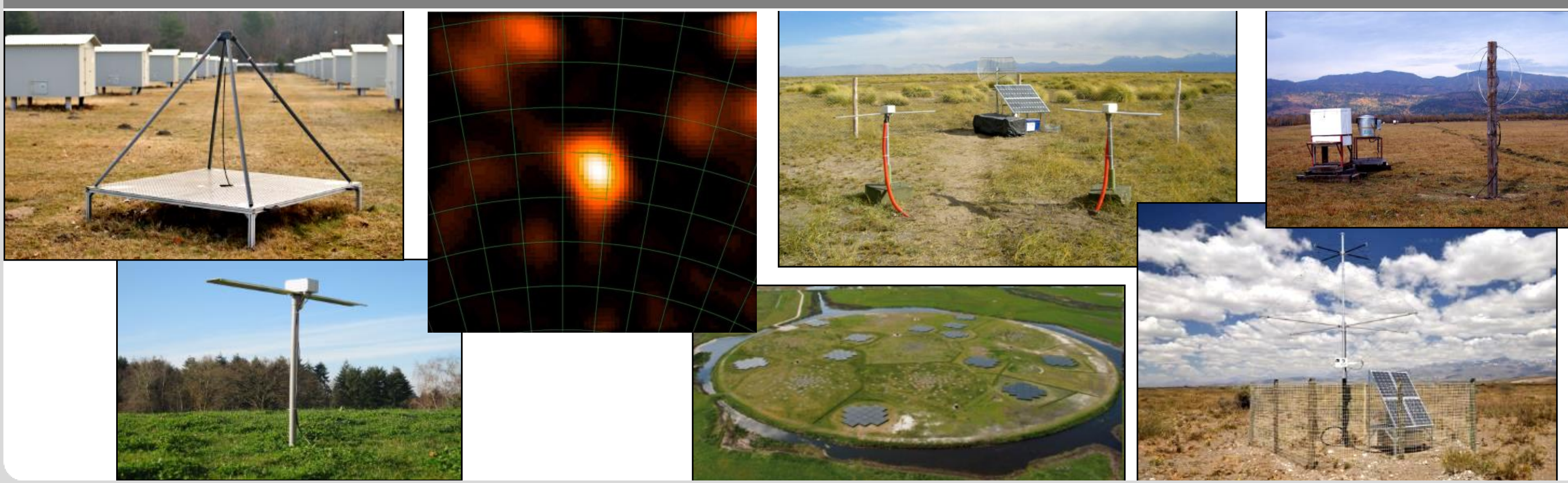
see also T. Huege,
Physics Reports 620 (2016) 1,
doi:10.1016/j.physrep.2016.02.001,
arXiv:1601.07426

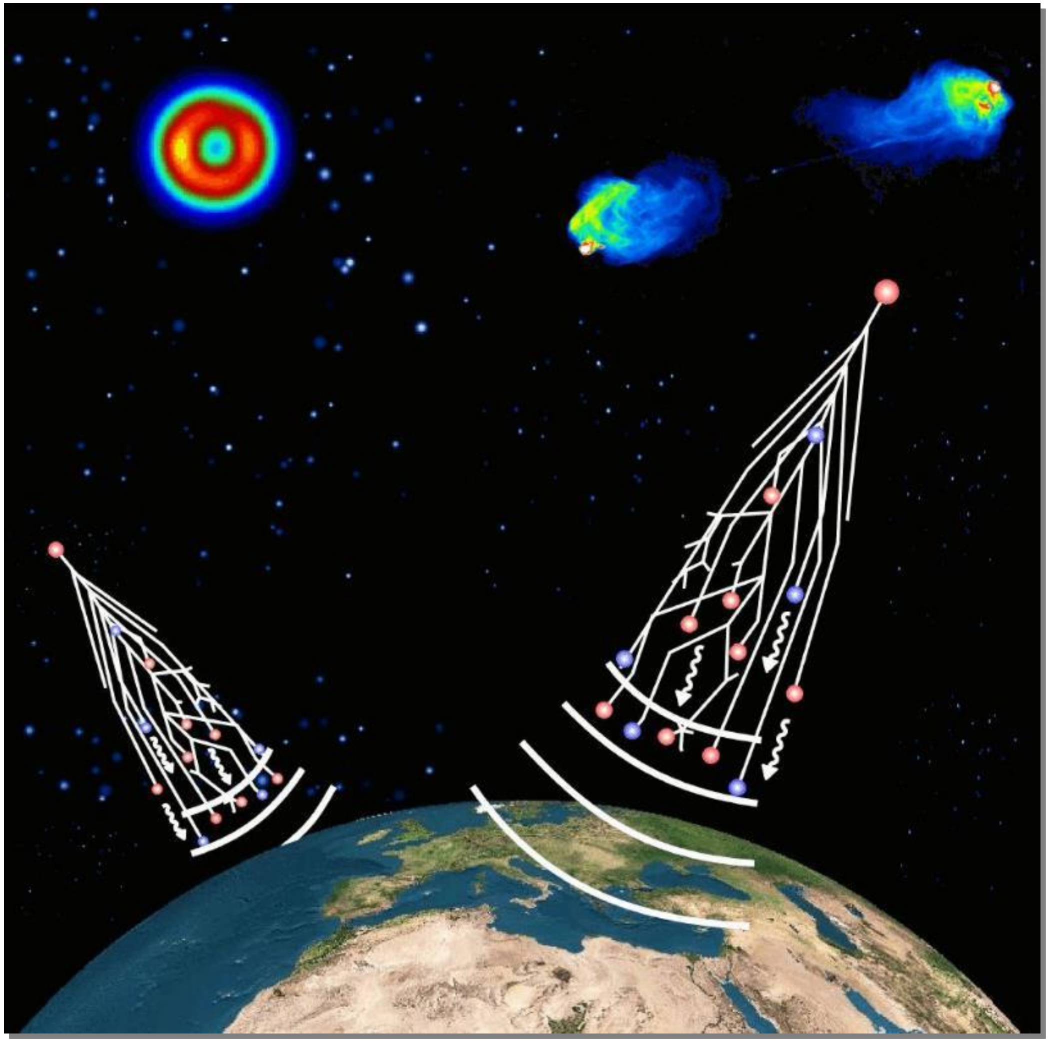
(VHF) Radio detection of cosmic rays – Achievements and future potential

Tim Huege (Karlsruhe Institute of Technology)

