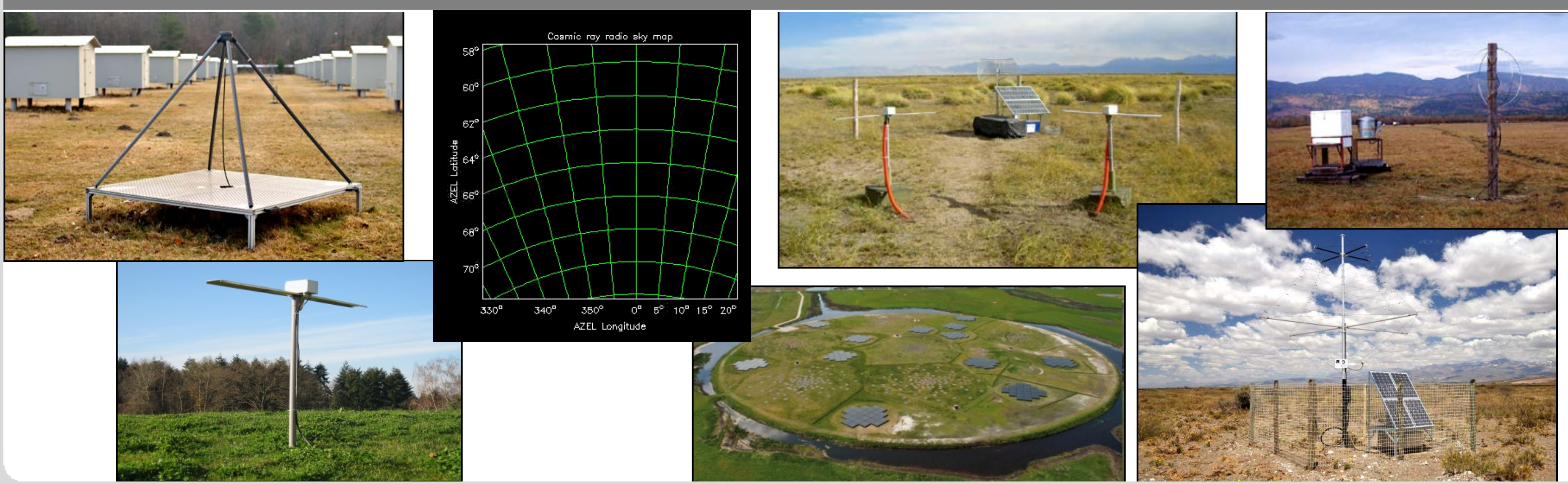
Karlsruhe Institute of Technology

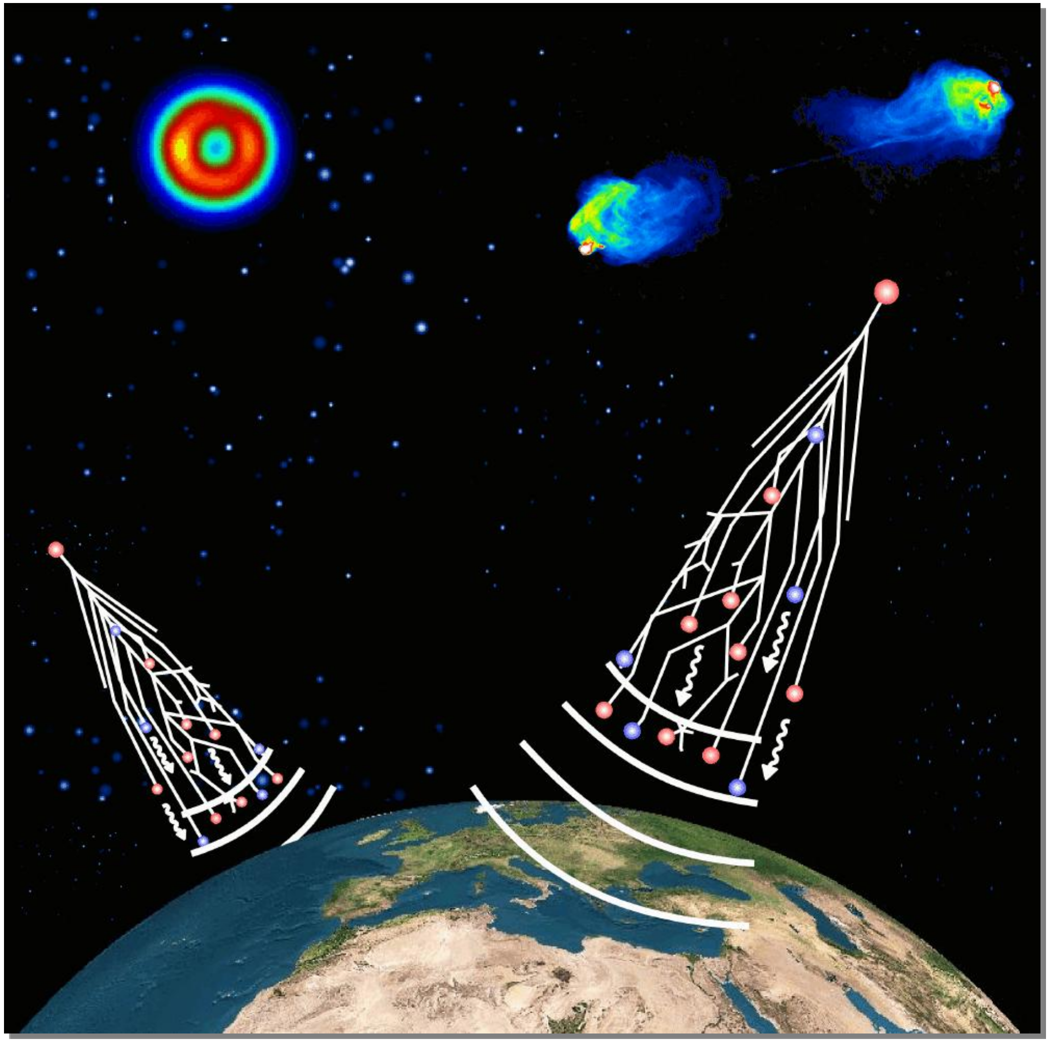
Digital radio detection of cosmic rays: achievements, status and perspectives

Tim Huege (Karlsruhe Institute of Technology)



Contents

- the promises of radio detection
- digital radio detection of cosmic rays
- future directions



To understand the sources of cosmic rays …

- we need to know their
  - arrival direction
  - energy
  - and mass
- we need large statistics
  - large effective areas and high duty cycles

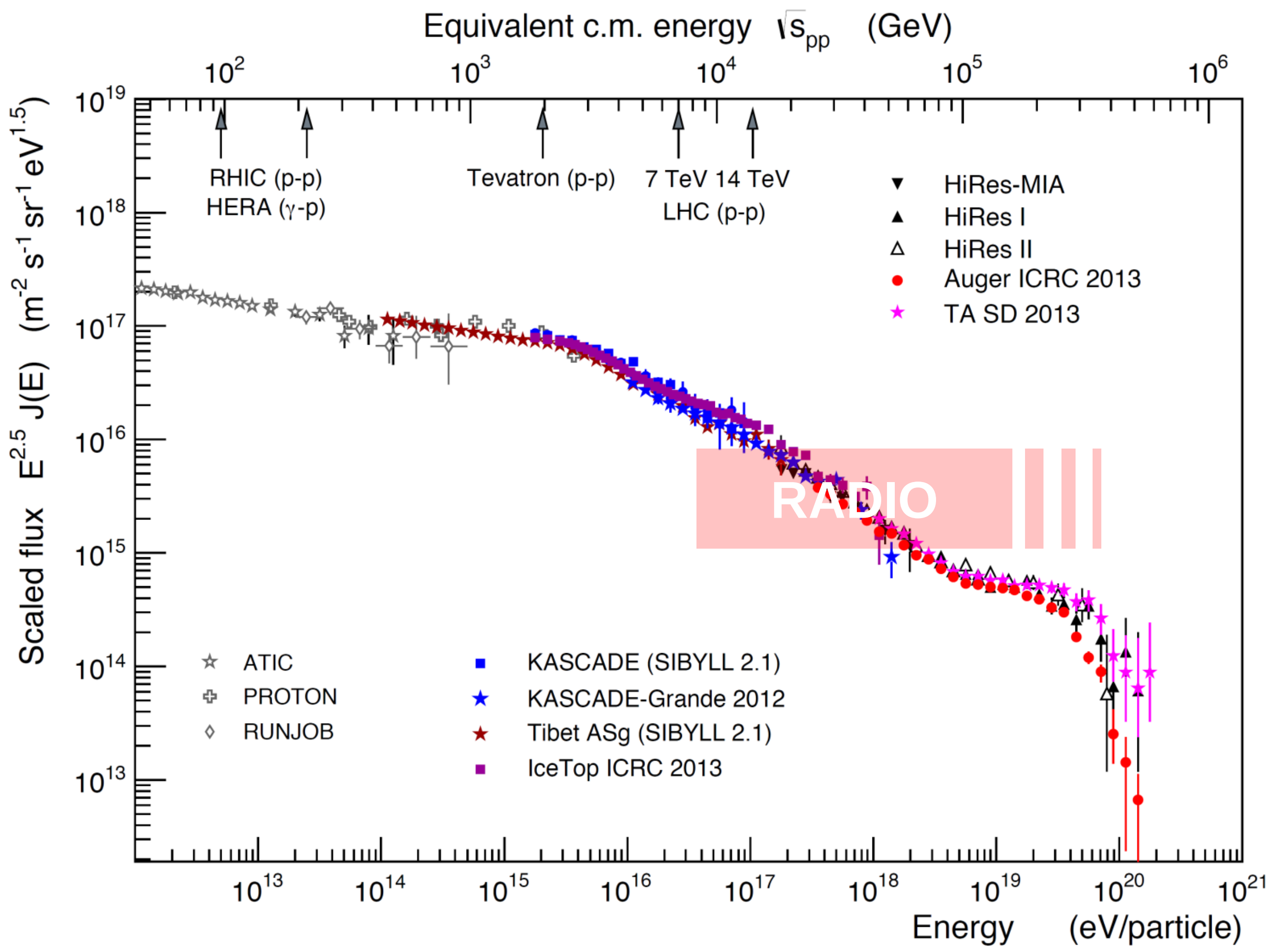


diagram by R. Engel

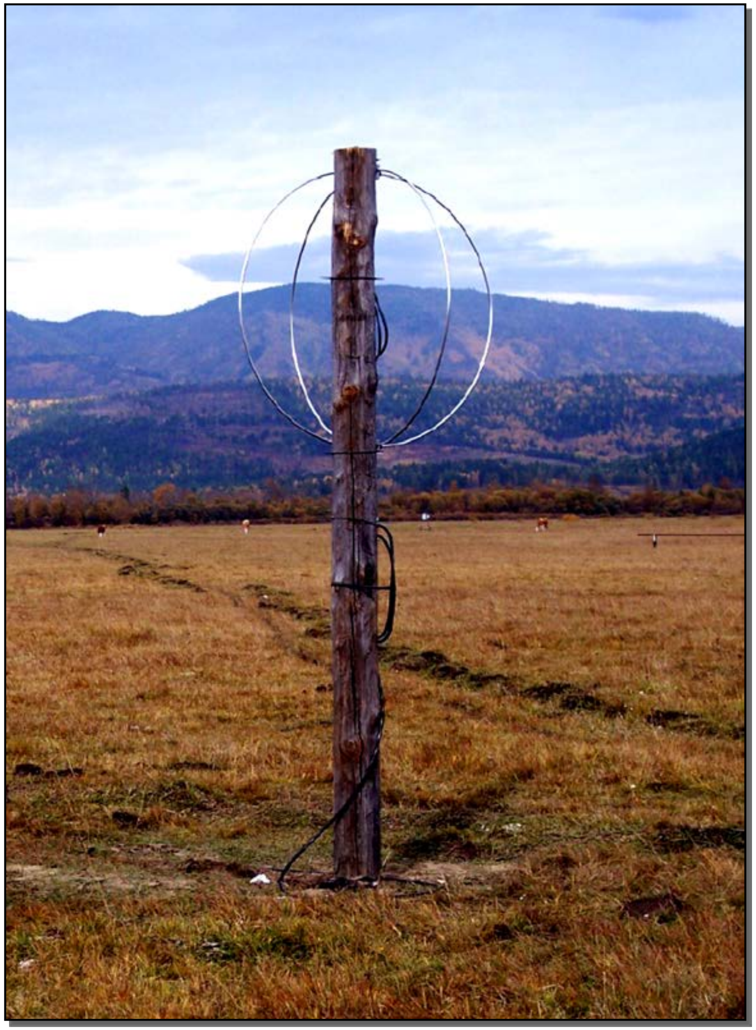
Limitations of current detection techniques

- particle detectors
  - sample showers only at a particular atmospheric depth
  - suffer from uncertainties in hadronic interaction models (muons)
- fluorescence detectors
  - allow calorimetric energy measurement
  - directly yield mass-sensitive depth of shower maximum (Xmax)
  - but have only ~10% duty cycle

The promises of radio detection

- information complementary to surface particle detectors
  - pure electromagnetic component
- calorimetric energy measurement
- near 100% duty cycle (cf. 10% of optical fluorescence detectors)
- Xmax sensitivity
- high angular resolution (< 0.5°)
- simple (potentially cheap) detectors

- *how well does it all work in practice and on large scales?*



Tunka-Rex

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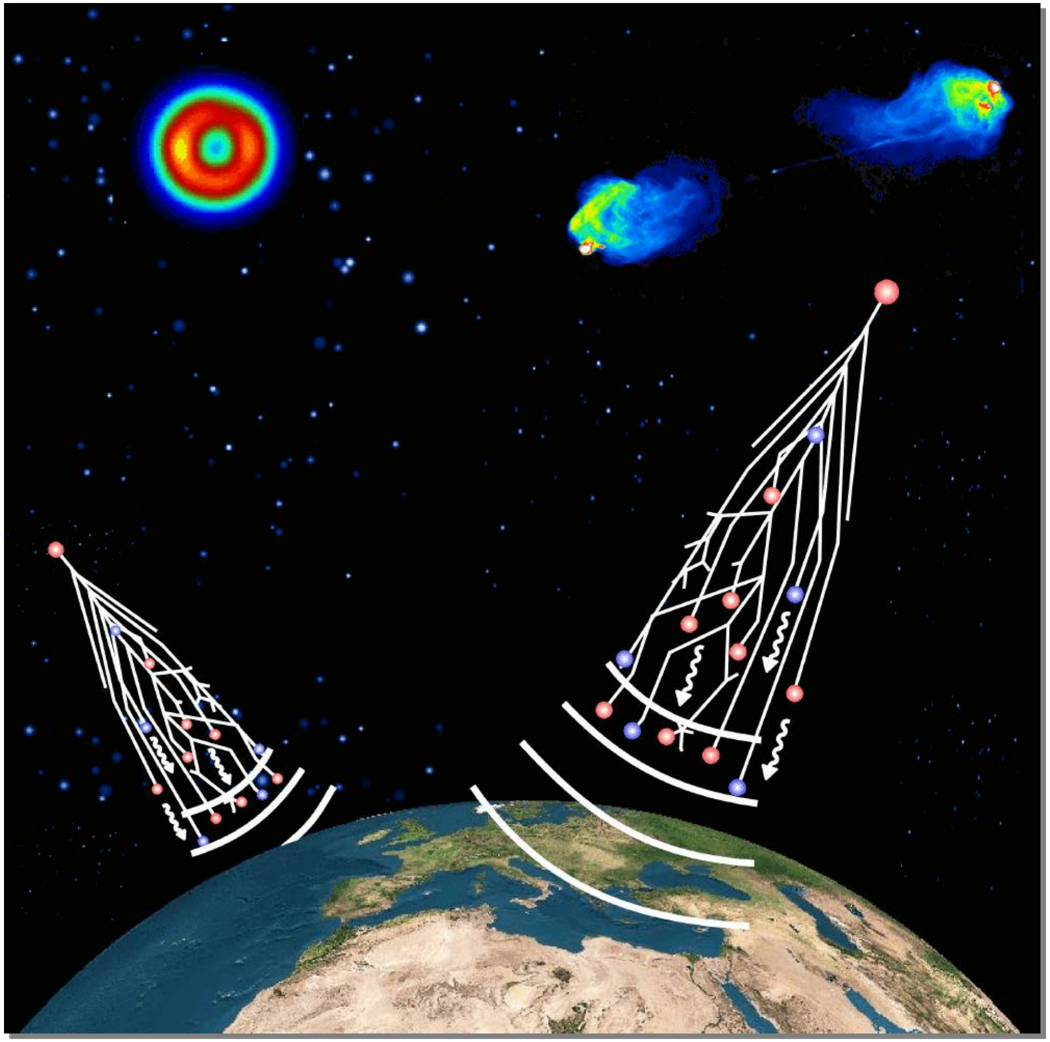
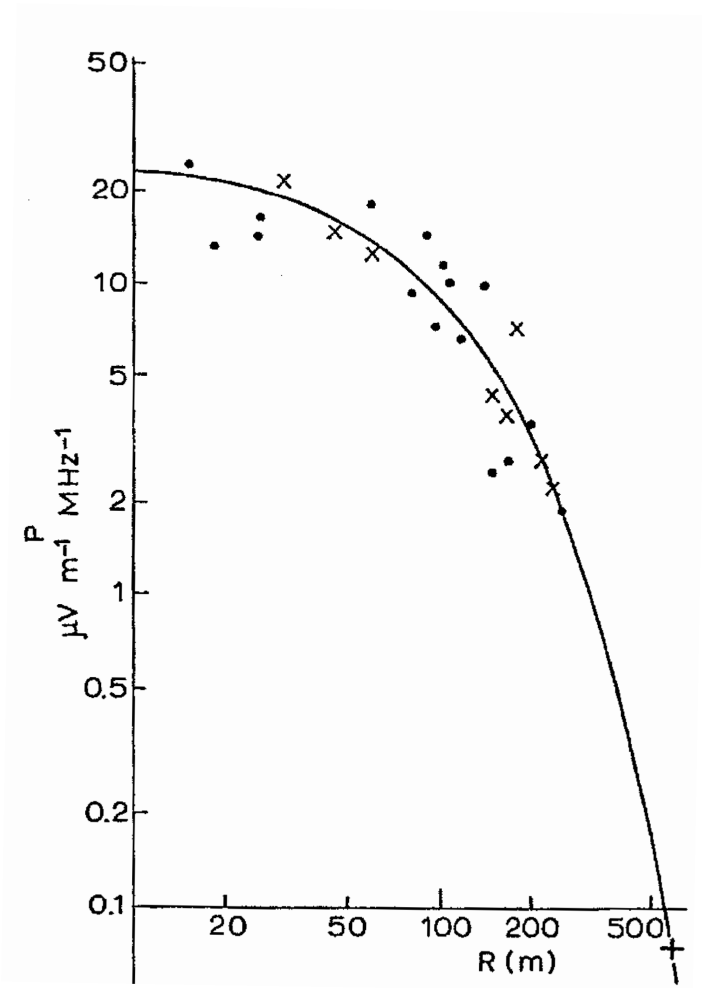


