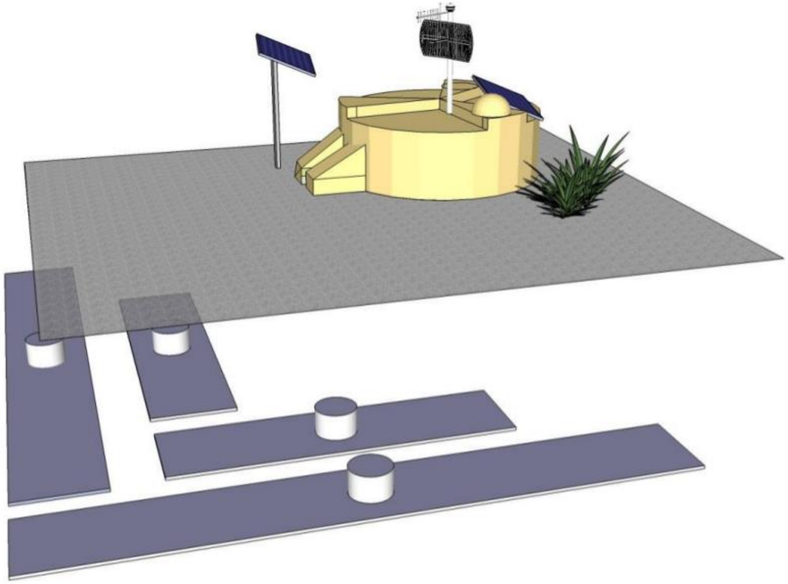


LOFAR Coll, PRD 90 (2014) 082003

Radio-Muon hybrid detection

- Statistical sensitivity of X_{max} to composition limited
- Electron/muon ratio provides complementary information
  → **Maximum accuracy requires radio + muon detectors!**
- Muon detectors could also provide trigger

Multi-Hybrid analyses under test at Pierre Auger Observatory



Conclusion

- Qualitative agreement on radio emission
  - geomagnetic + Askaryan effect + refractive index effects
- Several modern experiments optimizing precision for energy and shower maximum
  - precision becomes competitive to established techniques
  - radio technique close to applicability for cosmic-ray physics
- Scale uncertainties limit total accuracy
  - further improvements on calibration and models required
  - sufficient scale accuracy achievable by cross-calibration
  - radio ideal for air showers in combination with particle detectors

frank.schroeder@kit.edu
Institut für Kernphysik (IKP)