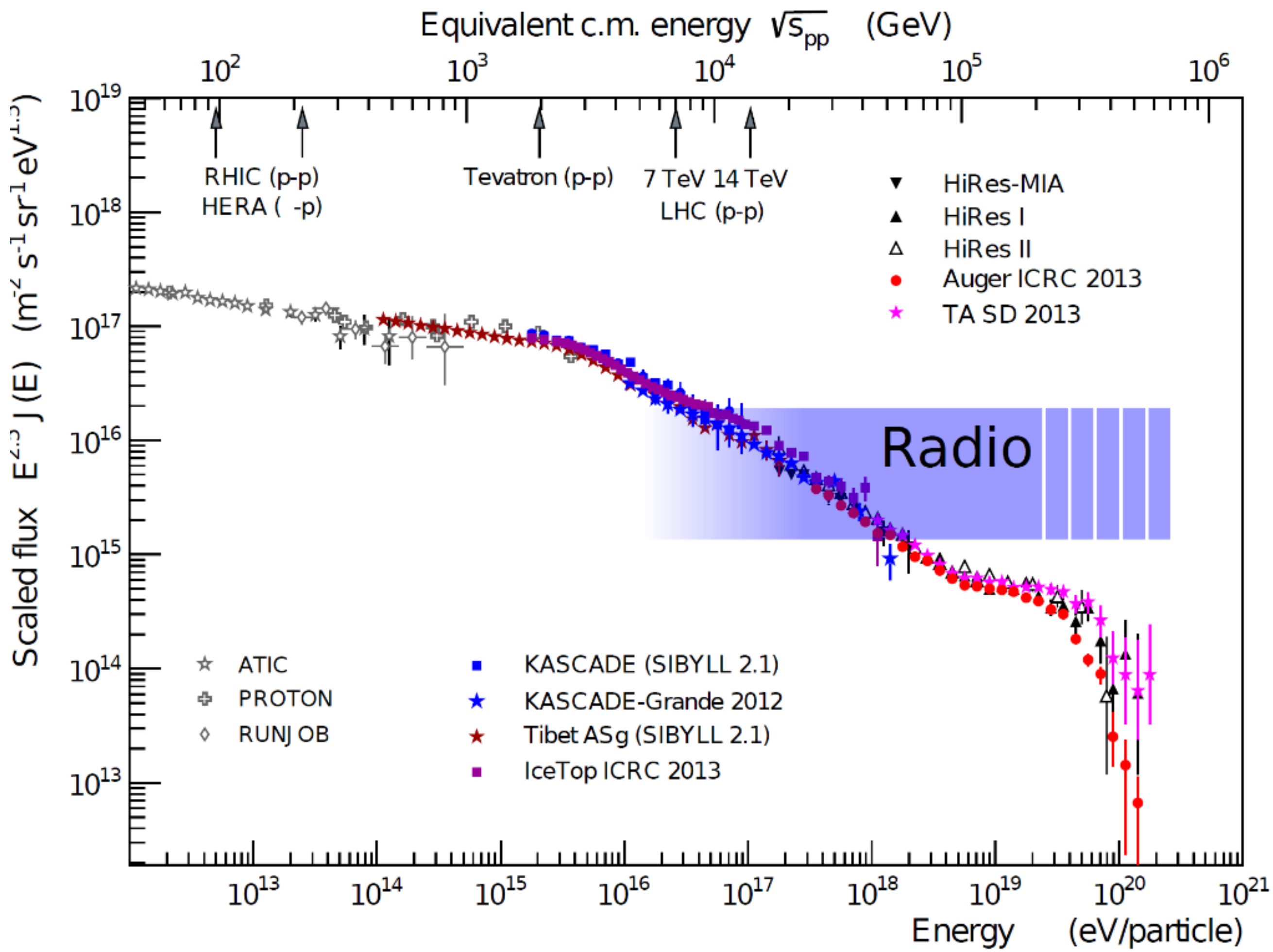


Contents

- achievements of radio detection
- what can radio do for (U)HECR science



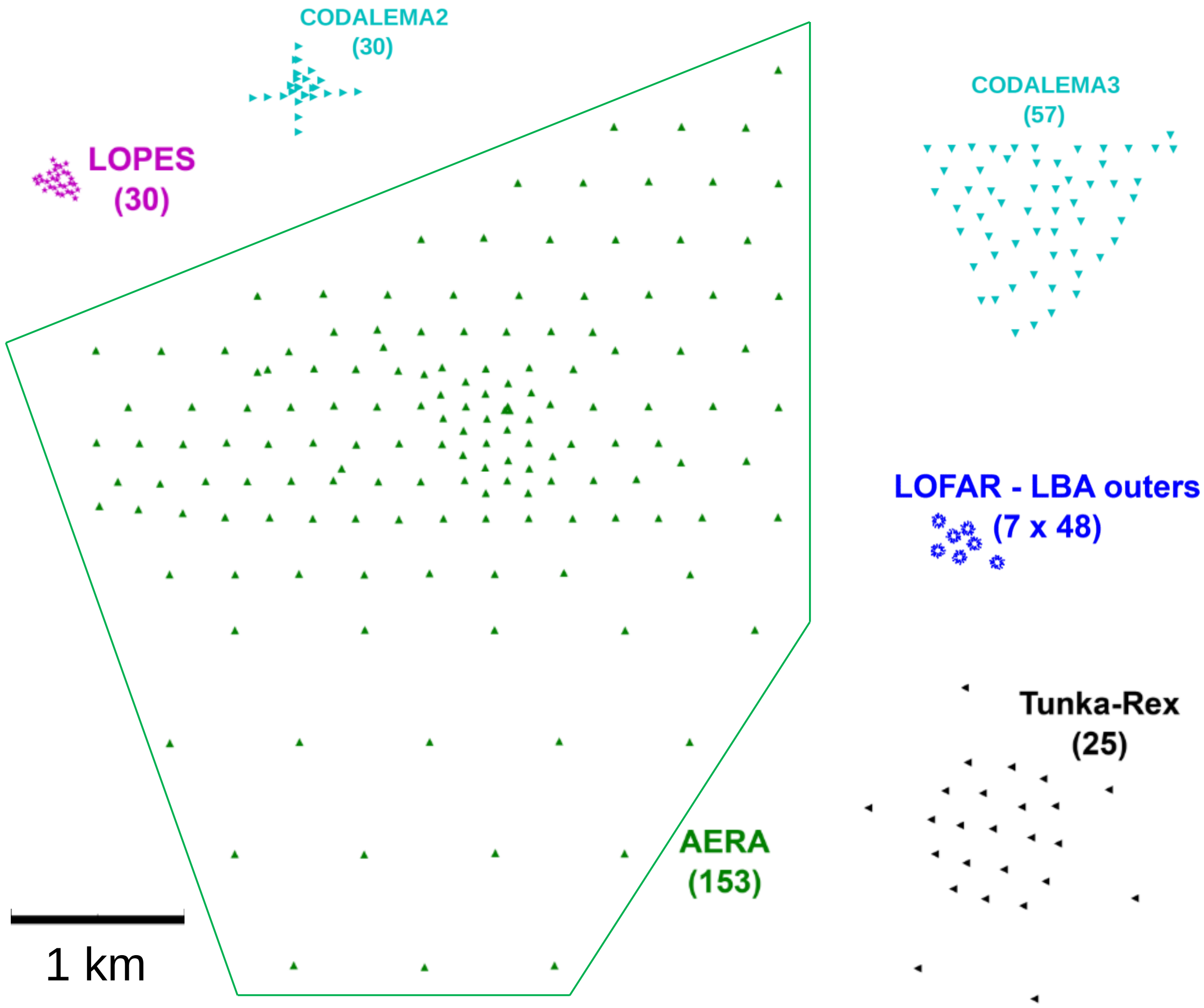
Radio detection of (U)HECR air showers



adapted from R. Engel

- most experience in VHF regime (30-80 MHz)
- low energies: radio signal hidden in Galactic noise
- very high energies: still need concepts to instrument largest areas

Comparison of ground experiments to scale



- from prototypes to large-scale experiments
- sparse vs. dense arrays

Strengths and limitations of radio detection

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- measures pure electromagnetic shower component
- no absorption in the atmosphere, calorimetric energy measurement
- near 100% duty cycle
- high angular resolution
- particle mass sensitivity
- simple (cheap) detectors
- required detector spacing
- direction-dependent threshold
- radio-backgrounds