State of the field in the 1970s



H.R. Allan (1971)

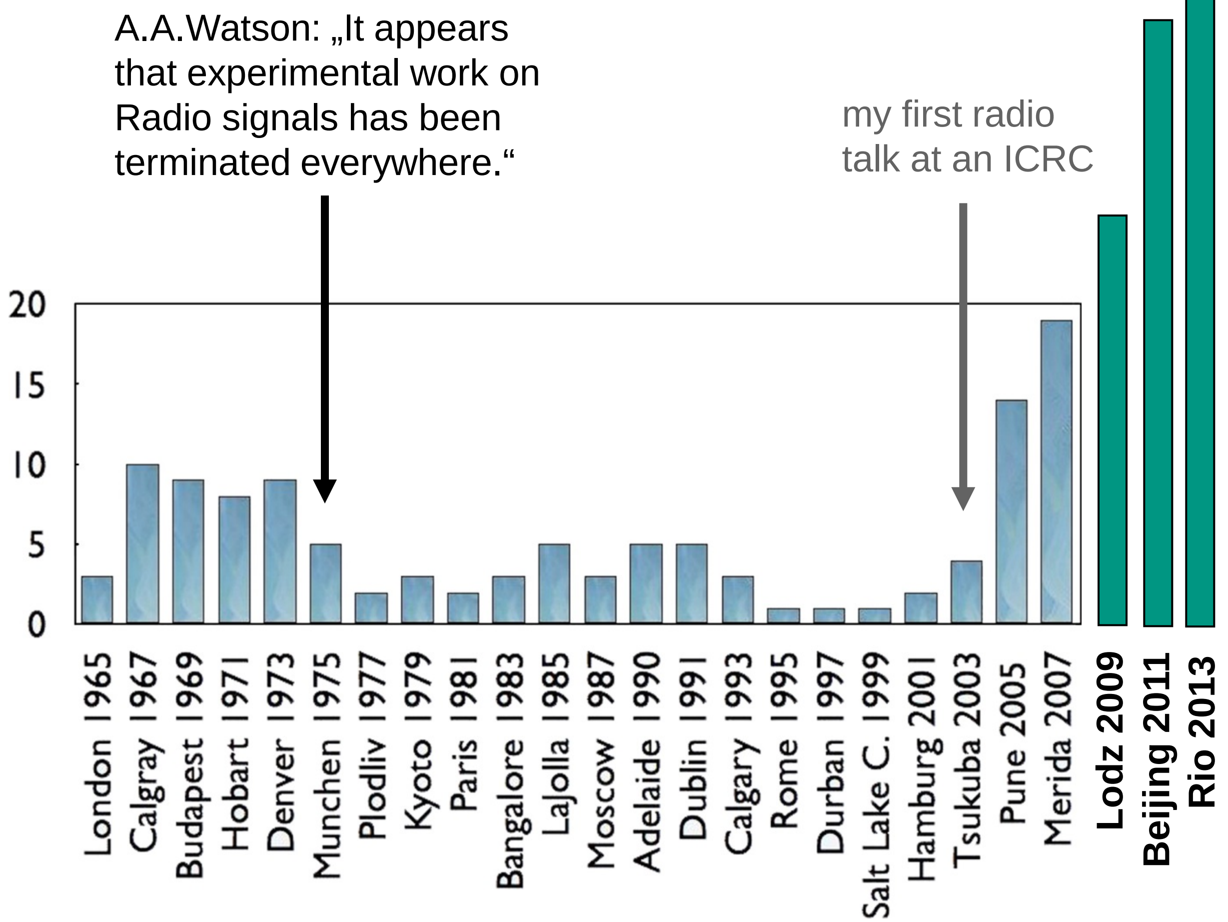
- consensus
  - dominantly geomagnetic emission
  - radio LDF decays roughly exponentially
  - signal detectable from 2 to 500 MHz
  - amplitude grows linearly with energy

$$E \propto \frac{\varepsilon_{radio}}{\sin\alpha \cdot \cos\theta \cdot \exp(-d/d_0)}$$

- rather unclear
  - absolute field-strengths?
  - additional emission mechanisms?
  - atmospheric electric field show-stopper?
  - radio sensitivity to primary mass?
  - …

Decline and revival of radio detection

- number of ICRC contributions related to radio detection of neutrinos or cosmic rays



T.C. Weekes, RADHEP2000

R.J. Nichol et al. (ANITA Coll.), NIM A 2011

First-Generation modern MHz experiments

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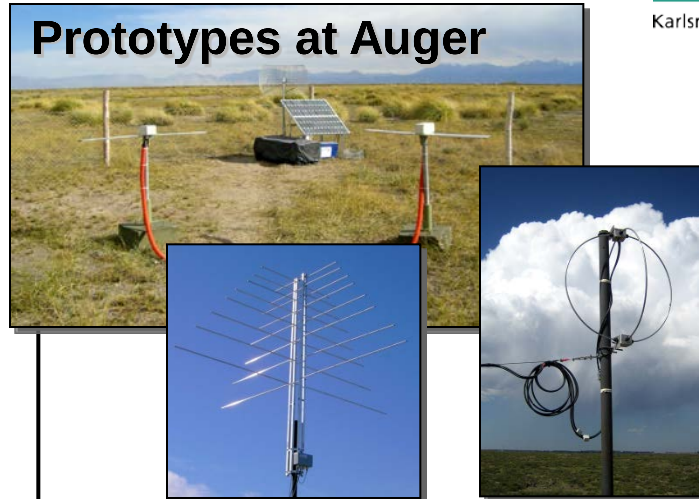
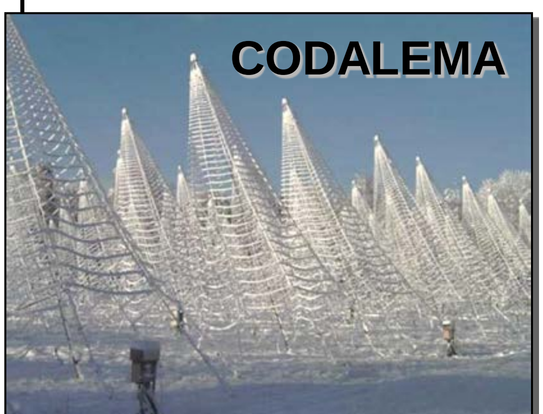
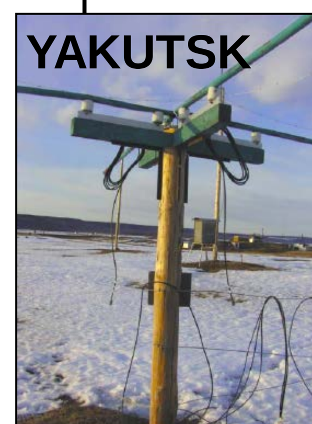


2002 | 2003 | 2004 | 2005 | 2006 | 2007 | 2008 | 2009 | 2010 | 2011 | … | …

Falcke & Gorham propose „geosyn-chrotron approach“





Second-Generation modern MHz experiments

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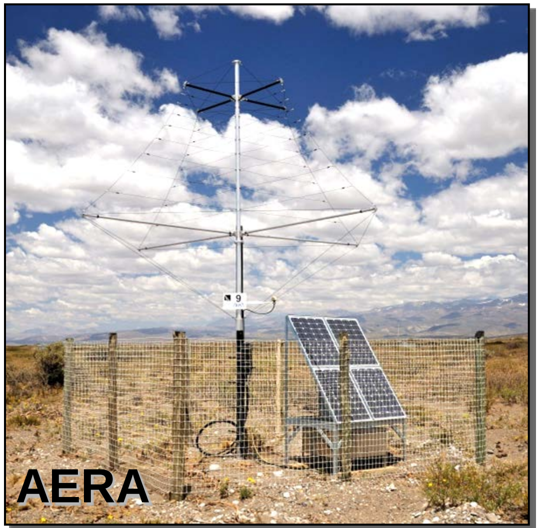

2010	2011	2012	2013

Radio emission physics

Modern models and Monte Carlo codes

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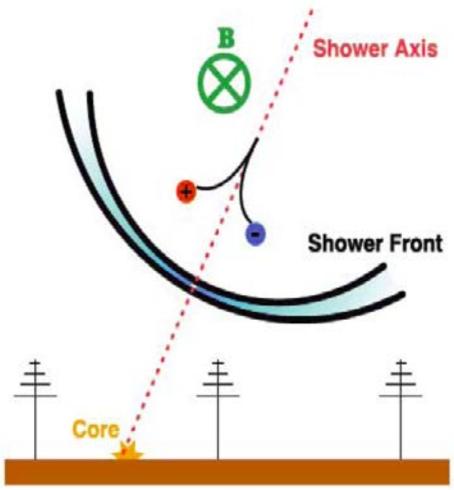
more „microscopic“

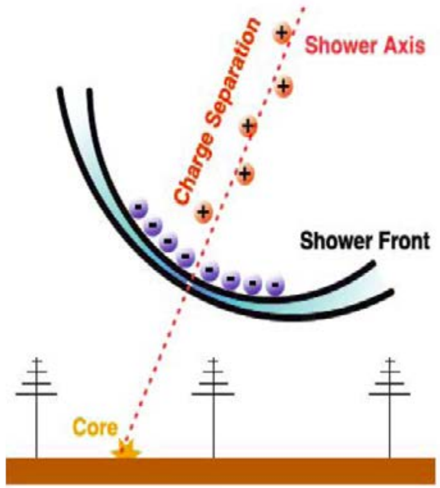
MGMR	time-domain, analytic, parametrized shower, fast, free parameters, summing up „mechanisms“
EVA	time-domain, parameterisation of distributions derived from cascade equations or MC
SELFAS2	time-domain, shower from universality, summing up vector potentials for tracks
REAS3.1	time-domain, histogrammed CORSIKA showers, endpoint formalism
ZHAireS	time- and frequency-domain, Aires showers, ZHS formalism
CoREAS	time-domain, CORSIKA showers, endpoint formalism

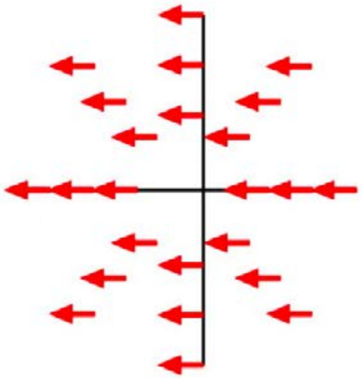
Radio emission physics as predicted by theory



- primary effect: geomagnetic field induces *time-varying* transverse currents

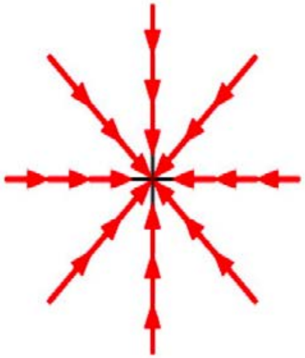
Kahn & Lerche (1967)





Askaryan (1962,1965)

- secondary effect: *time-varying* net charge excess (Askaryan effect)

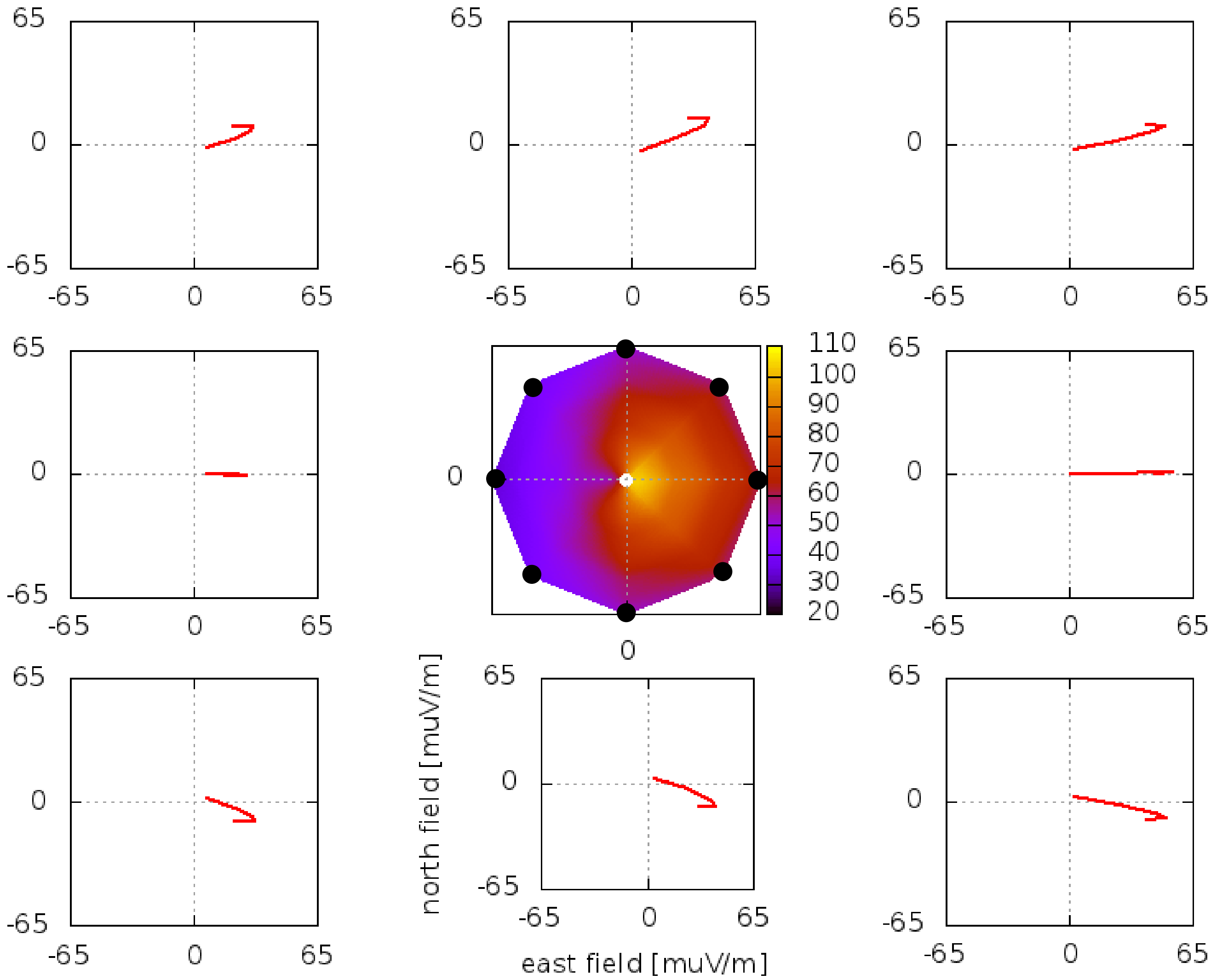


„***v*** x ***B***"

Diagrams by H. Schoorlemmer & K.D. de Vries

„***radial***"