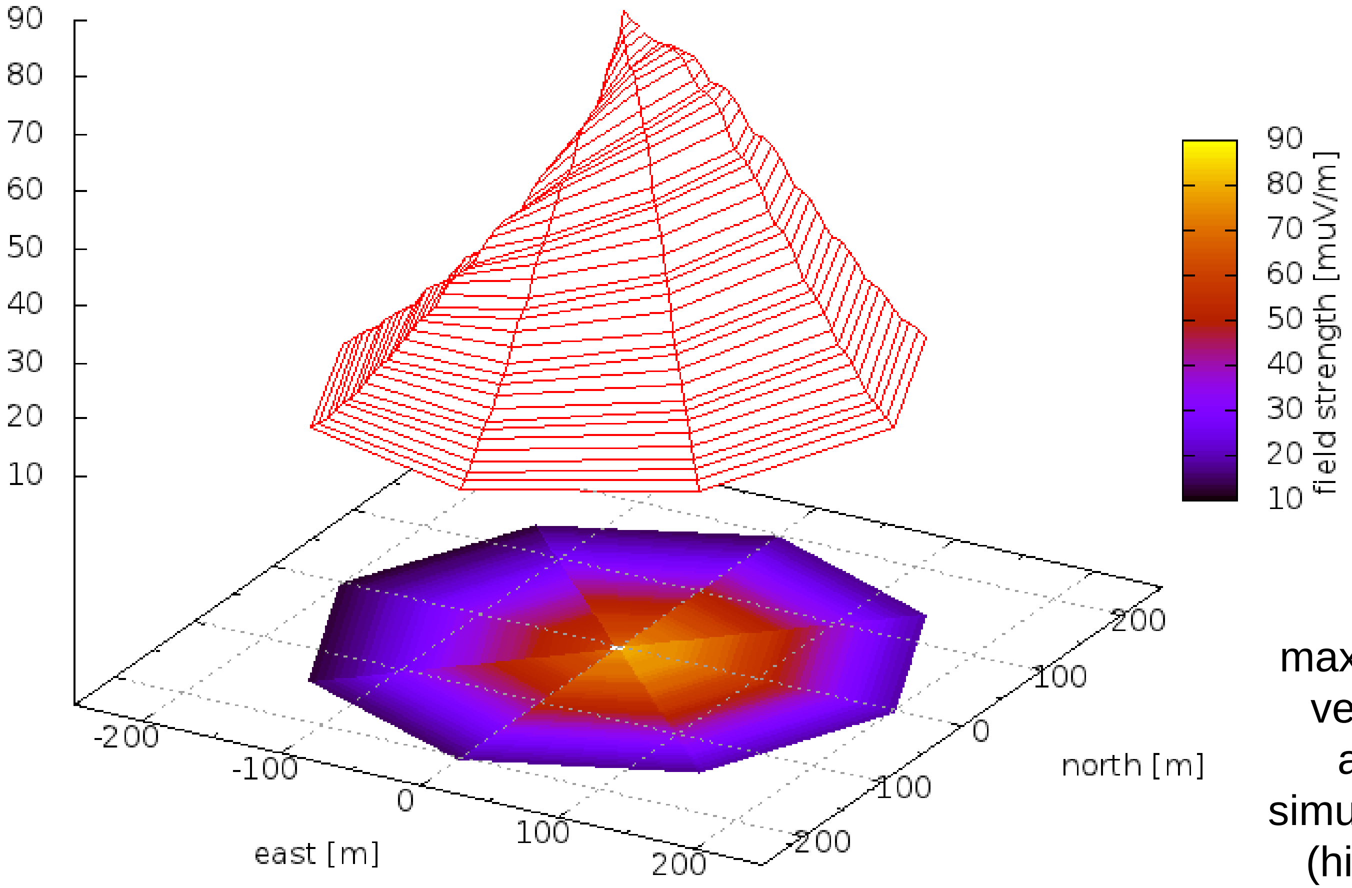
A decade of radio-emission modelling

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**

first principle calculations

Complexity of radio-emission footprint

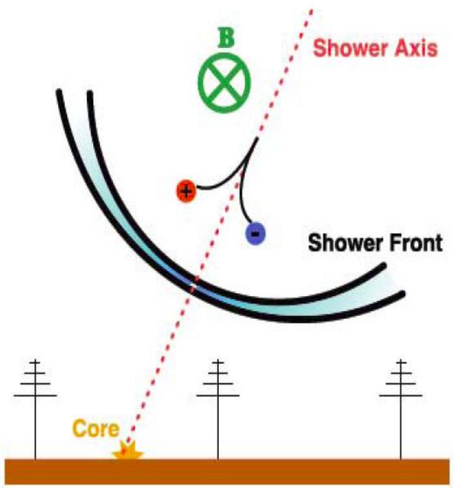


maximum amplitude of vertical iron shower at 40-80 MHz as simulated with CoREAS (higher frequencies: Cherenkov ring)

TH et al., ARENA2012

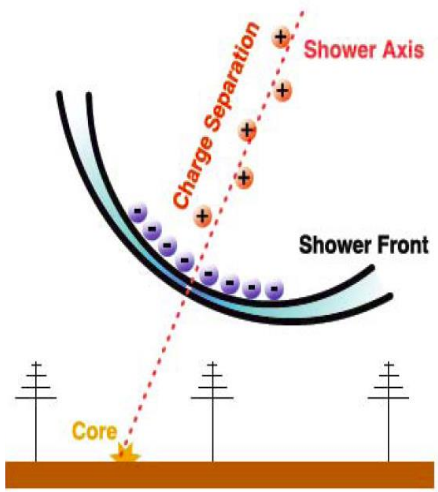
Macroscopic interpretation of radio emission

Karlsruhe Institute of Technology



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

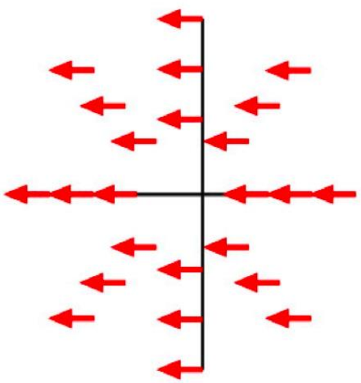
Kahn & Lerche (1967)



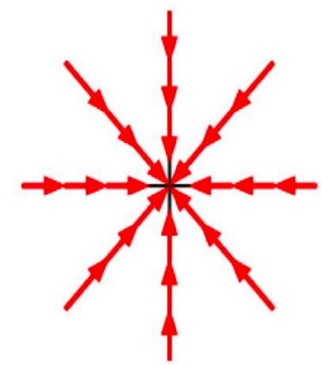
Askaryan (1962,1965)

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

Pierre Auger Coll., Phys. Rev. D 89 (2014) 052002.