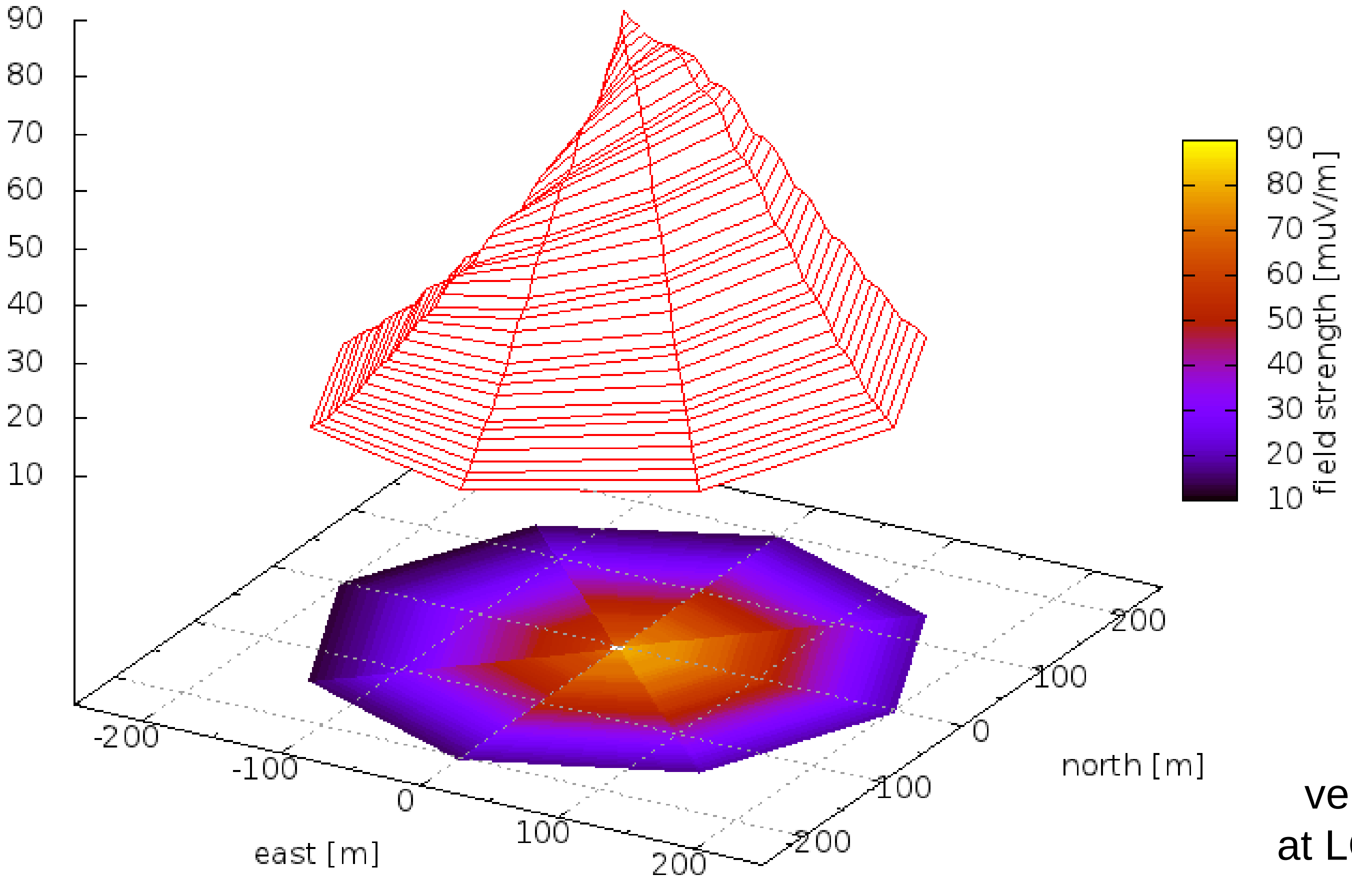
Complexity of signal polarization



- time evolution of electric field vector
- superposition of geomagnetic and charge excess emission leads to *elliptical* polarization

CoREAS simulations, TH et al., ICRC2013, #548

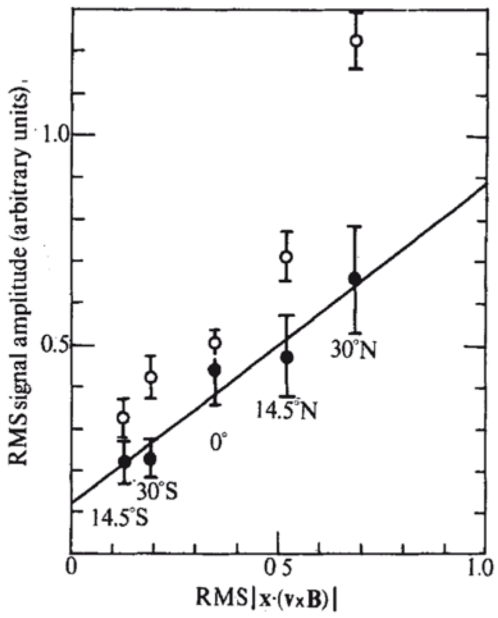
Complexity of radio LDF



vertical iron shower
at LOPES frequencies
simulated with CoREAS

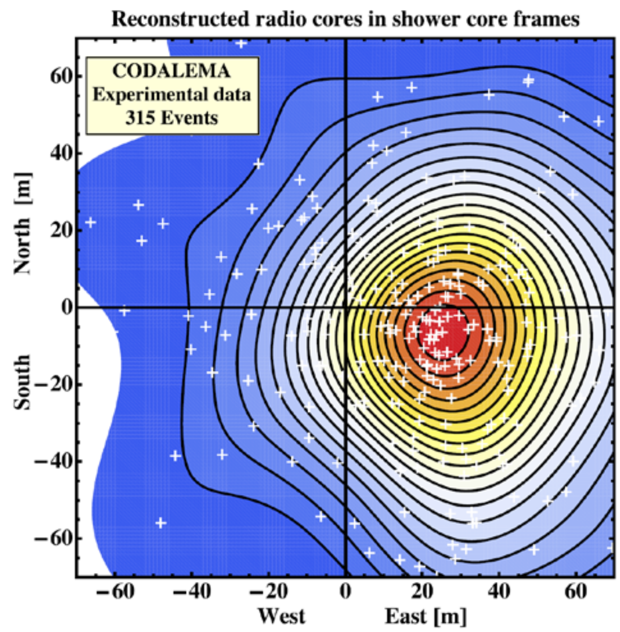
TH et al., ARENA2012

Geomagnetic seen by all – but charge excess?



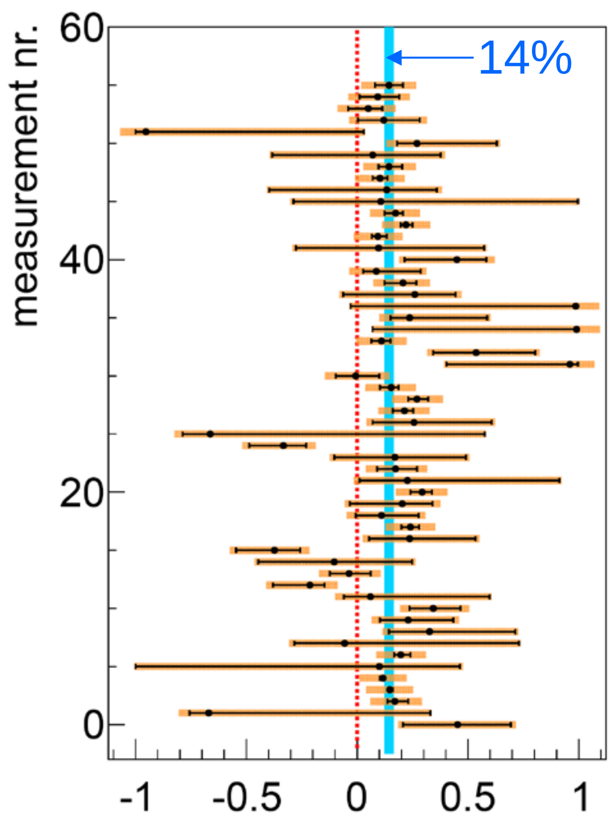
- observation of a non-geomagnetic emission component of 14 ± 6% at 22.5 MHz

Prescott, Hough, Pidcock, Nature (1971)



- CODALEMA reports core-shift ↔ east-west asymmetry ↔ charge-excess at ICRC 2011

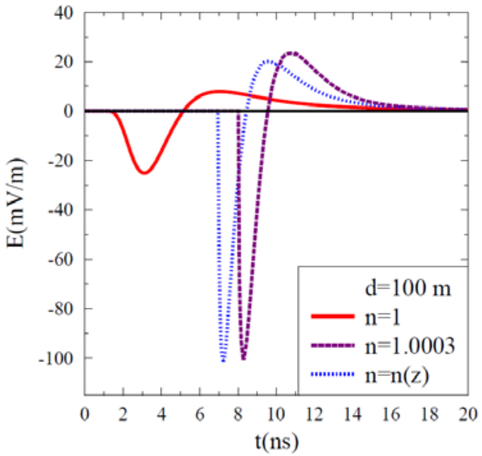
V. Marin et al. (CODALEMA Coll.), ICRC2011



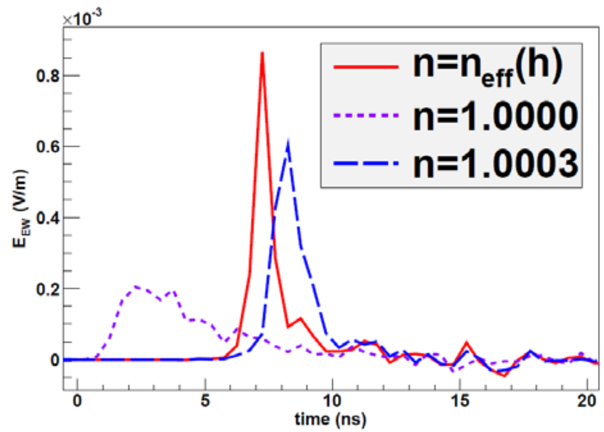
- AERA quantifies radial component to 14 ± 2%

Pierre Auger Coll., ICRC2013, id #661

Refractive index effects

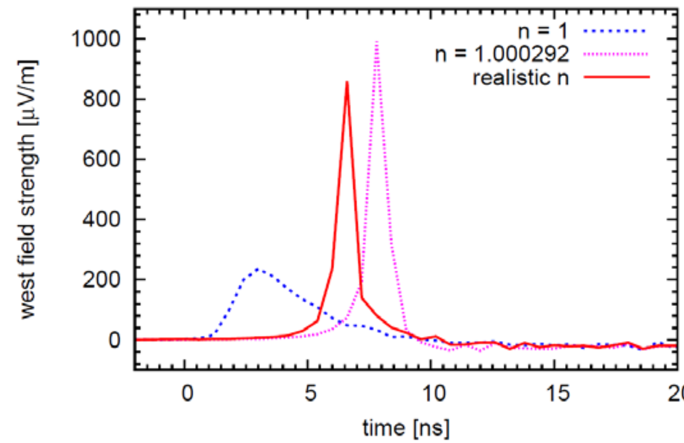


K.D. de Vries et al,
PRD (2010)

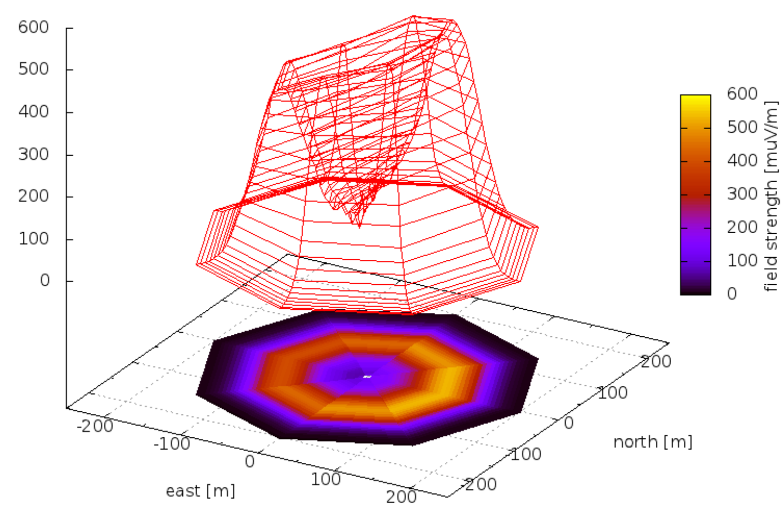


Alvarez-Muniz et al.,
Astrop. Phys. (2011)

M. Ludwig et al., ICRC 2011



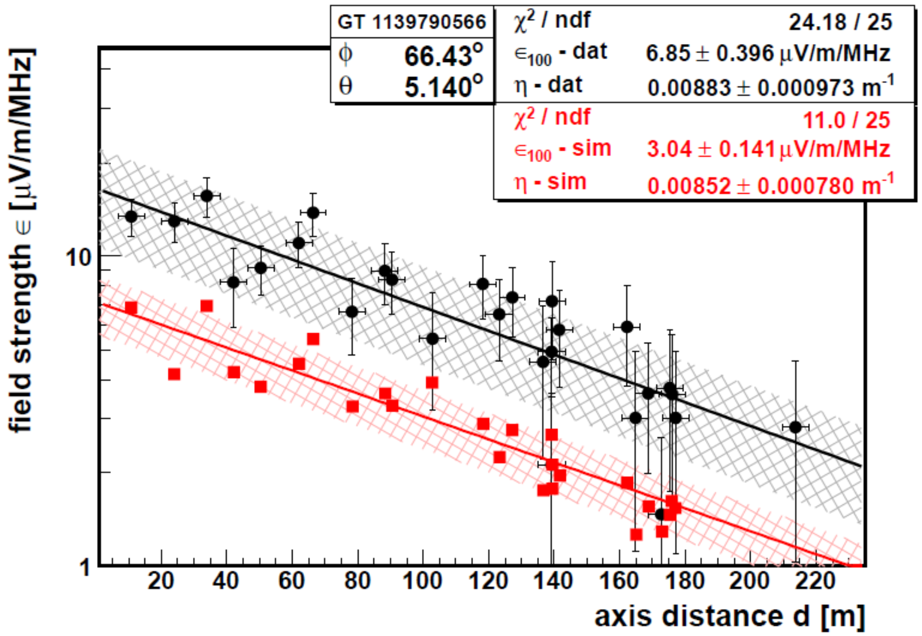
- time compression of radio pulses along the Cherenkov angle
  - power at high frequencies, up to several GHz
  - Cherenkov ring arises



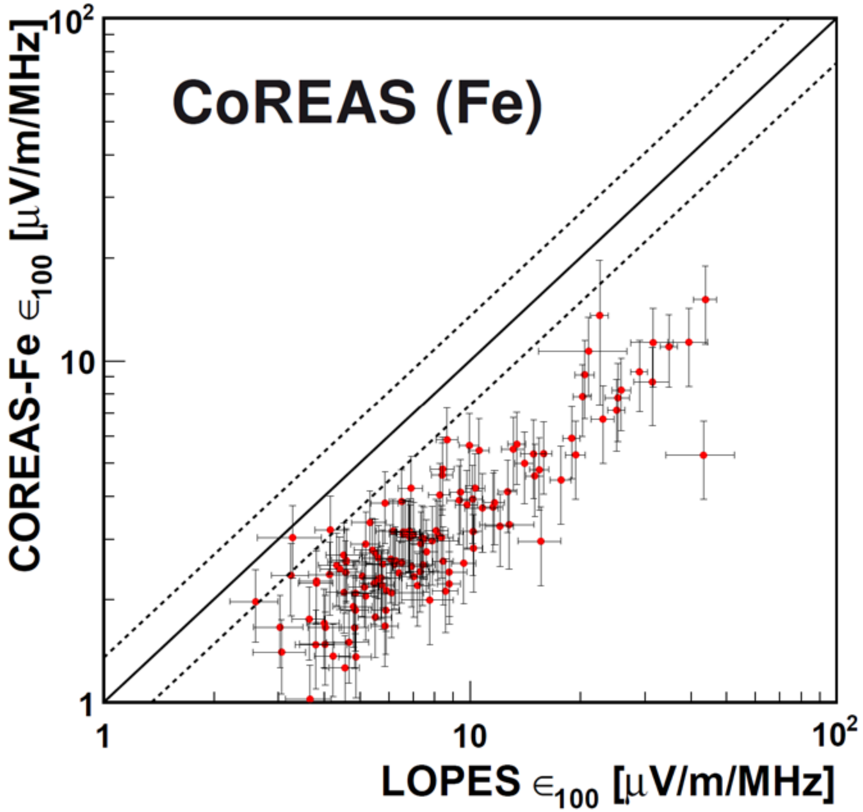
TH et al., ARENA2012

300-1200 MHz

Comparison of simulations with LOPES data

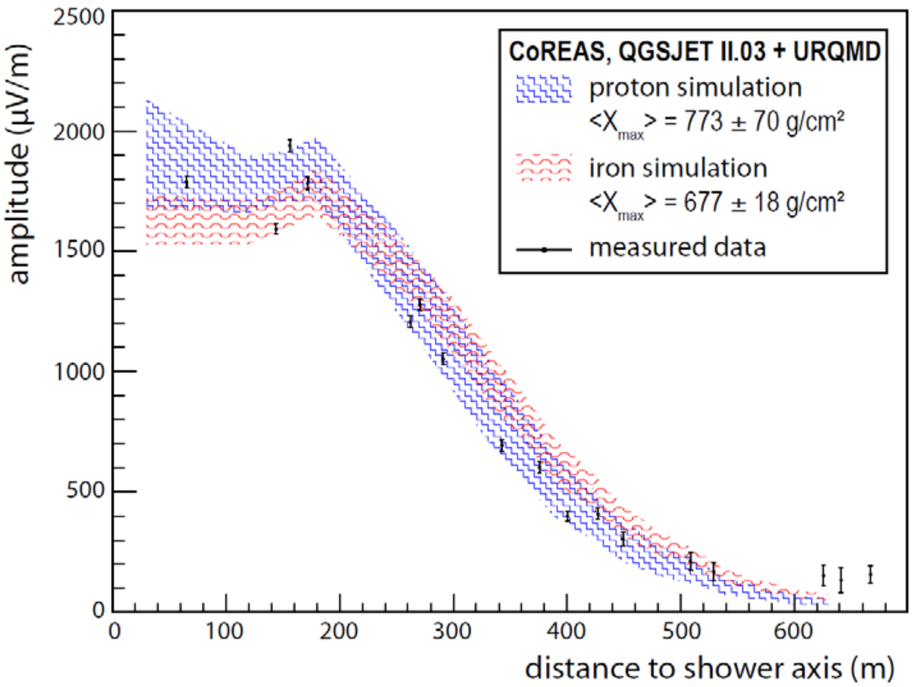


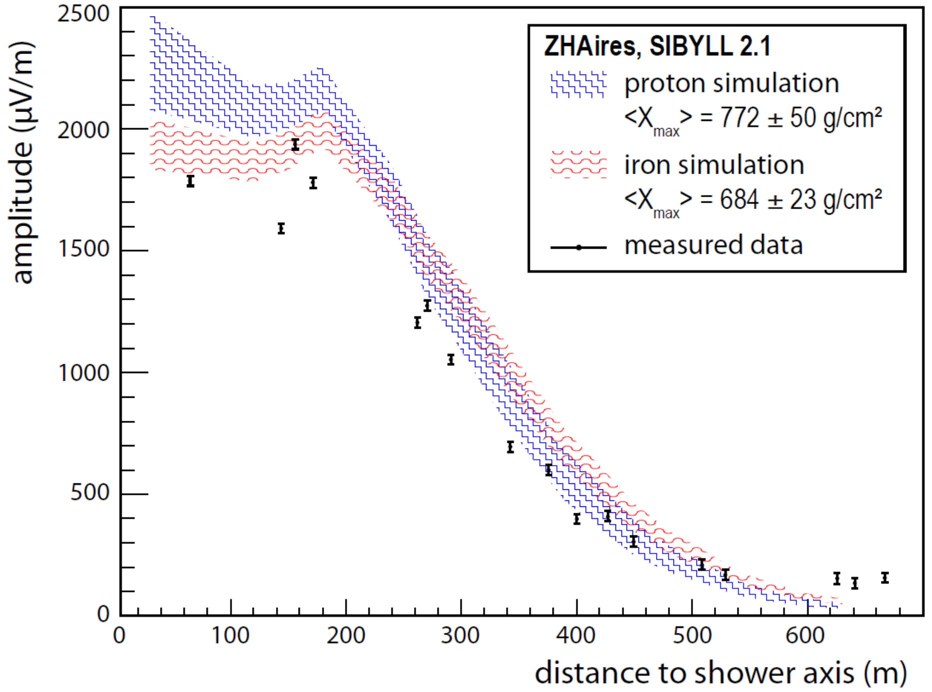
M. Ludwig et al. (LOPES Coll.), ARENA2012



- qualitative agreement with LOPES data, but amplitude mismatch
  - universal factor of ~2 – calibration problem?

Comparison of simulations with AERA data

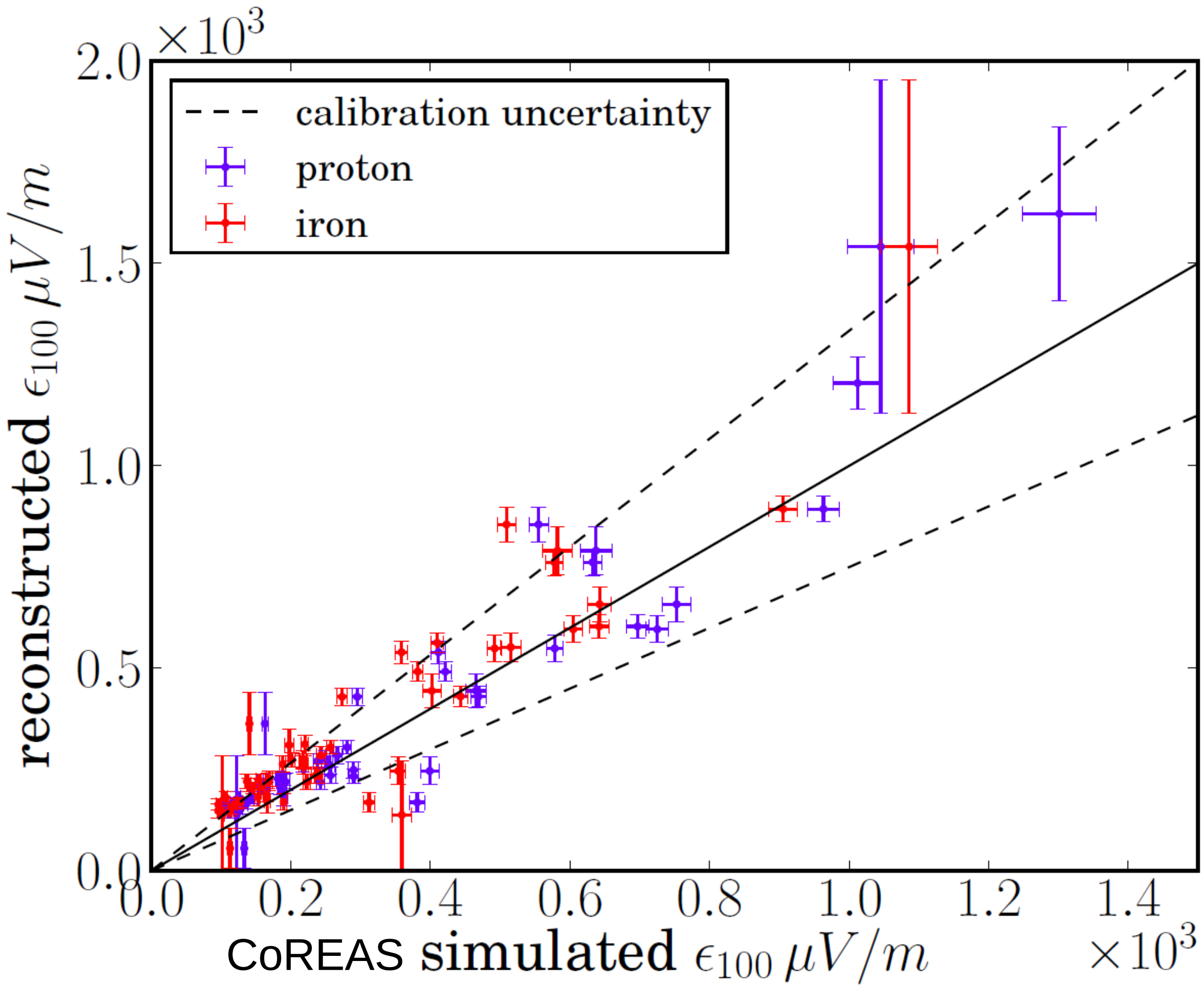




- AERA provides detailed, well-calibrated event data
- simulations can reproduce measurements
  - absolute amplitude
  - complex LDF

Pierre Auger Collaboration, ICRC2013, id #899

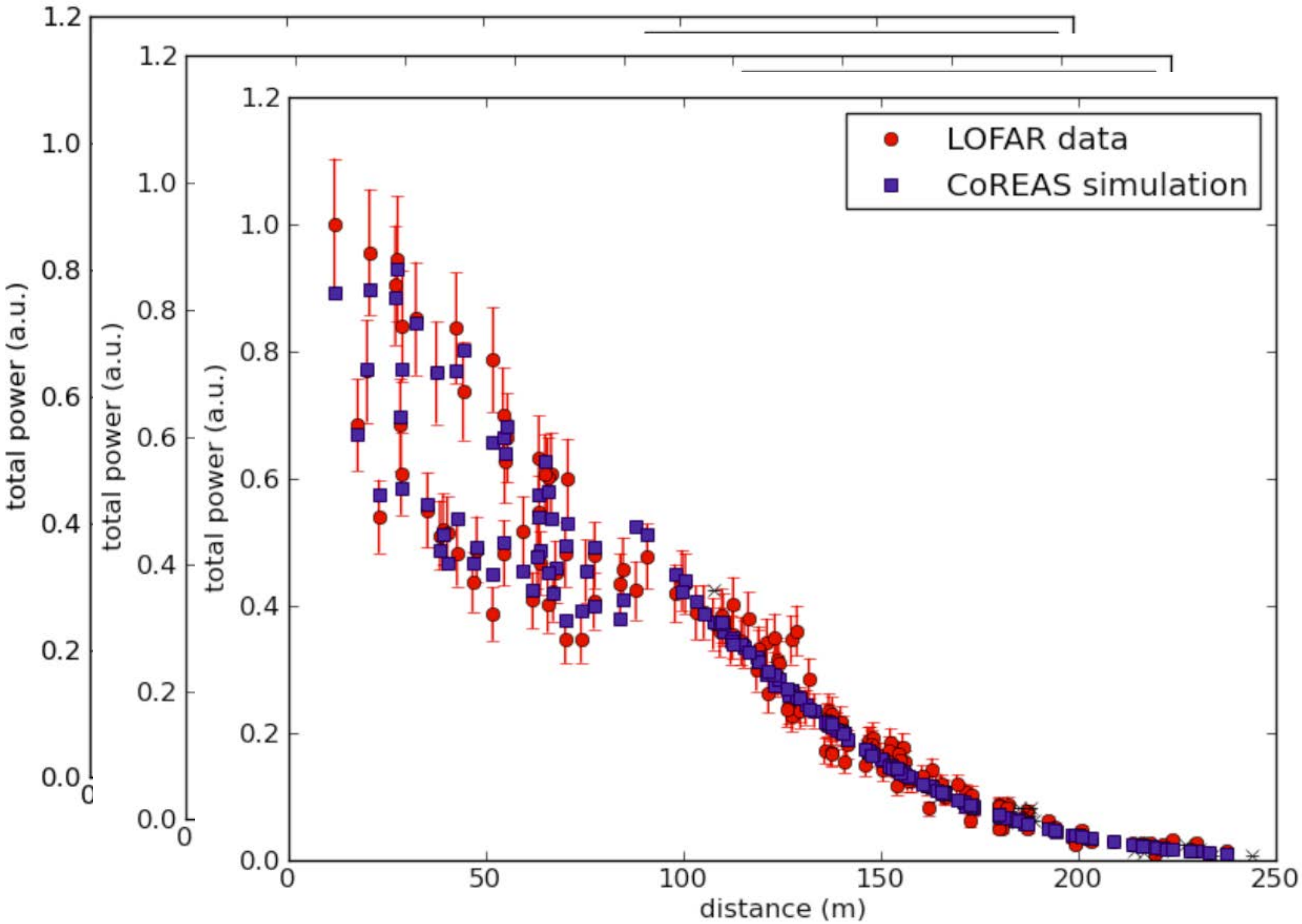
Comparison of simulations with Tunka-Rex data



- absolute amplitudes of CoREAS sims and Tunka-Rex data agree within uncertainties

see talk Y. Kazarina

Comparison of simulations with LOFAR data

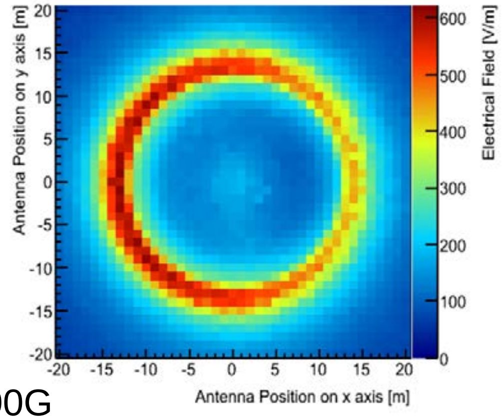


S. Buitink for the LOFAR Collaboration, ICRC2013, id #579

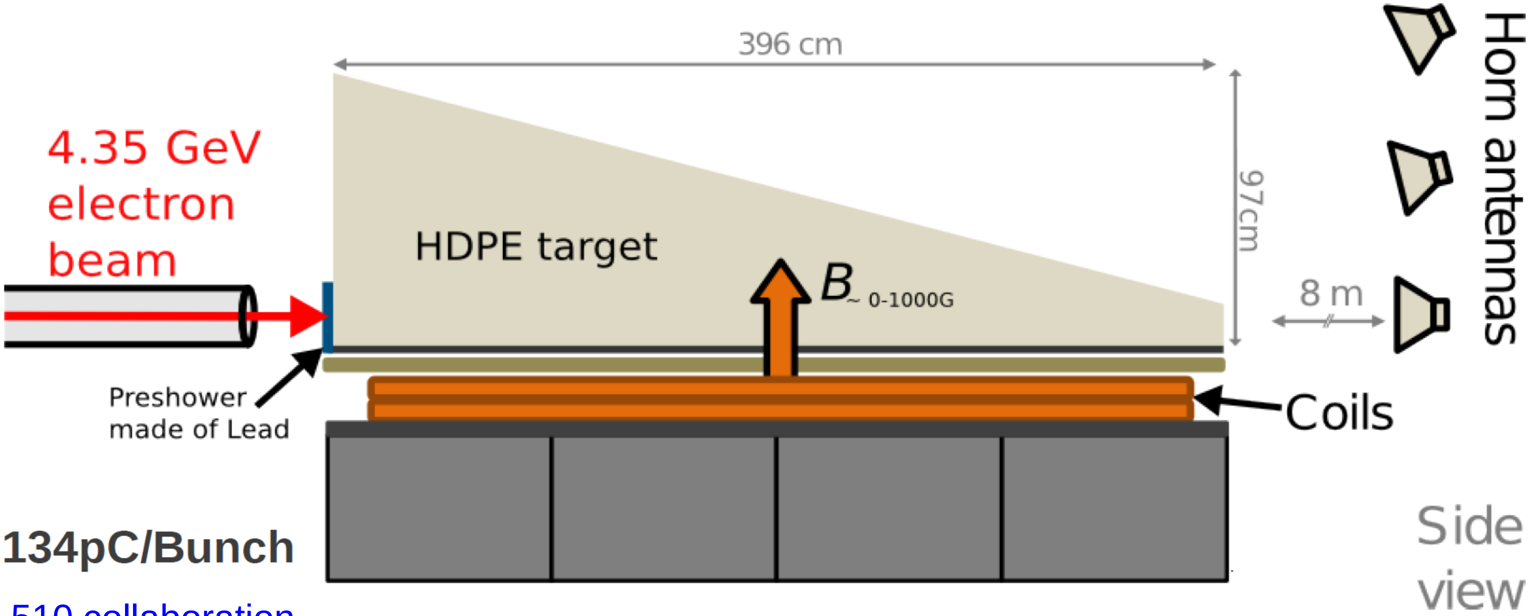
- measurement of individual shower with extreme level of detail
- data can be reproduced by simulations
- see geomagn., charge excess and Cherenkov effects
- but: no calibration of absolute amplitude scale yet

Lab experiment: SLAC T-510

- particle shower in high-density polyethylene
- ANITA (300-1200 MHz) & VHF antennas
- tunable magnetic field up to 1000 G
- verify simulations in a controlled environment



GEANT4 sim, 1000G



~ 134pC/Bunch

T-510 collaboration

Event detection

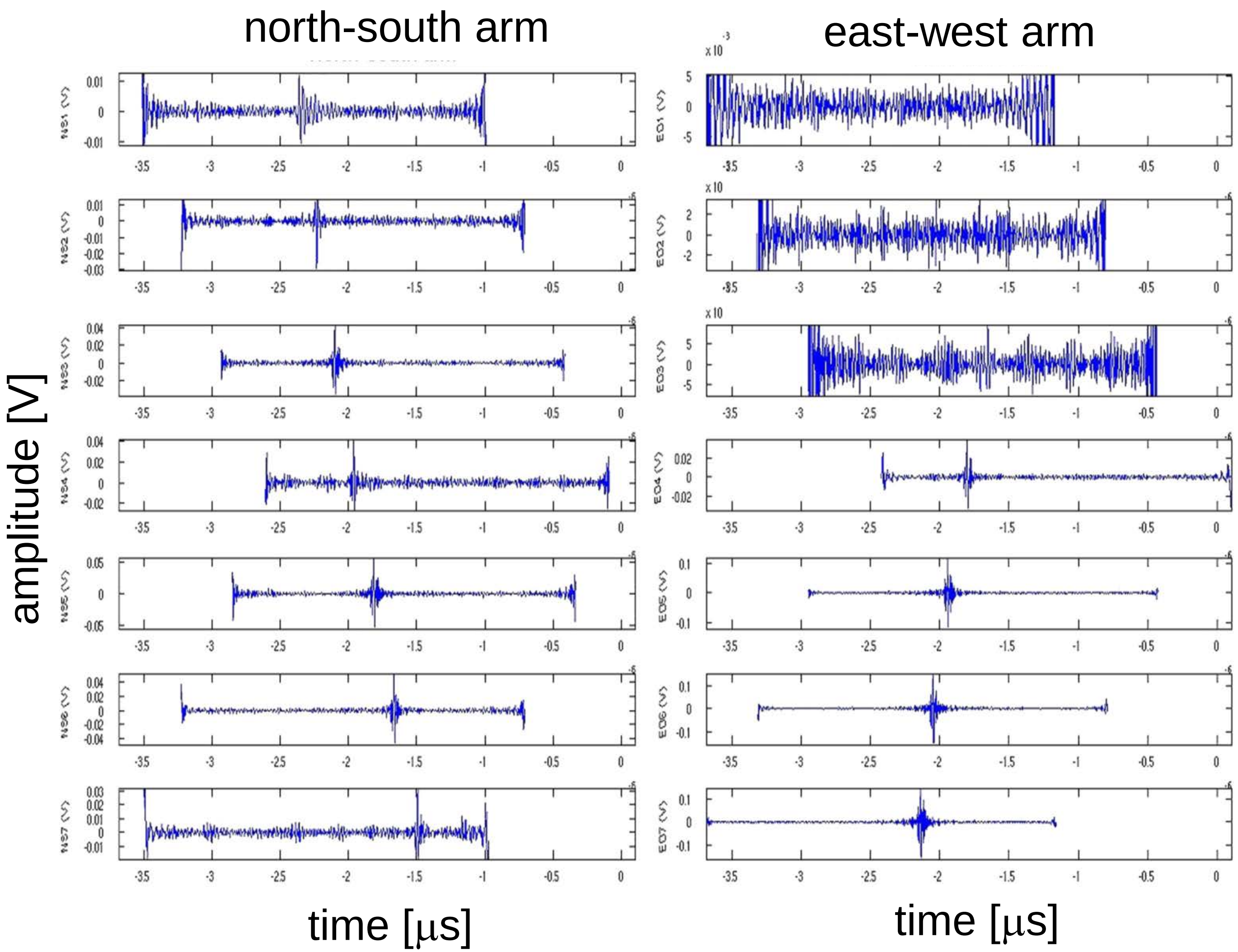
External versus self-triggering

- external triggering works well
  - LOPES
  - CODALEMA
  - AERA
  - LOFAR

Is a self-triggering stand-alone radio detector what we really need? Do we not strive to do hybrid measurements anyway?