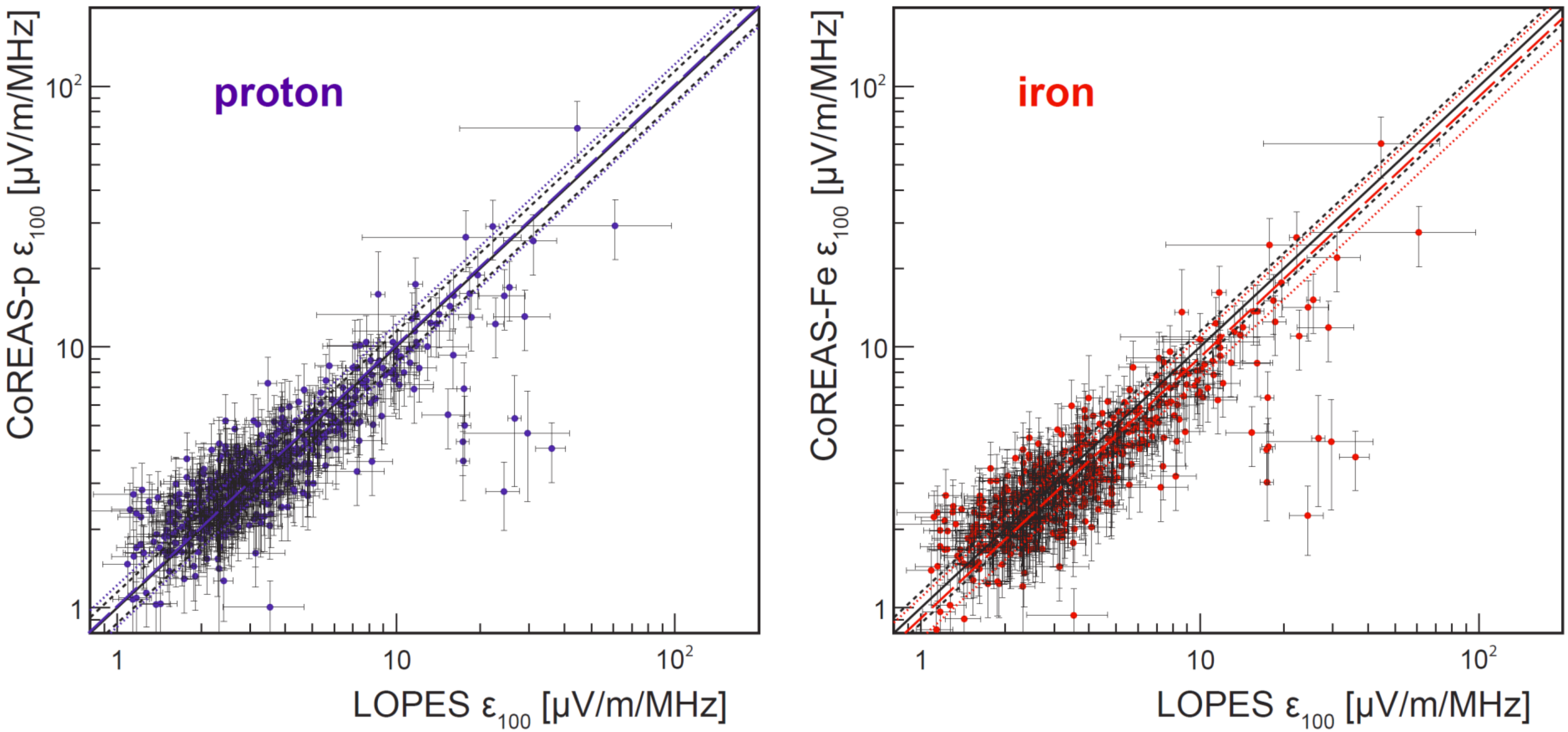
„*v* x *B*“



„radial“

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

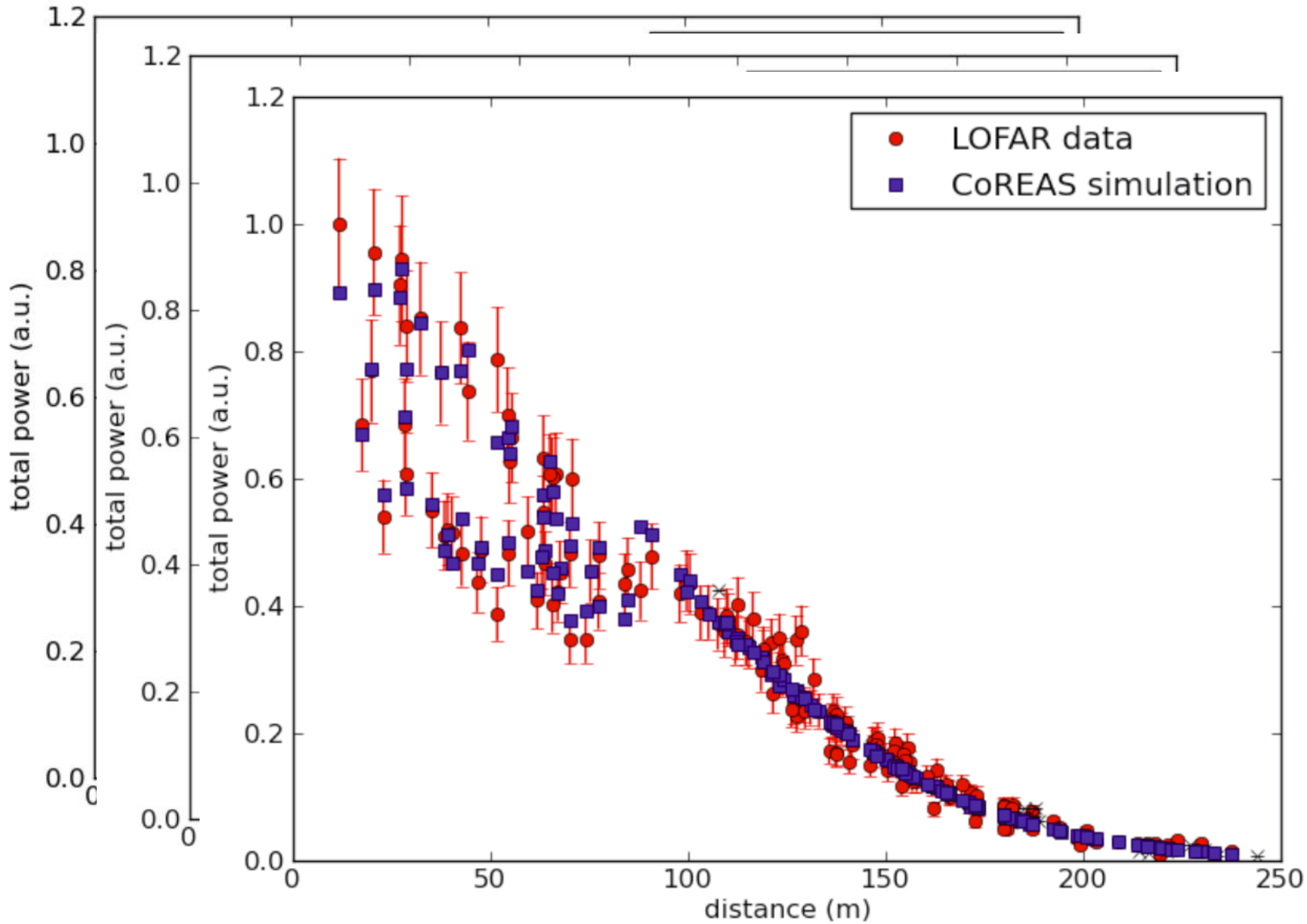
Comparison of simulations with LOPES data



- very good agreement, well within systematic uncertainties
- the absolute scale is predicted correctly!
- see also results from AERA & Tunka-Rex

LOPES Coll., Astropart. Phys. 75 (2016) 72-74.

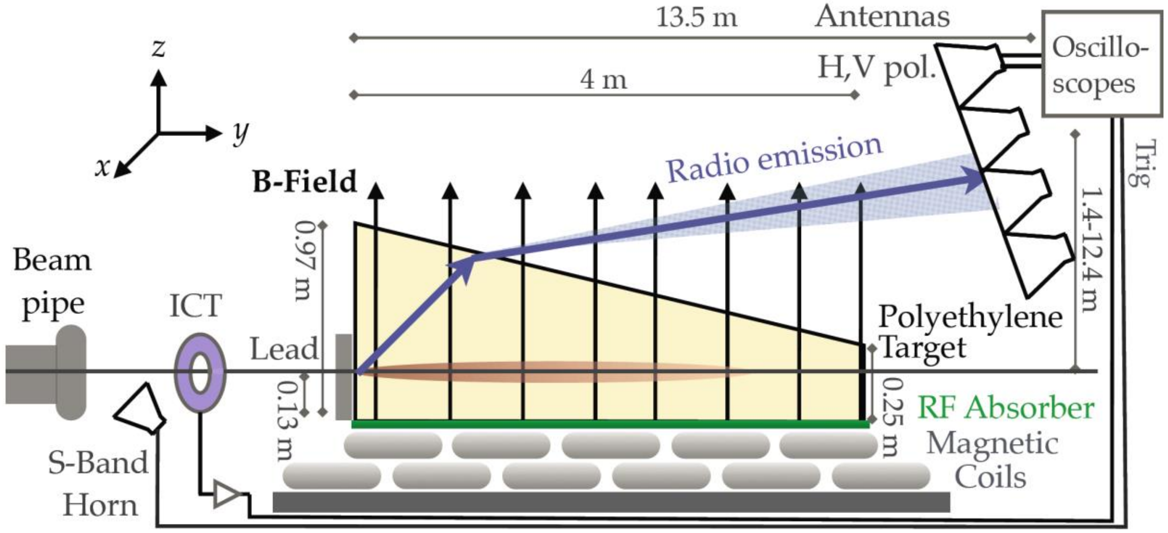
Comparison of simulations with LOFAR data

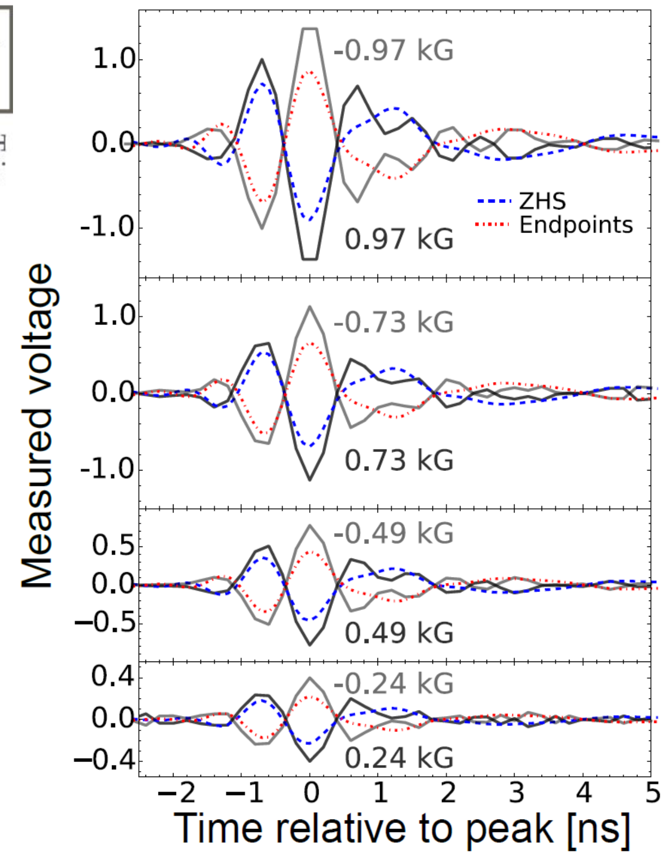


- measurement of individual shower with extreme level of detail
- data can be reproduced by simulations
- see geomagn., charge excess and Cherenkov effects

S. Buitink, A. Corstanje, J. E. Enriquez, et al., Phys. Rev. D 90 (2014) 082003.

Lab-Experiment: SLAC T-510





- electromagnetic particle shower in strong magnetic field, controlled conditions
- cross-check first-principle calculations
  - agree within systematic uncertainties (~35%)

Belov et al. (T-510 Collaboration), PRL116 (2016) 141103

Strengths and limitations of radio detection

- radio signal can be predicted from first principles
- measures pure electromagnetic shower component
- no absorption in the atmosphere, calorimetric energy measurement
- near 100% duty cycle
- high angular resolution
- particle mass sensitivity
- simple (cheap) detectors
- required detector spacing
- direction-dependent threshold
- radio-backgrounds

emission well-understood, can be used to set energy scale

Tim Huege <tim.huege@kit.edu>

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emission well-understood, can be used to set energy scale

direct comparison to FD, little influence of hadronic interactions

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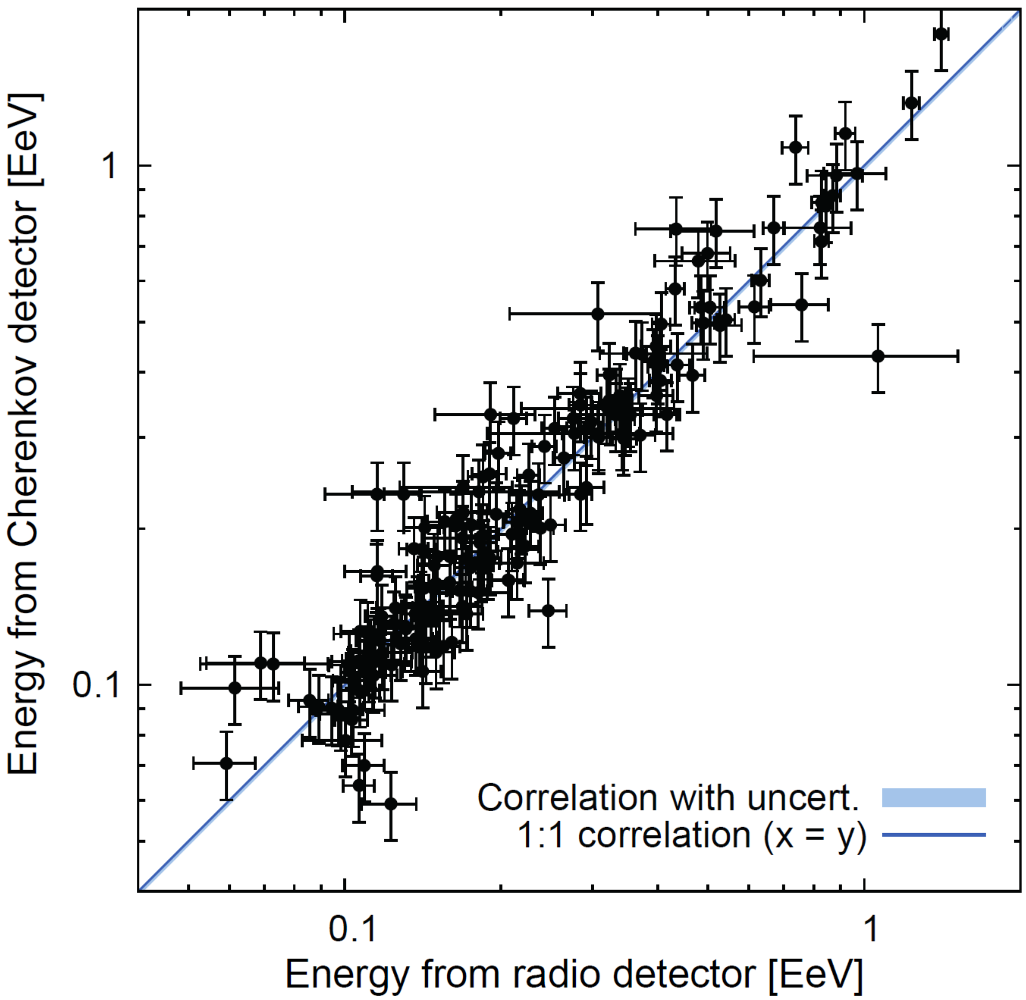
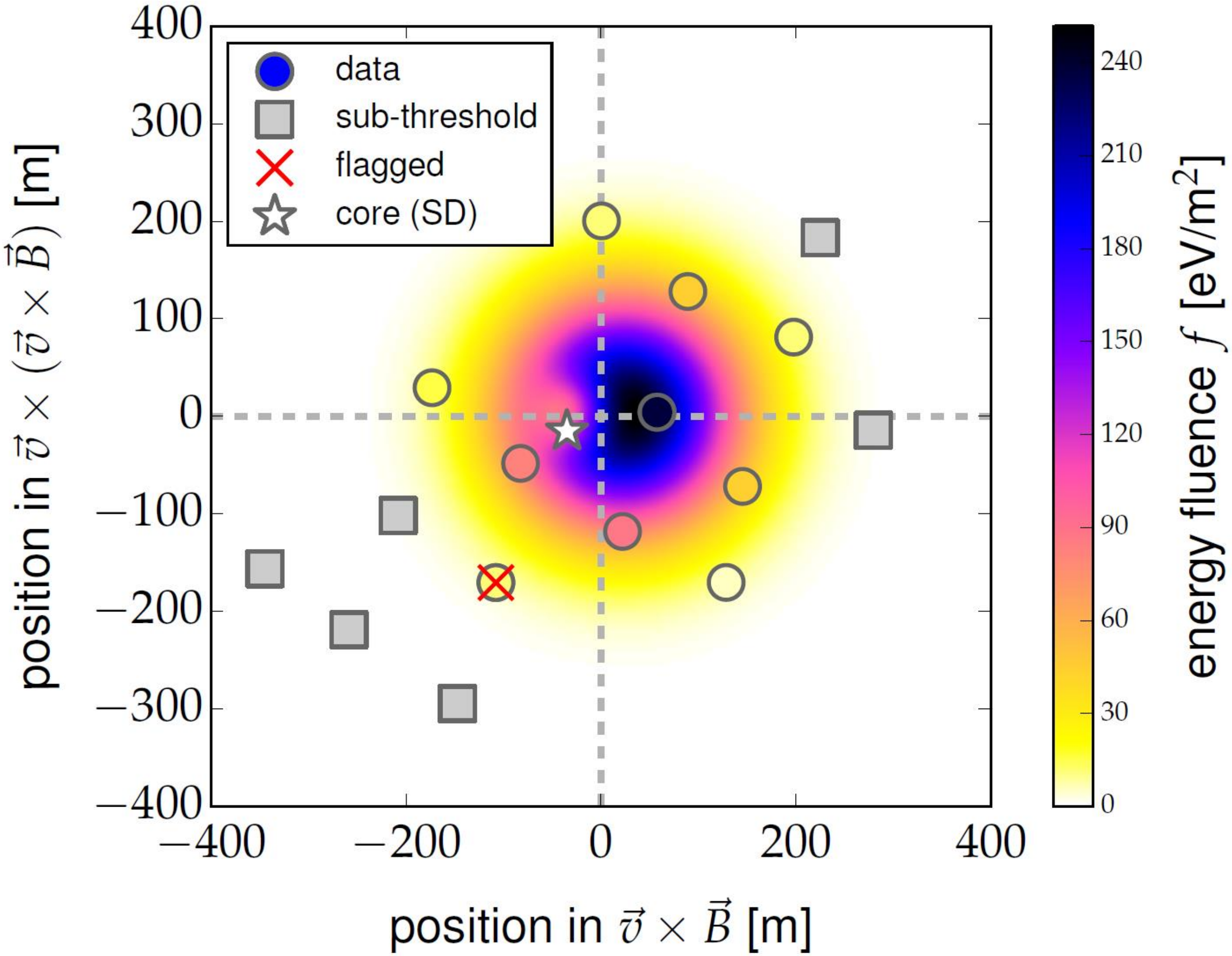
Tunka-Rex energy reconstruction



- use amplitude at characteristic lateral distance as energy estimator
  - accuracy: absolute scale fits nicely with CoREAS simulations
  - precision: 20% combined resolution of radio and optical Cherenkov detectors (~15% alone)
- see also comparable results from LOPES

Tunka-Rex Coll., JCAP (2016) arXiv:1509.05652.

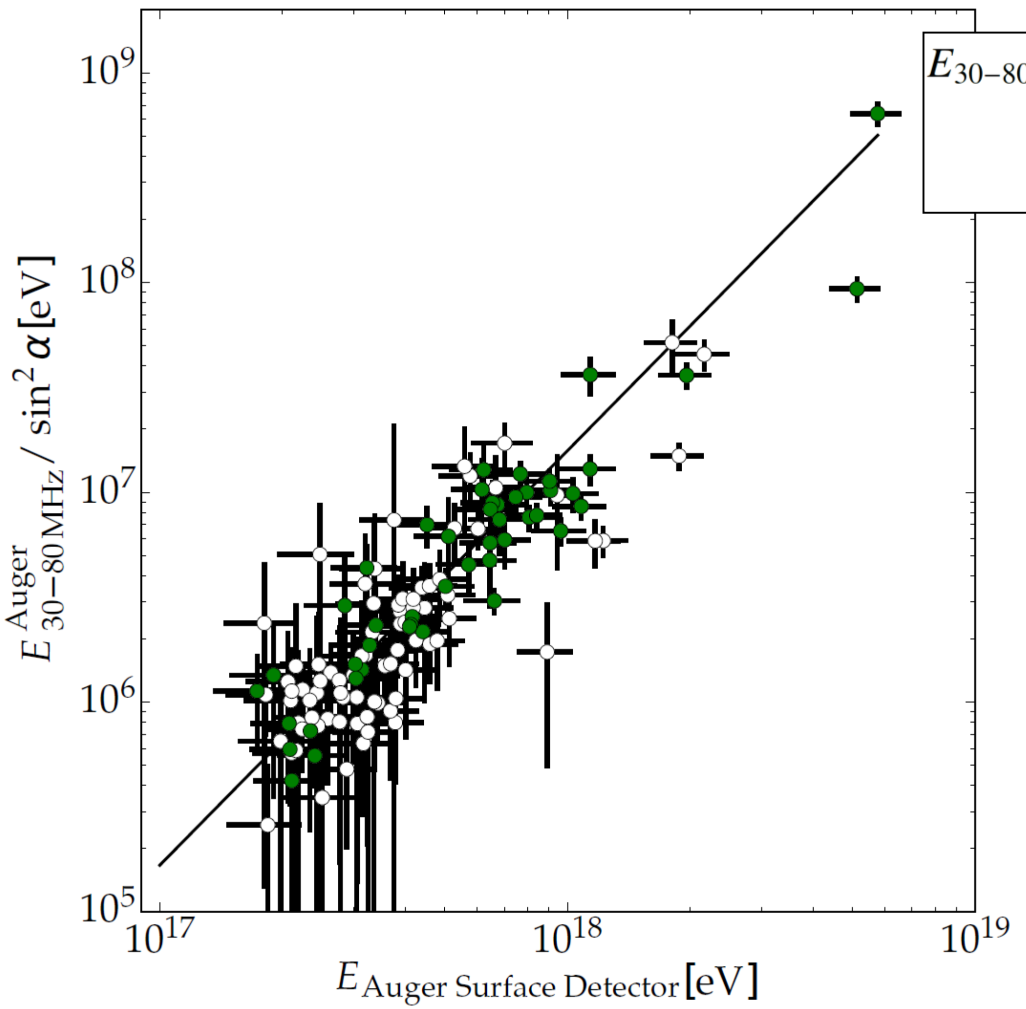
AERA energy reconstruction – radiation energy