- self-triggering is very challenging
  - transient noise (RFI)
- it has been done successfully
  - TREND
  - AERA prototype and AERA
  - CODALEMA-III
- but: radio trigger purity is very low
  - need coincidence with other detector for clear identification
  - or need to use many details of radio signal (LDF, polarization) to identify air showers - what is realistic in a low-level trigger?

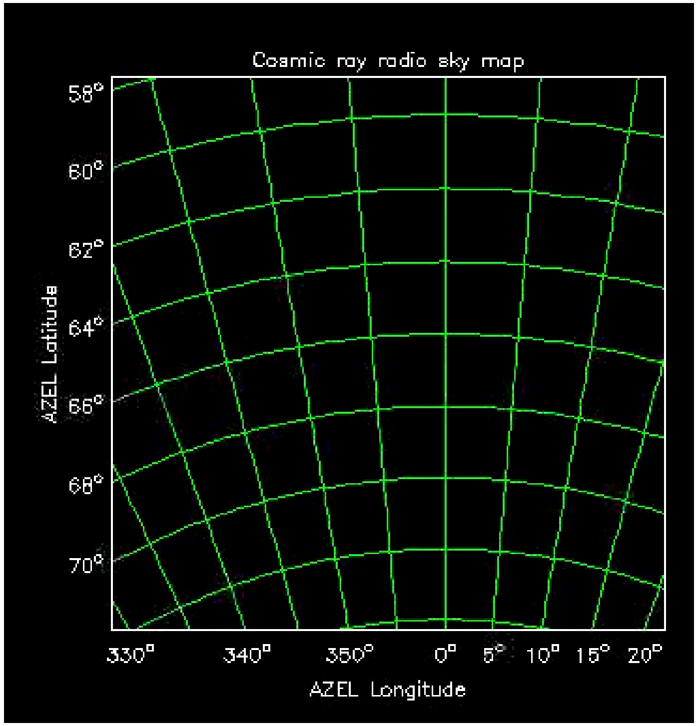
Direction reconstruction with pulse timing



- CODALEMA approach
- analyse channels individually (no inter-ferometry)
- direction from peak timings
- as for particle detectors

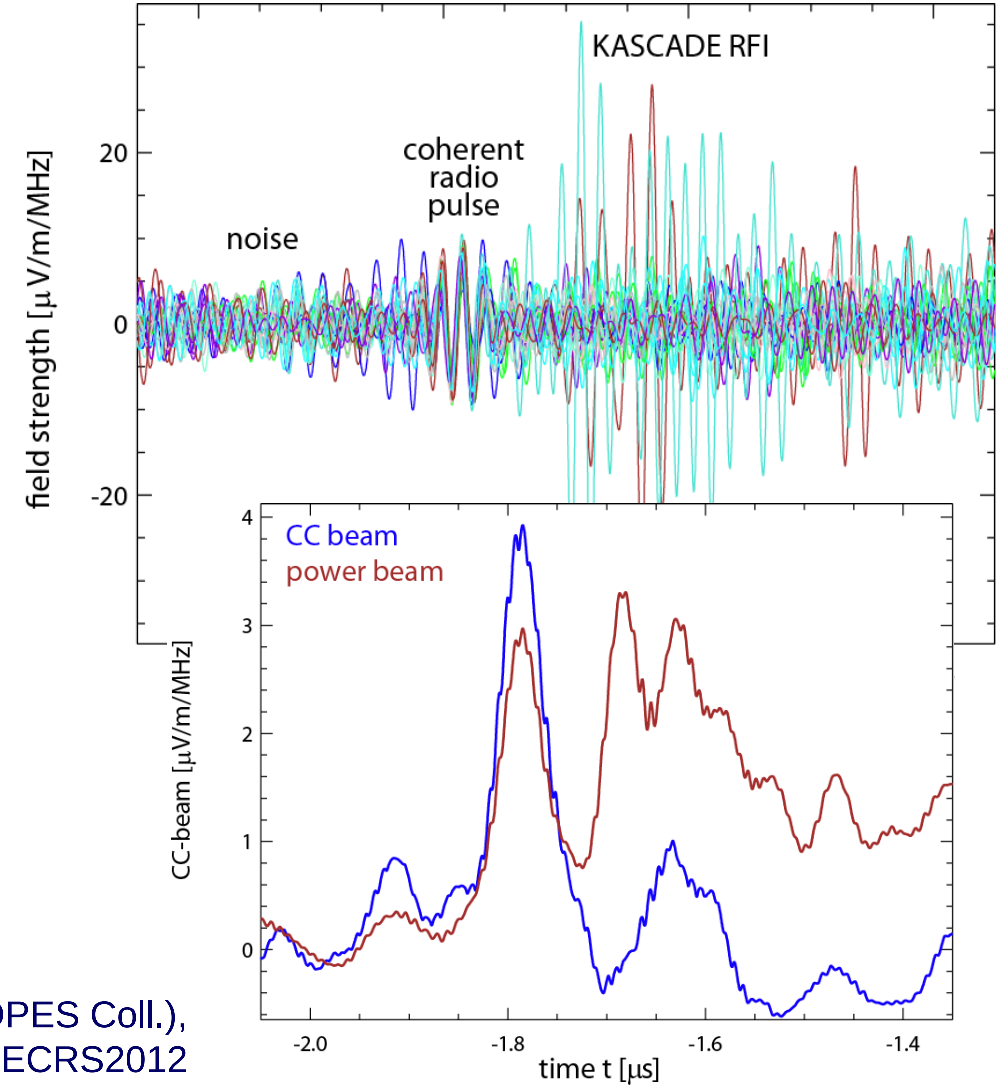
P. Lautridou et al (CODALEMA coll.), ARENA 2008

Direction reconstruction with interferometry



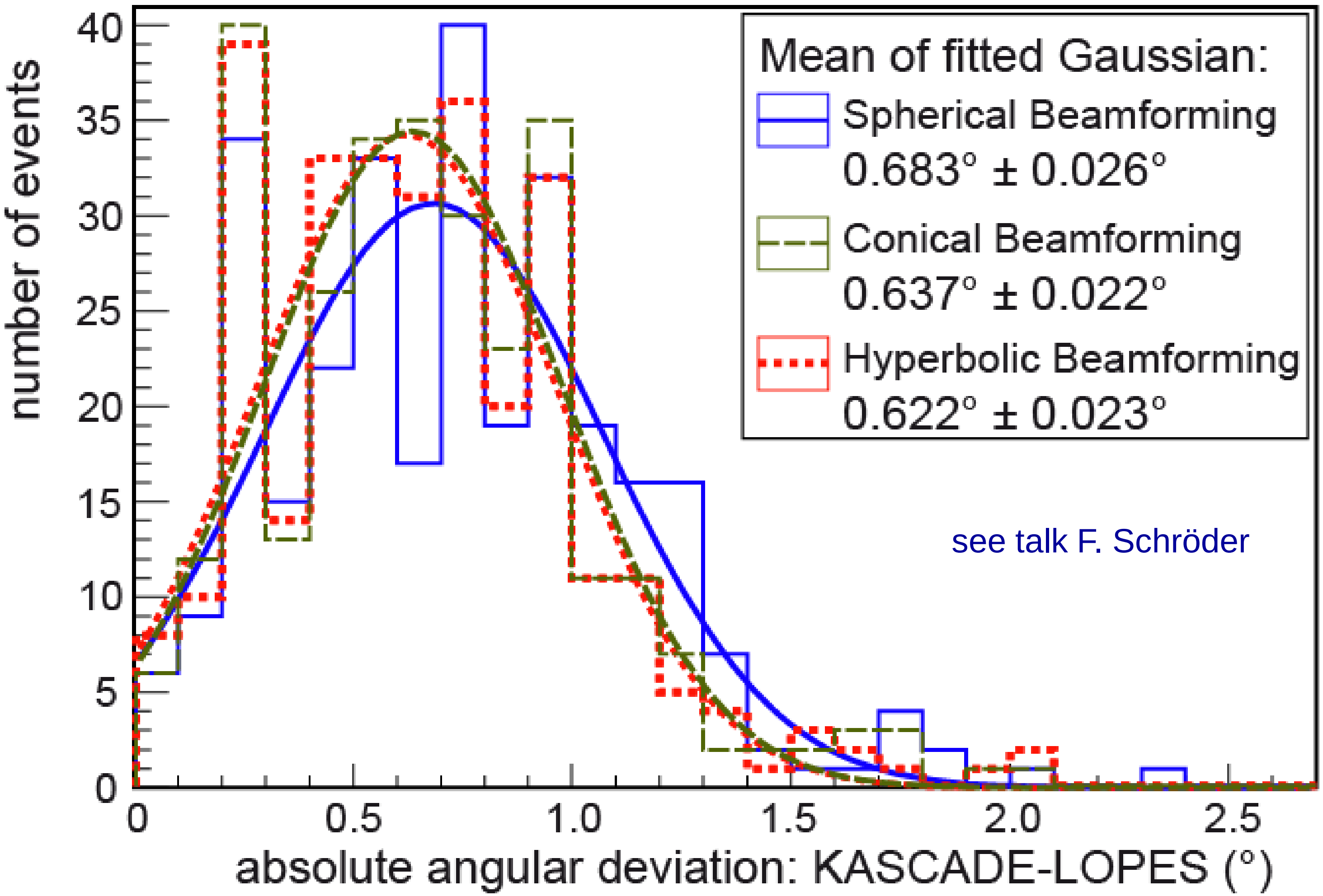
Sky map of a cosmic ray radio flash

H. Falcke et al. (LOPES Coll.), Nature 2005



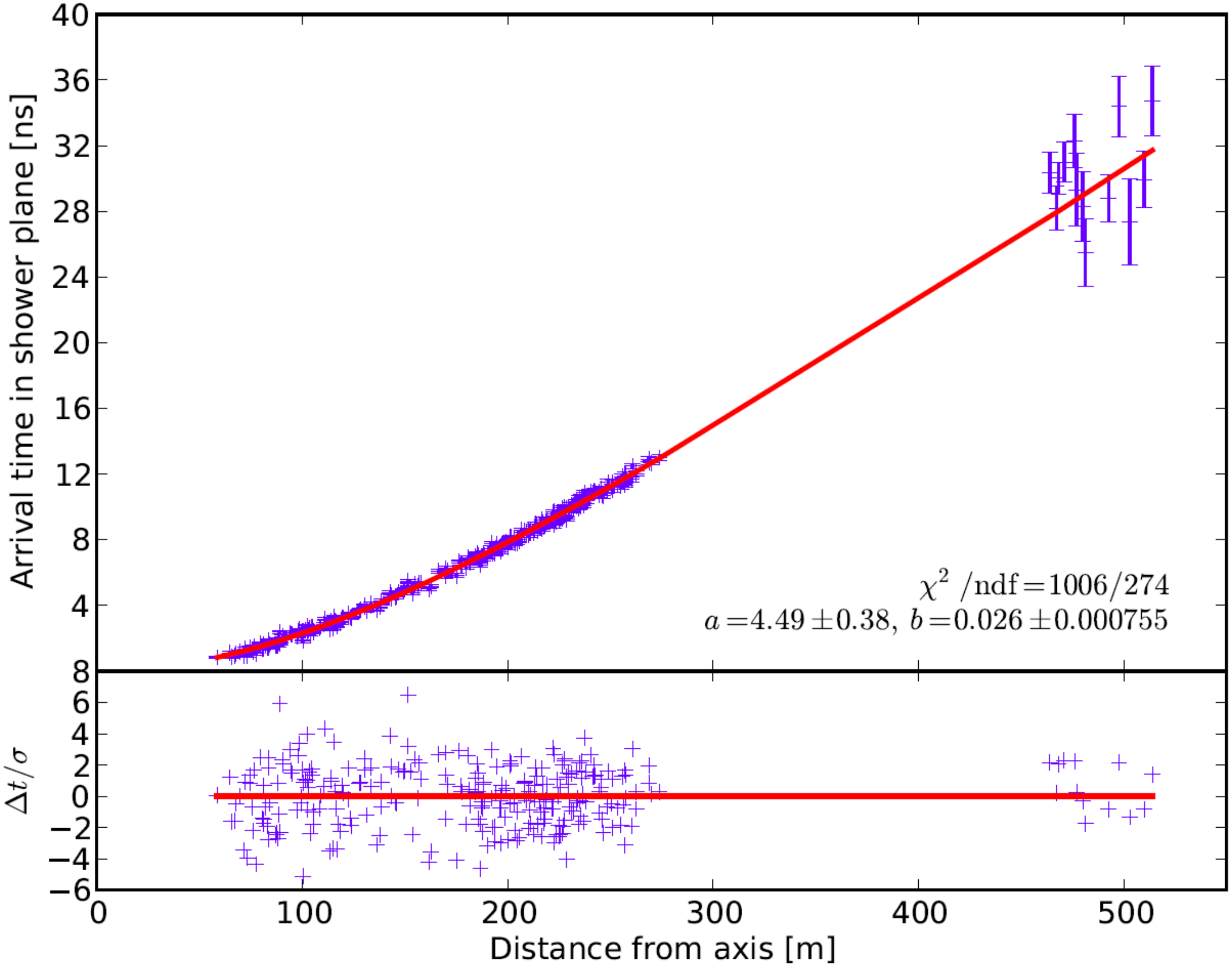
F.G. Schröder et al. (LOPES Coll.), ECRS2012

Accuracy of direction reconstruction



- no bias wrt. KASCADE
- bigger arrays should do even better
- hyperbola works best

Wavefront measured by LOFAR



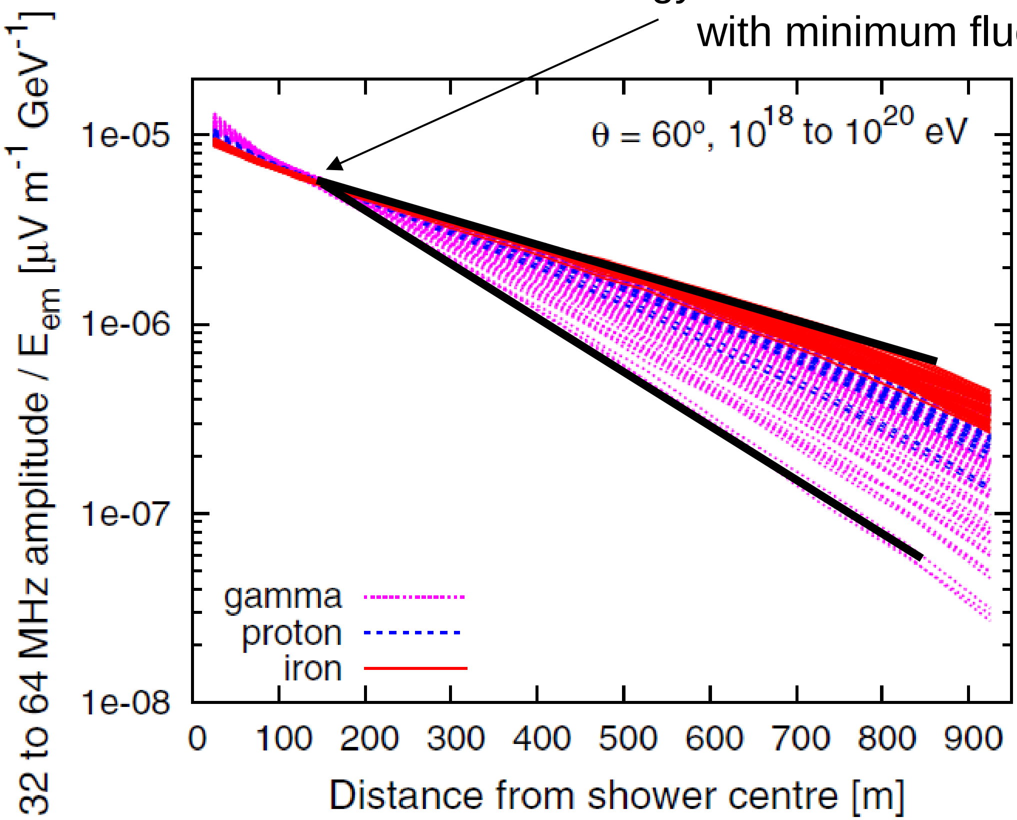
- clearly hyperbolical wavefront

LOFAR, arXiv:1404.3907

Energy determination

Expected energy sensitivity of radio detection

energy determination at distance
with minimum fluctuations

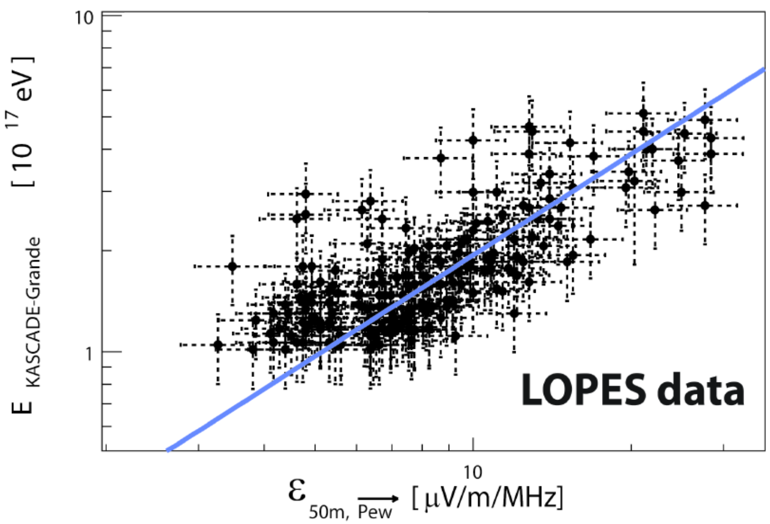


Fe – flat
p – steeper, fluctuating
γ – steepest, fluctuating

TH, Ulrich, Engel
(Astrop. Phys. 2008)