Piere Auger Coll., Phys Rev. D (2016), arXiv:1508.04267.

- at each antenna calculate energy fluence from time-integration of Poynting flux
- then integrate energy fluence over area using 2D signal distribution model

„Radiation energy“ as energy estimator



Piere Auger Coll., Phys Rev. Lett. (2016), arXiv:1605.02564.

$$E_{30-80\,\mathrm{MHz}} = (15.8 \pm 0.7\,(\mathrm{stat}) \pm 6.7\,(\mathrm{sys}))\ \mathrm{MeV} \times \left(\sin\alpha \frac{E_{\mathrm{CR}}}{10^{18}\,\mathrm{eV}} \frac{B_{\mathrm{Earth}}}{0.24\,\mathrm{G}}\right)^2 . \qquad (10)$$

- energy resolution ~17%
- of 10^{18} eV, only 10^7 eV go into radio signals
- radiation energy gives a calorimetric measurement of the energy in the electromagnetic cascade
- this value can be measured by any experiment, so cross-calibrate energy scales against the Auger scale

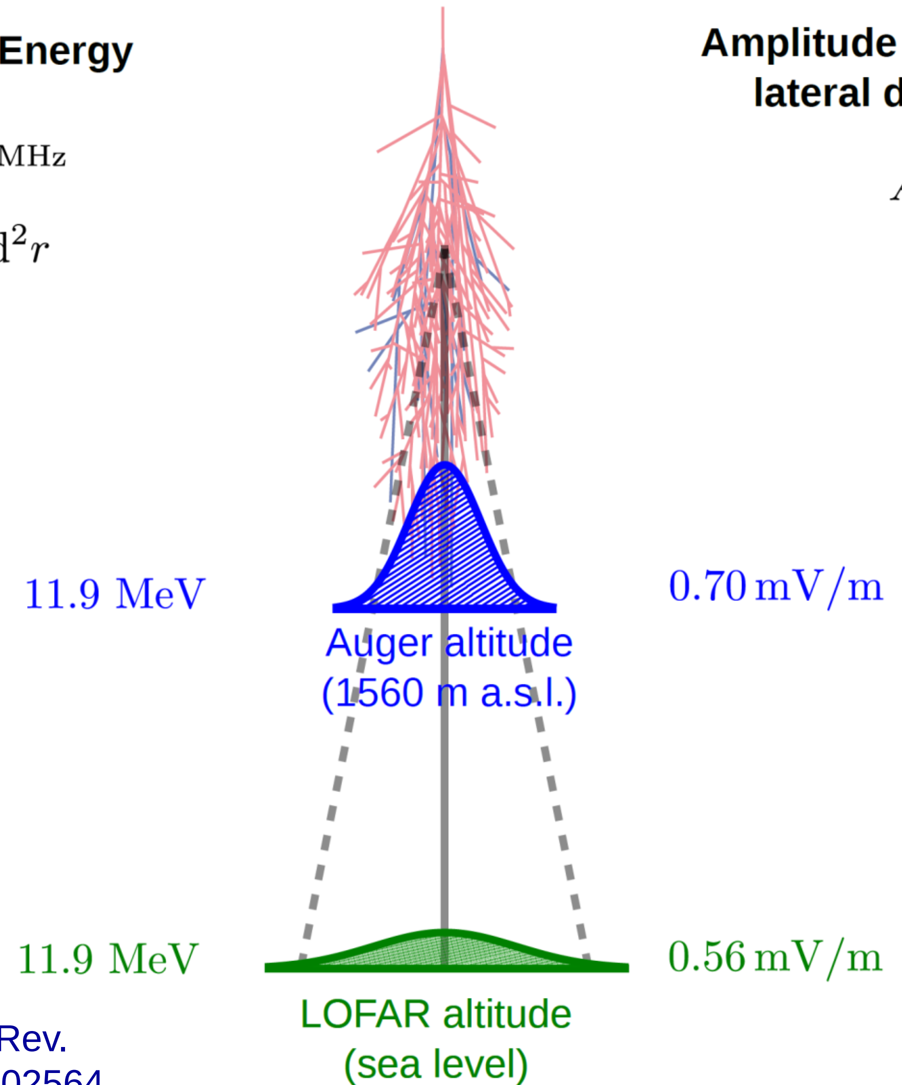
Radiation energy and energy-scale calibration

Radiation Energy

$$E_{30-80\,\mathrm{MHz}}$$
$$\propto \int A^2 \mathrm{d}^2 r$$

Amplitude at optimal lateral distance

$$A$$

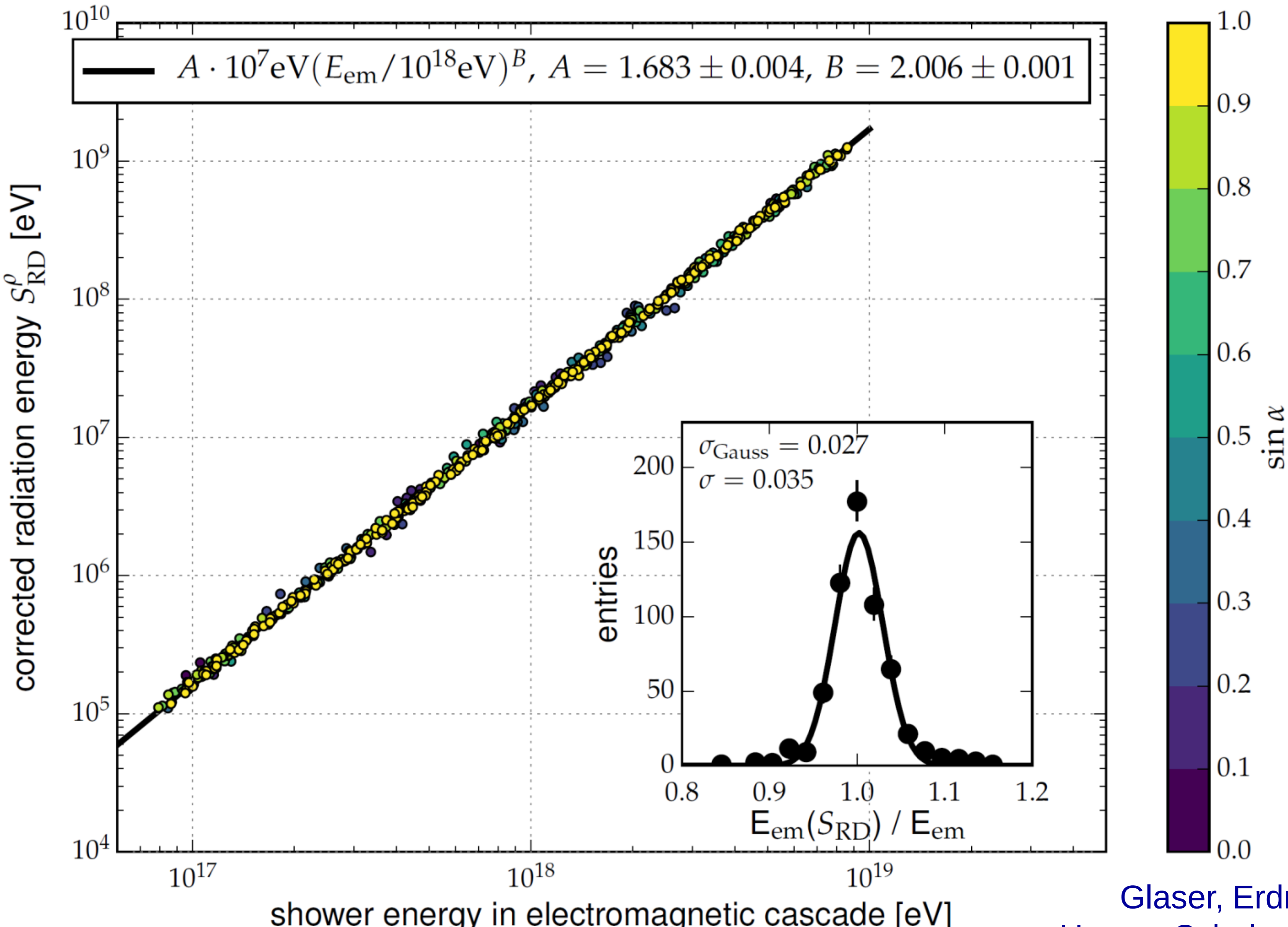


The Radiation Energy reflects the calorimetric energy of the air shower. It is independent of observation altitude.

The optimal lateral distance and the amplitude measured there vary with observation altitude (even after charge-excess and zenith-angle correction).

Piere Auger Coll., Phys Rev. Lett. (2016), arXiv:1605.02564.

Radiation energy and electromagnetic energy



- radiation energy has been studied in detail
- very good correlation with electromagnetic energy, less than 5% intrinsic scatter

Glaser, Erdmann, Hörandel, Huege, Schulz, JCAP 09 (2016) 024

Strengths and limitations of radio detection

- radio signal can be predicted from first principles
  emission well-understood, can be used to set energy scale
- measures pure electromagnetic shower component
  direct comparison to FD, little influence of hadronic interactions
- no absorption in the atmosphere, calorimetric energy measurement
  σ_E < 15%, possibly below 10%, cross-calibration between detectors
- near 100% duty cycle
- high angular resolution
- particle mass sensitivity
- simple (cheap) detectors
- required detector spacing
- direction-dependent threshold
- radio-backgrounds

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Strengths and limitations of radio detection

Karlsruhe Institute of Technology

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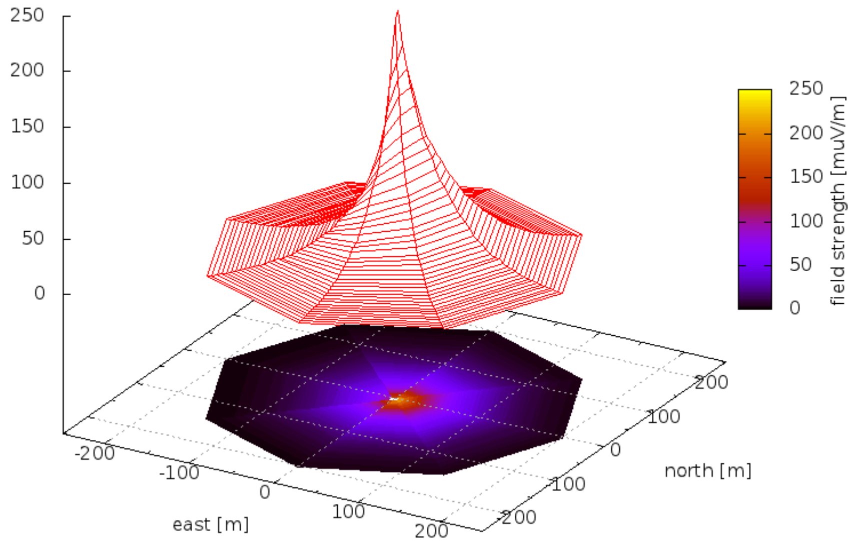
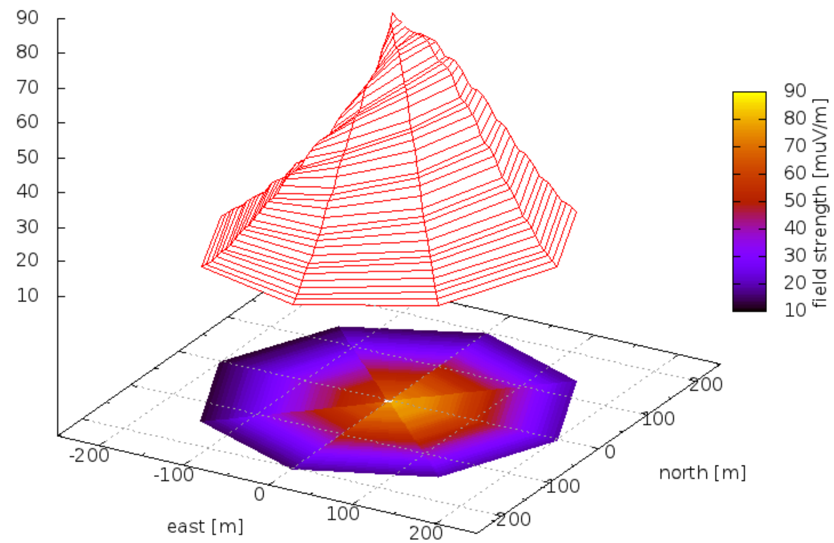
Lateral distribution as probe for composition

- relativistic forward beaming of emission: geometrical distance from source to observer influences emission pattern