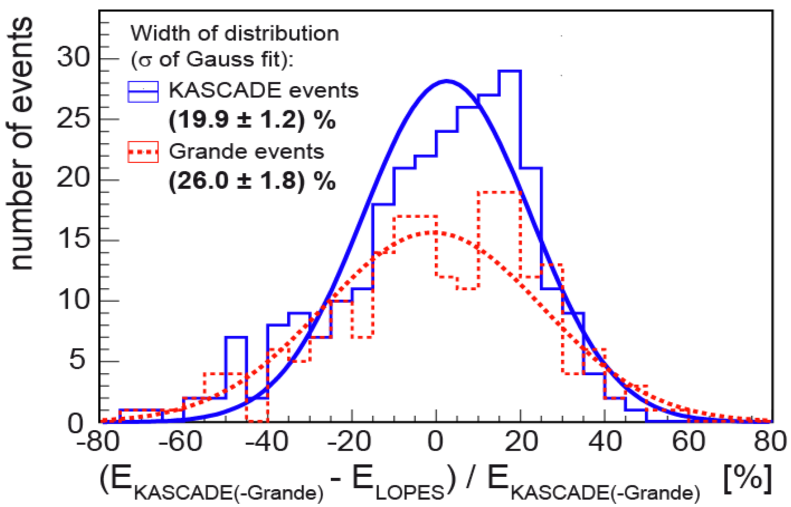
- linear scaling & characteristic distance for best energy estimate

LOPES energy correlation



- linear correlation with 20-25% combined LOPES-KASCADE-Grande energy resolution
  - radio probably better, limited by KASCADE-Grande energy uncertainty of ~20%
  - simulations: ~8% intrinsic

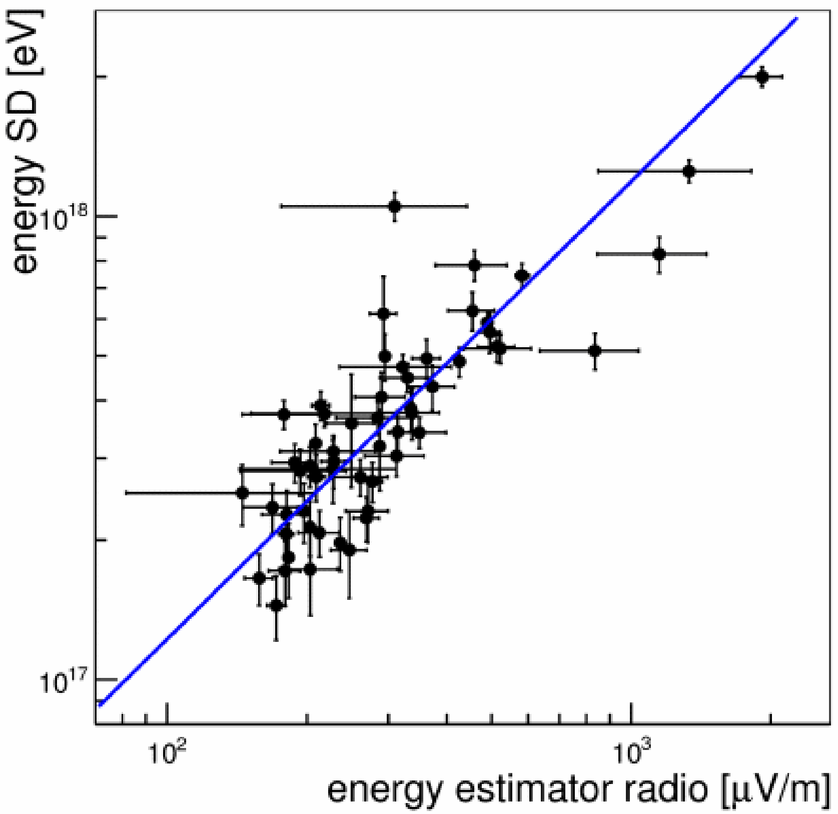
N. Palmieri et al. (LOPES Coll.), ICRC2013, id #439

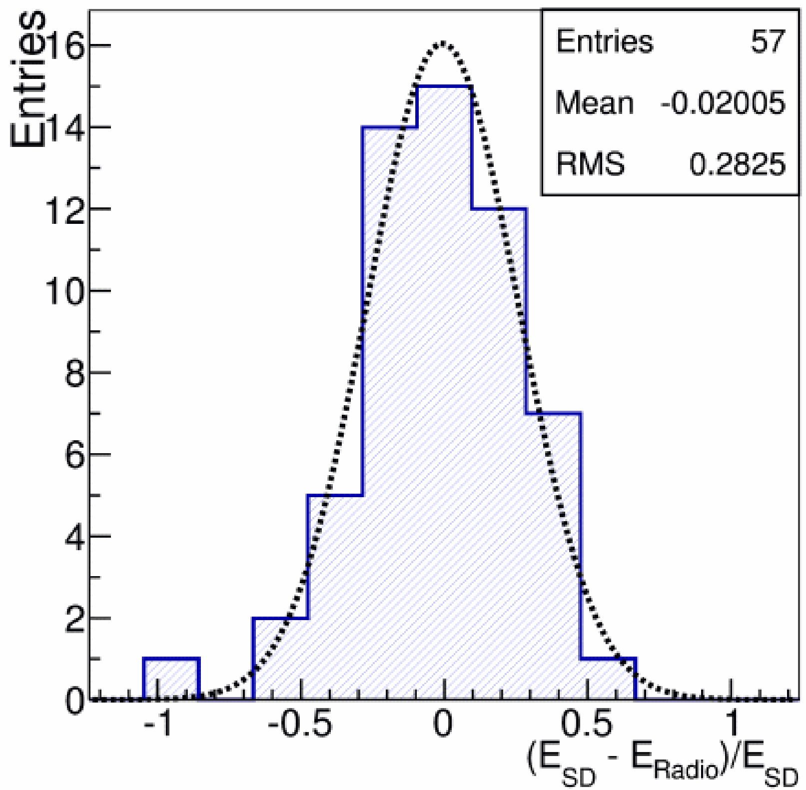


- also works with interferometric analysis, yielding again ~20% uncertainty

F.G. Schröder et al. (LOPES Coll.), ARENA2012

AERA energy correlation

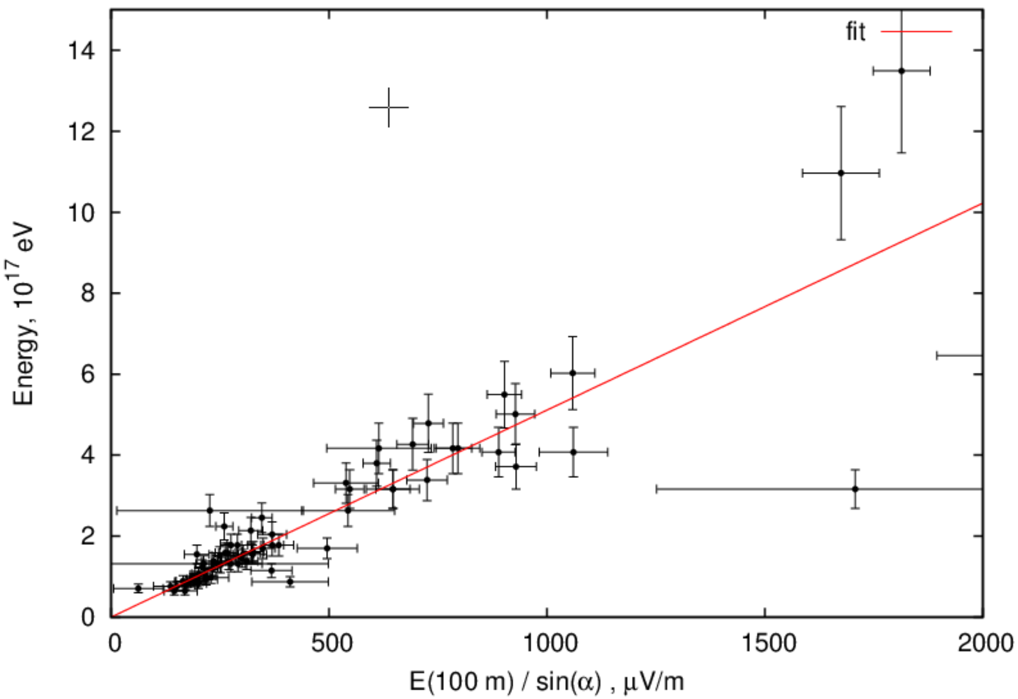


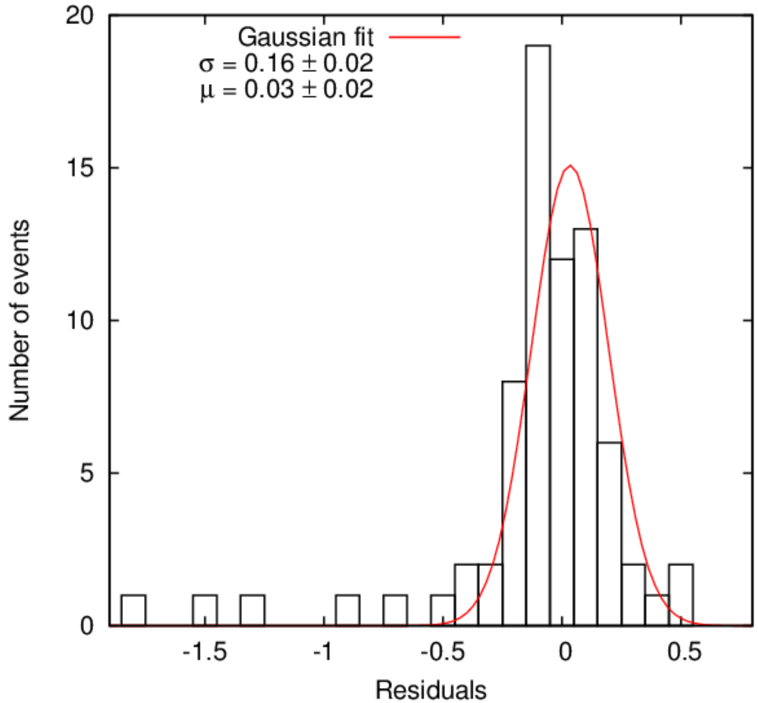


- amplitude at ~110 m distance yields combined surface detector – radio uncertainty of ~25-30%

see talk Q. Dorosti

Tunka-Rex energy correlation





- radio amplitude at 100 m has only ~16% deviations from optical Cherenkov detector energy

see talk Y. Kazarina

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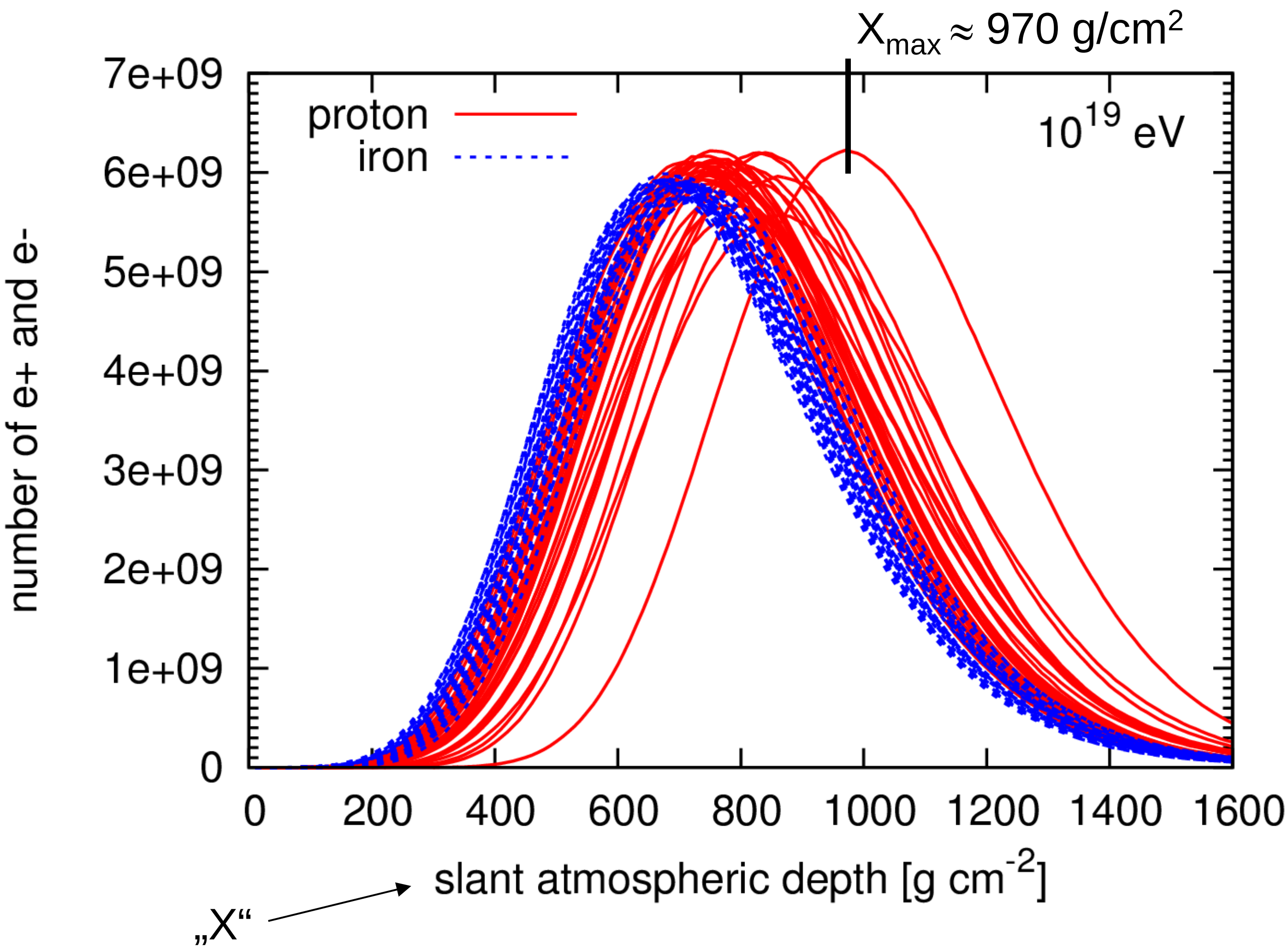
Mass sensitivity

Depth of shower maximum (Xmax) and mass

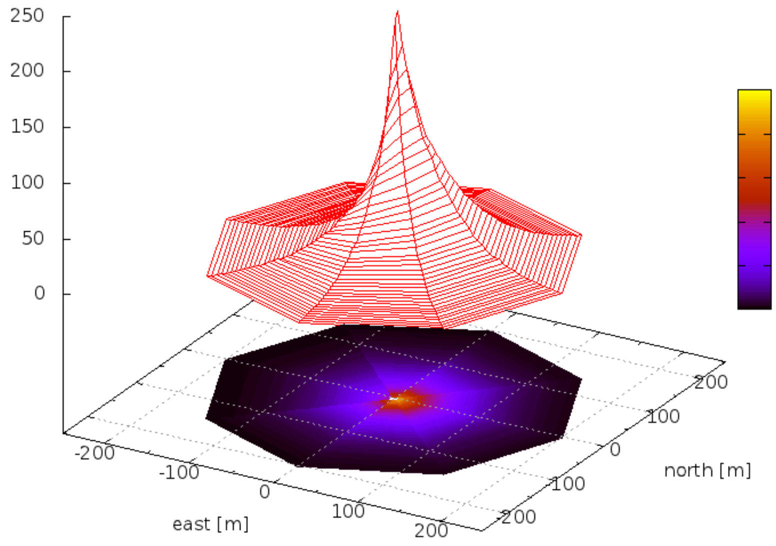


- X_{max} and RMS(X_{max}) provide information about cosmic ray mass
- directly measured by fluorescence detectors, resolution ≈15-20 g/cm^2

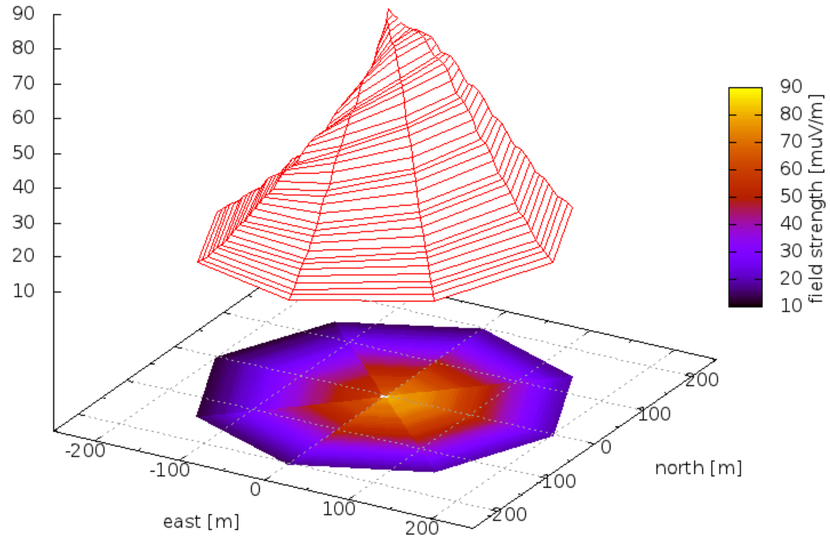
Lateral distribution as probe for composition

- simulations for proton and iron primaries show systematic differences

TH et al., ARENA2012



vertical proton shower
at LOPES frequencies
simulated with CoREAS



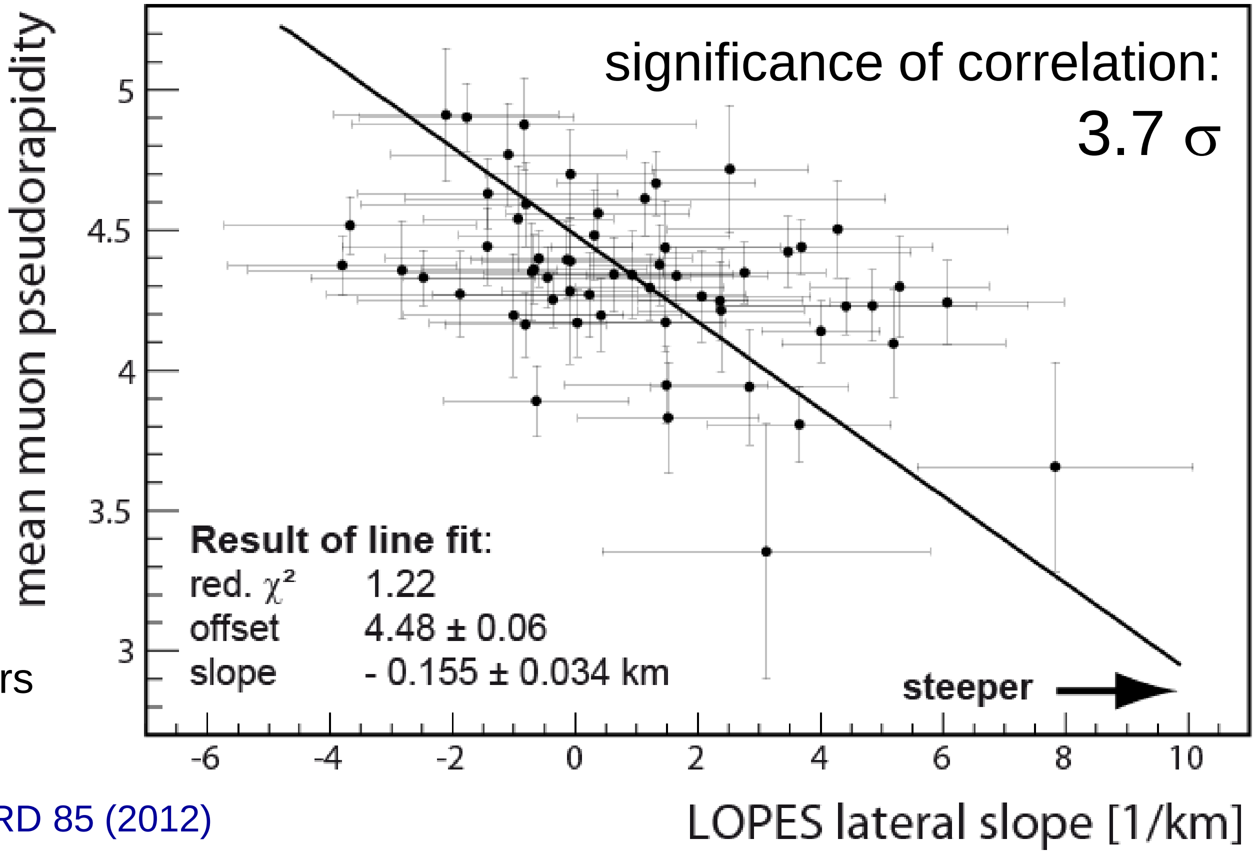
vertical iron shower
at LOPES frequencies
simulated with CoREAS

Experimental proof from LOPES

- radio is sensitive to longitudinal shower development
  (direct sensitivity to geometrical distance)
- Sensitivity to geometrical distance implies X_{max} sensitivity

old showers

young showers

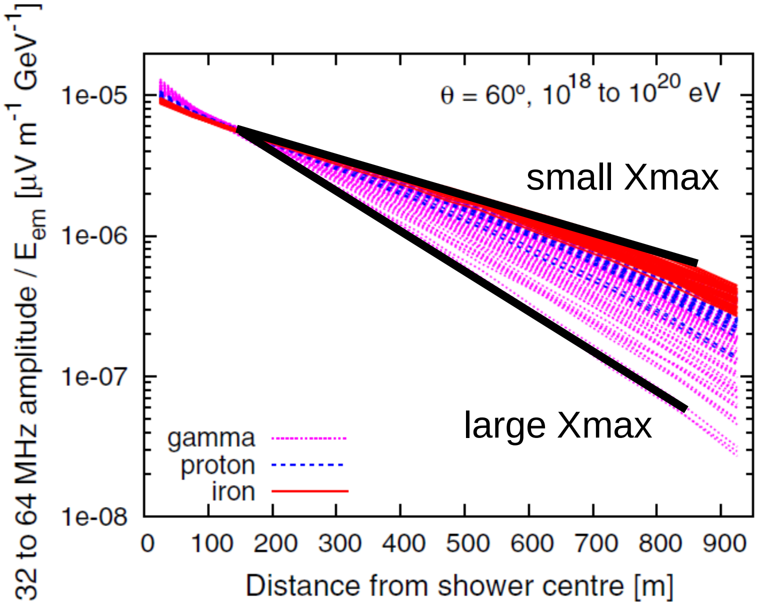


59 events:
after corr. for axis distance + zenith angle

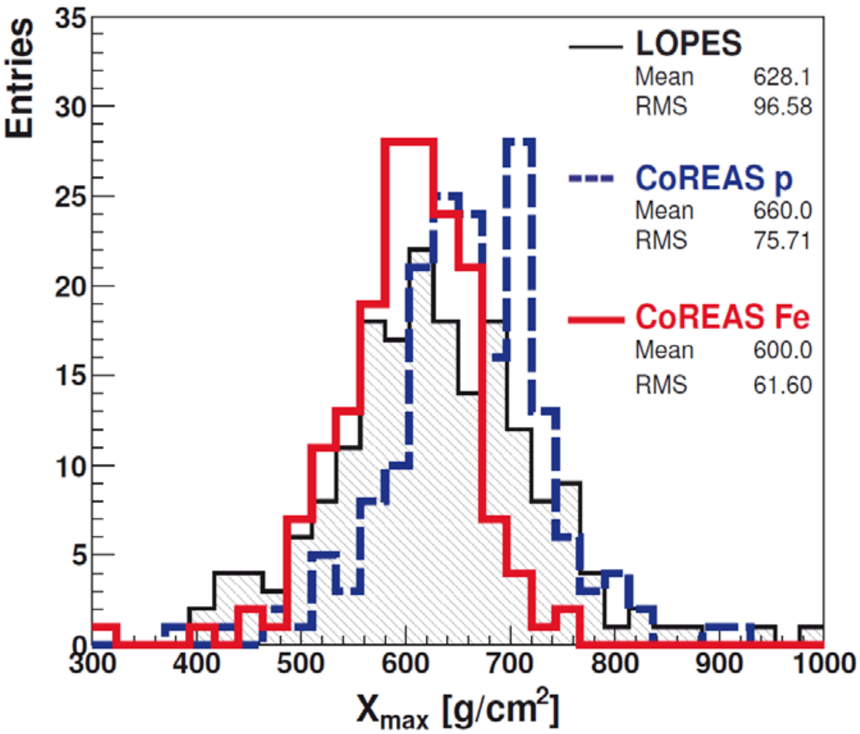
LOPES Coll. PRD 85 (2012)

Xmax reconstruction with LOPES

- with simulations, radio LDF slope can be related to Xmax
- using parameterisations derived with CoREAS simulations, Xmax is estimated for each individual LOPES event (method $\sigma_{Xmax} \sim 50$ g/cm^2)

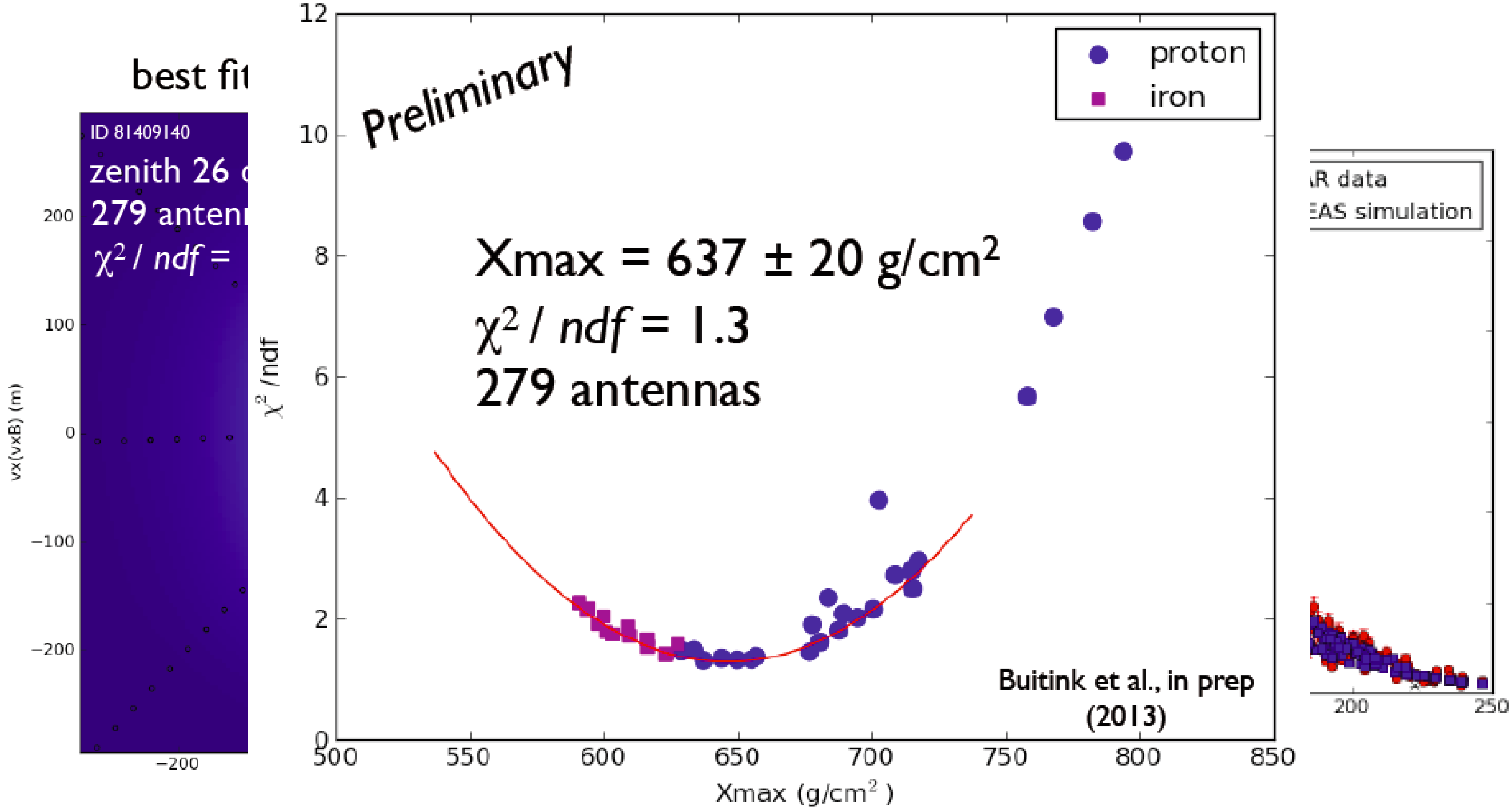


TH, Ulrich, Engel (Astrop. Phys. 2008)



N. Palmieri et al. (LOPES Coll.), ICRC2013, id #439

Global fit of particle and radio LDF with LOFAR

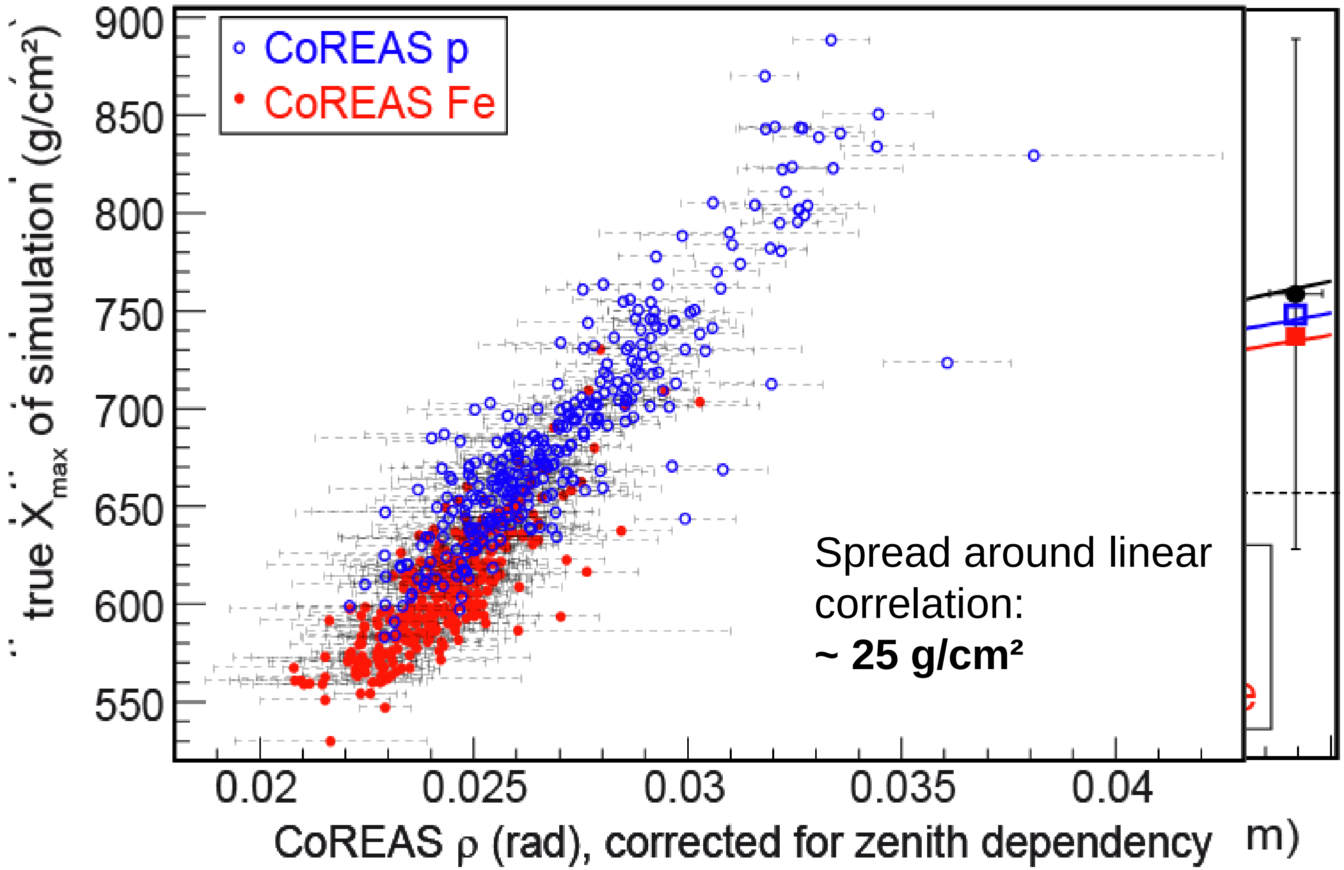


- global fit to CoREAS simulations gives Xmax to ~20 g/cm^2

S. Buitink for the LOFAR Collaboration, ICRC2013, id #579

X_{max} via radio wavefront

- infer pulse arrival times relative to plane wave
- determine **cone angle** from fit → value of **Xmax**



see talk F. Schröder

Contents

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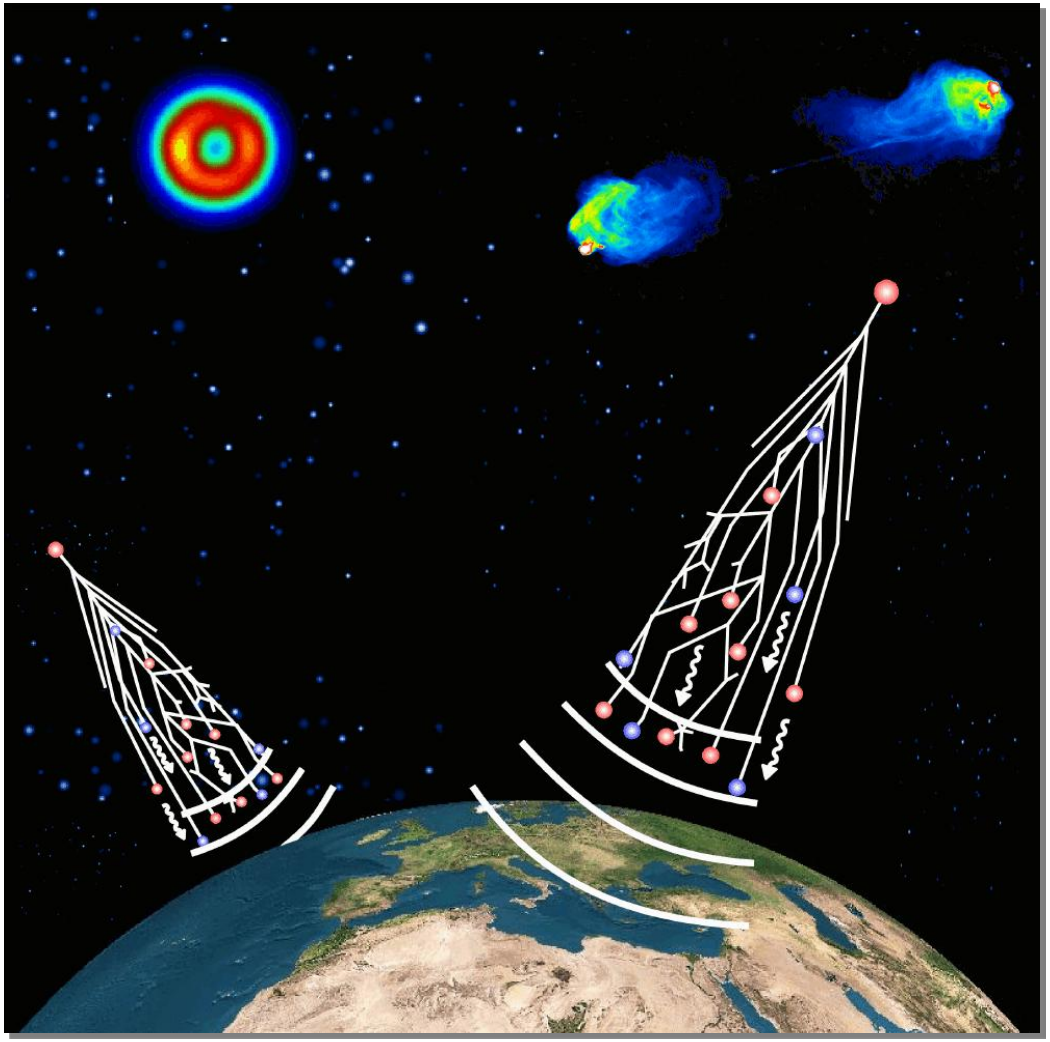
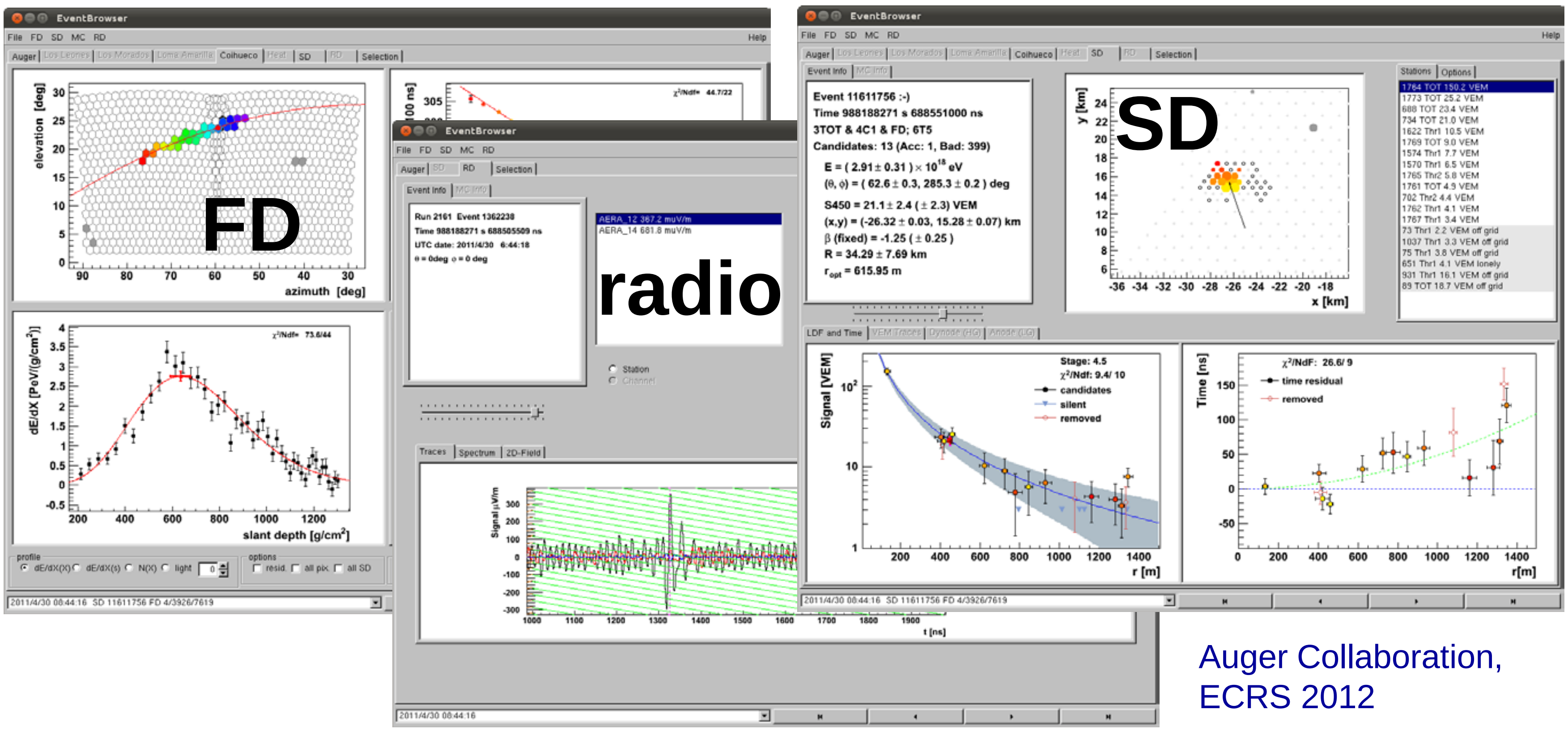
- digital radio detection of cosmic rays
- future directions



Expectations for the new experiments

- LOFAR: details of emission physics, global fits to data including Xmax
- AERA: high energies, Xmax correlation with fluorescence data
- Tunka-REX: economic, Xmax correlation with optical Cherenkov data

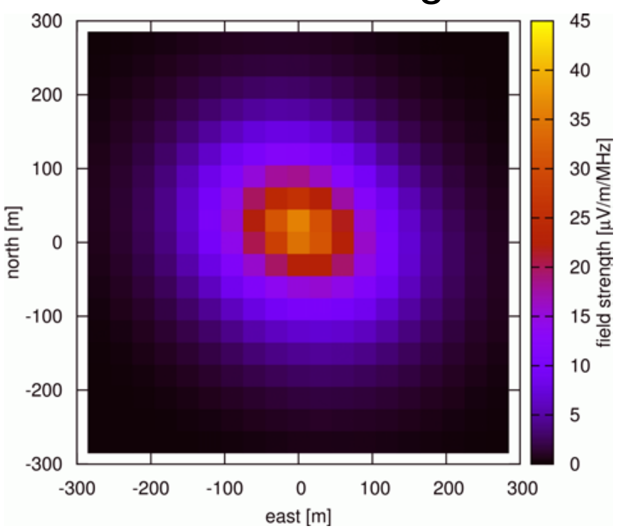


Auger Collaboration, ECRS 2012

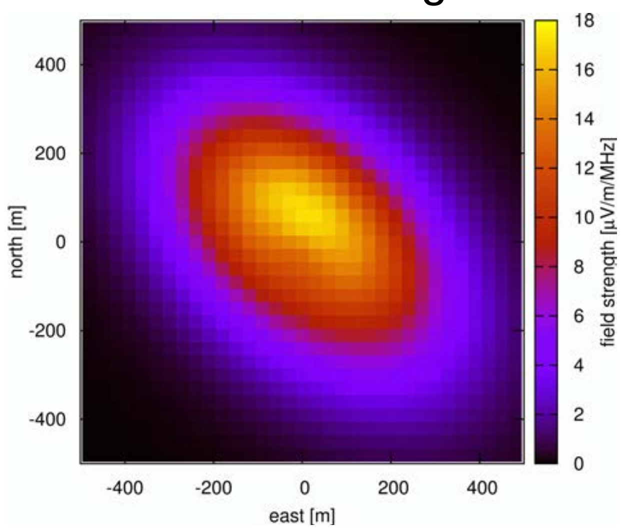
Large area needs large antenna spacings

- radio detection works well, but illuminated area is usually limited
  - investigate inclined showers
  - investigate lower frequencies
  - investigate hybrid analysis with single radio antenna
    - Xmax from pulse shape, spectral index?
    - Xmax from wavefront timing?

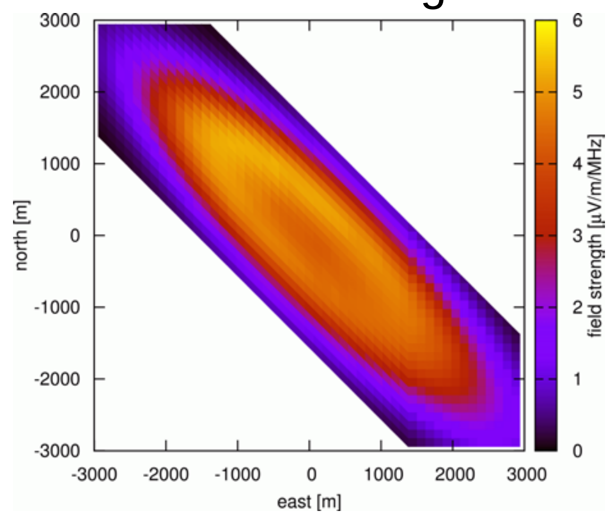
30° zenith angle



50° zenith angle



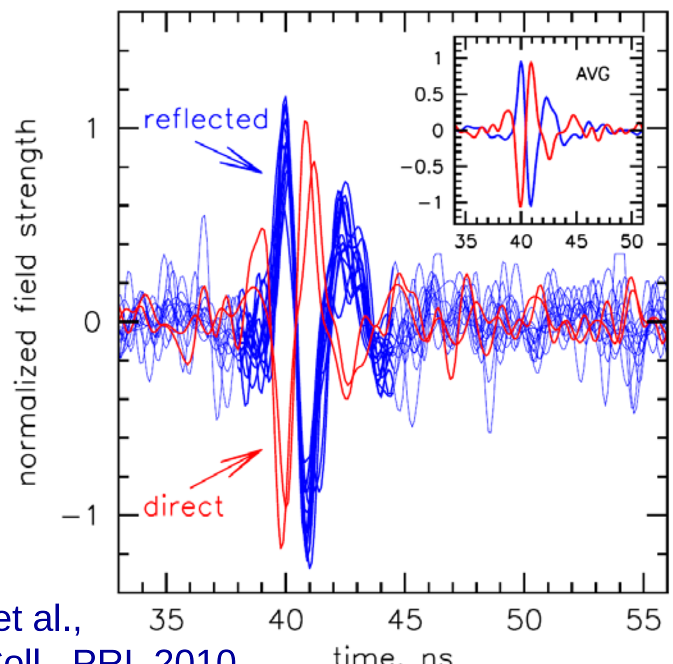
75° zenith angle



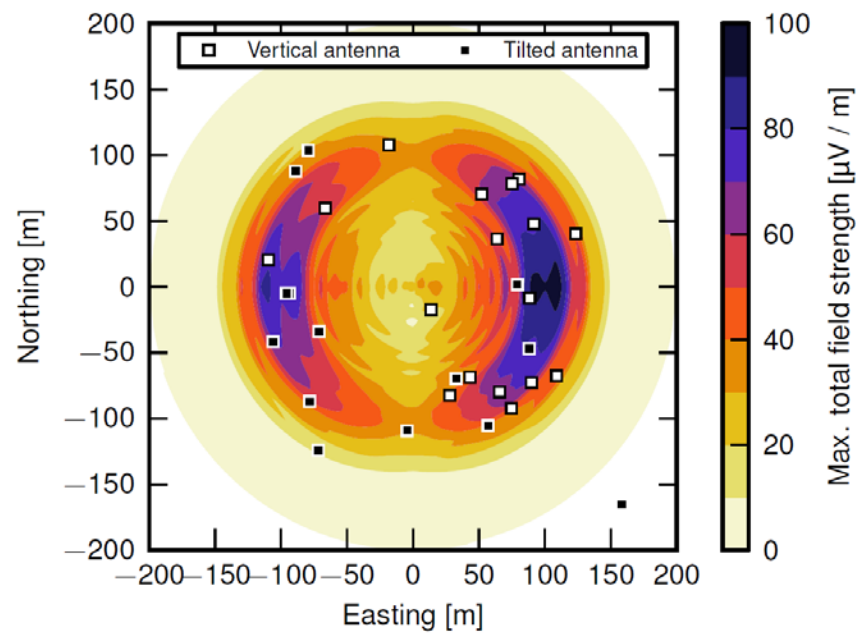
TH et al., ICRC2013, id #548

High-frequency measurements

- ANITA has detected 16 CR events during its 2nd flight (300-1200 MHz)
- CROME has detected 30 cosmic ray events (3400-4200 MHz)
- emission can likely be explained by Cherenkov-compressed MHz signal
- Xmax can be determined from Cherenkov ring diameter
- limited solid angle, but may still be interesting (see SWORD, …)



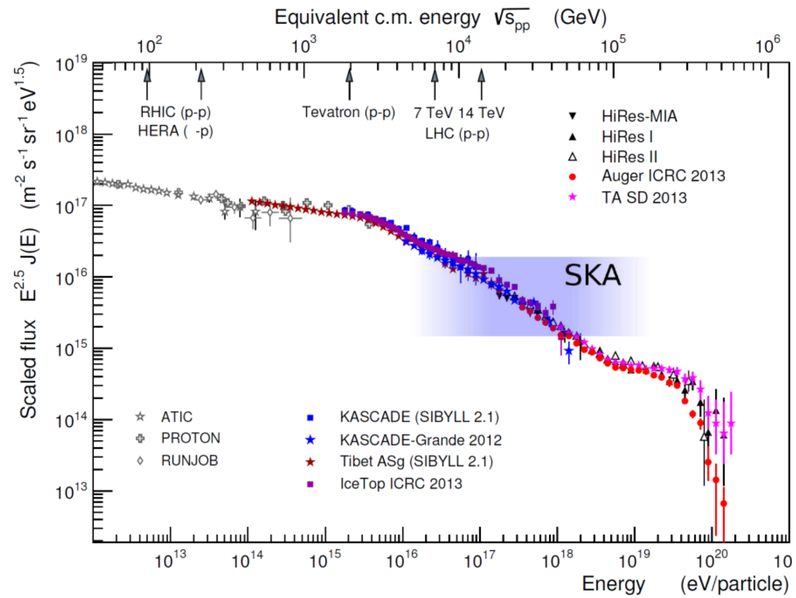
Hoover et al.,
ANITA Coll., PRL 2010

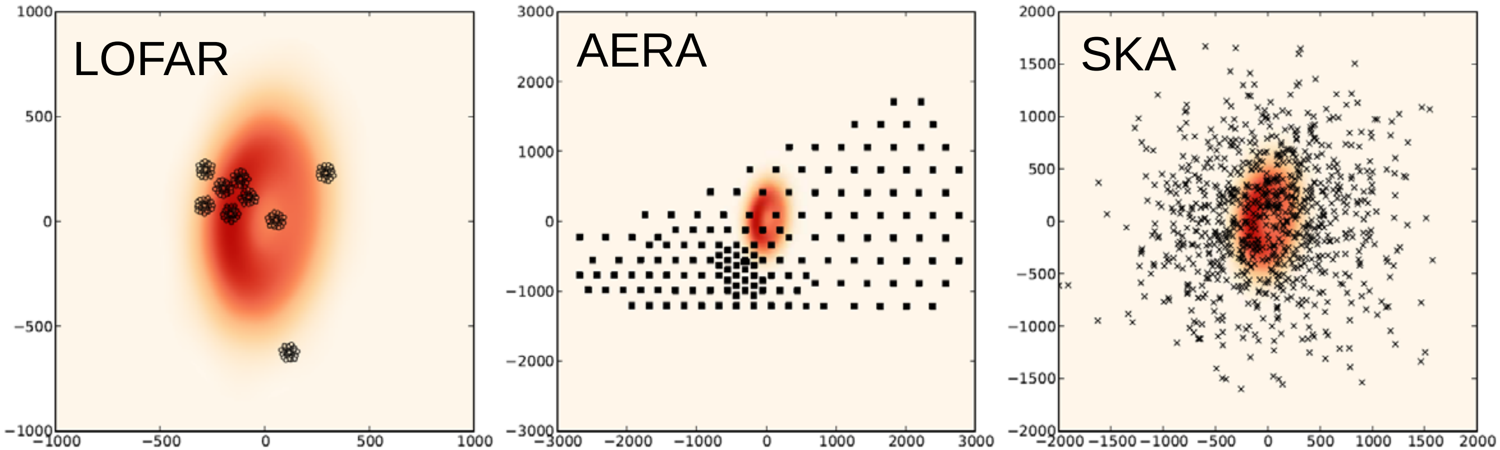


CROME Coll., arXiv:1306.6738

SKA-low as an air shower detector

- uniform coverage, broad-band detection (50-350 MHz, today 30-80 MHz)
- ultra-high precision mass measurements for Galactic to extragalactic CRs transition
- study of hadronic interactions at beyond-LHC energies
- precise „air shower tomography“
- studying potential connections between lightning and CRs
- but: would need significant upgrades!





Summary and conclusions

- radio detection of CRs has boomed and matured in the last decade
- we have clearly established
  - event detection (externally and self-triggered)
  - detailed understanding of complex emission physics
  - determination of arrival direction (<0.5°)
  - determination of air shower energy (<~20%, maybe 10%?)
  - radio signal sensitivity to air shower evolution
- we still need to demonstrate
  - how well Xmax determination can work in practice (~20 g/cm^2?)
  - how we can scale everything to truly large areas/high energies
- the second-generation experiments strive to do just that
- the SKA has significant potential for air shower physics