TH et al., ARENA2012

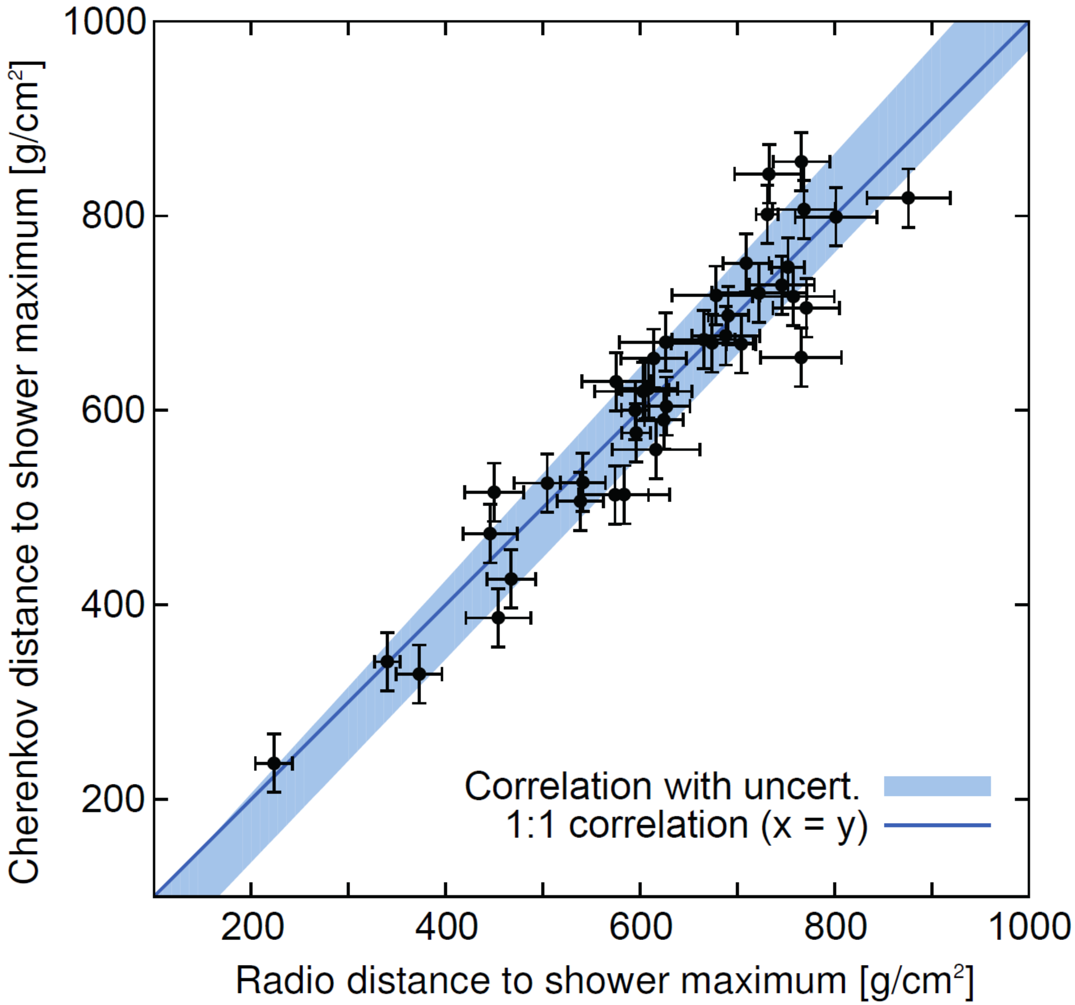


vertical proton shower
at 40-80 MHz
simulated with CoREAS



vertical iron shower
at 40-80 MHz
simulated with CoREAS

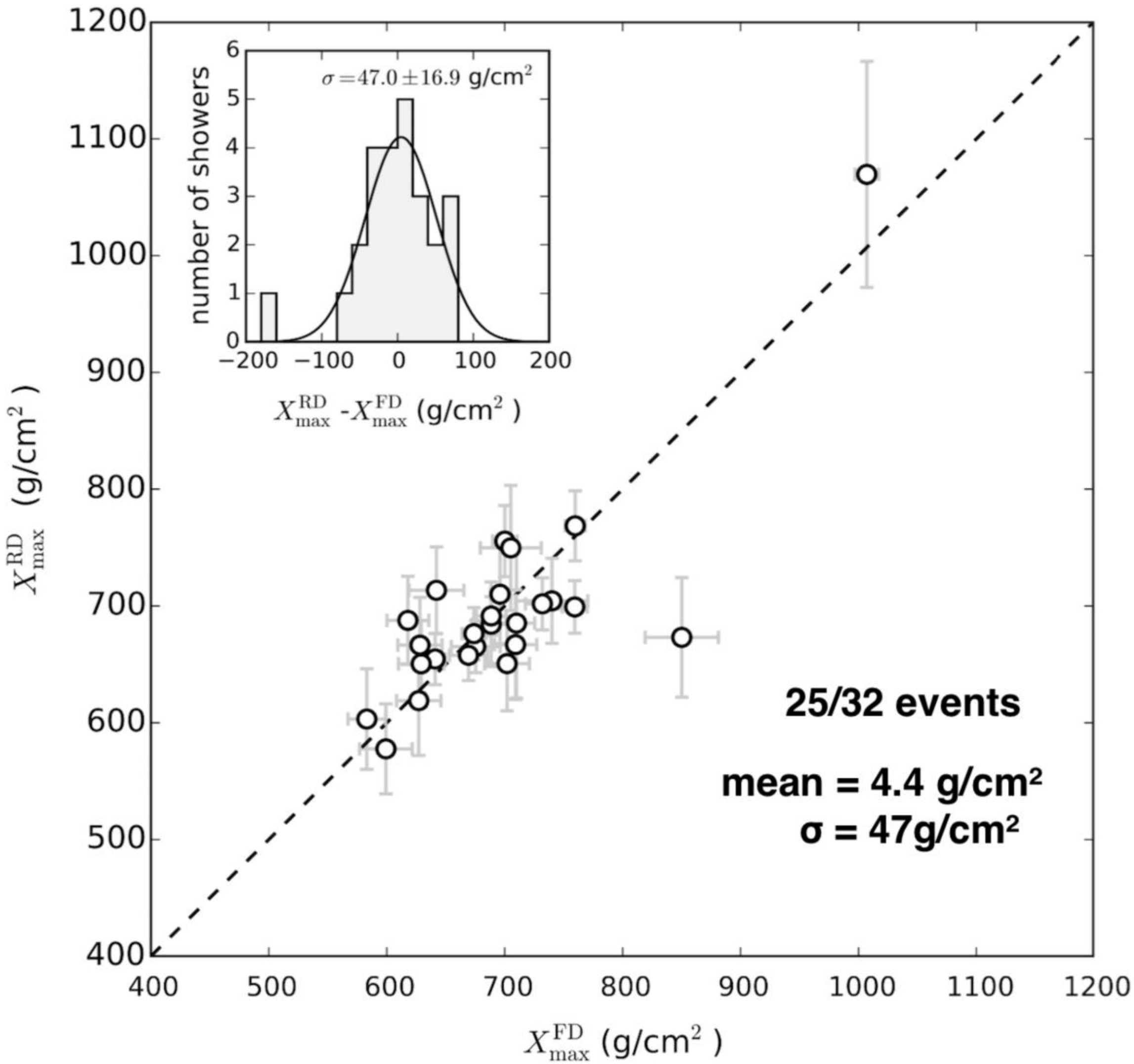
Experimental Xmax validation by Tunka-Rex



- slope of radio-LDF as Xmax estimator
- Xmax from optical Cherenkov detectors and radio antennas agrees very well
- combined Xmax resolution ~50 g/cm^2, Tunka alone ~28 g/cm^2

Tunka-Rex Coll., JCAP (2016), arXiv:1509.05652.

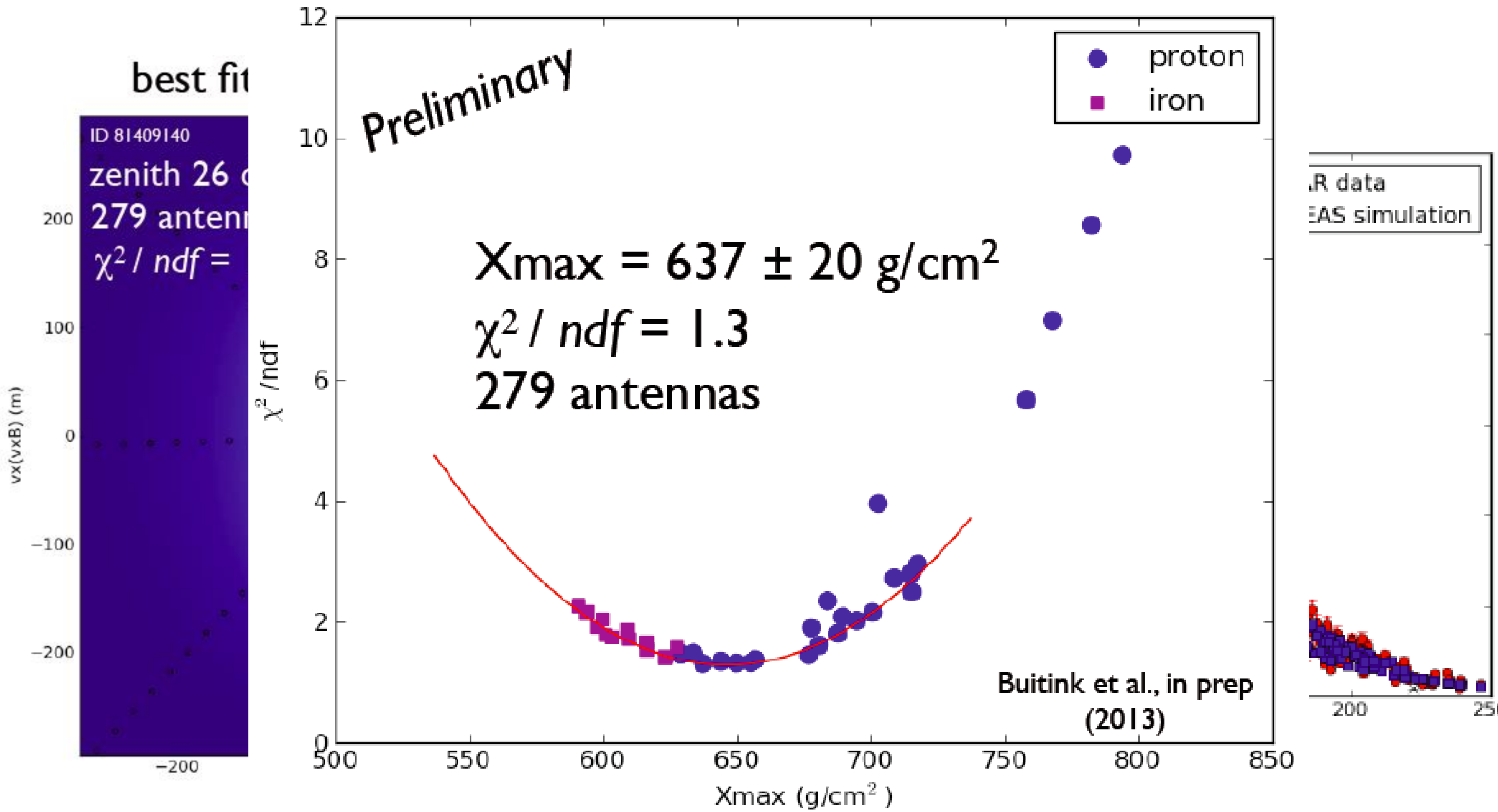
Experimental Xmax validation by Auger



- currently various reconstruction approaches being tested in AERA
- current combined FD-RD resolution of ~45 g/cm², so AERA alone <~40 g/cm²
- still room for improvement (only uses amplitude information)

F. Gaté for the Pierre Auger Coll., ARENA2016, arXiv:1609.06510

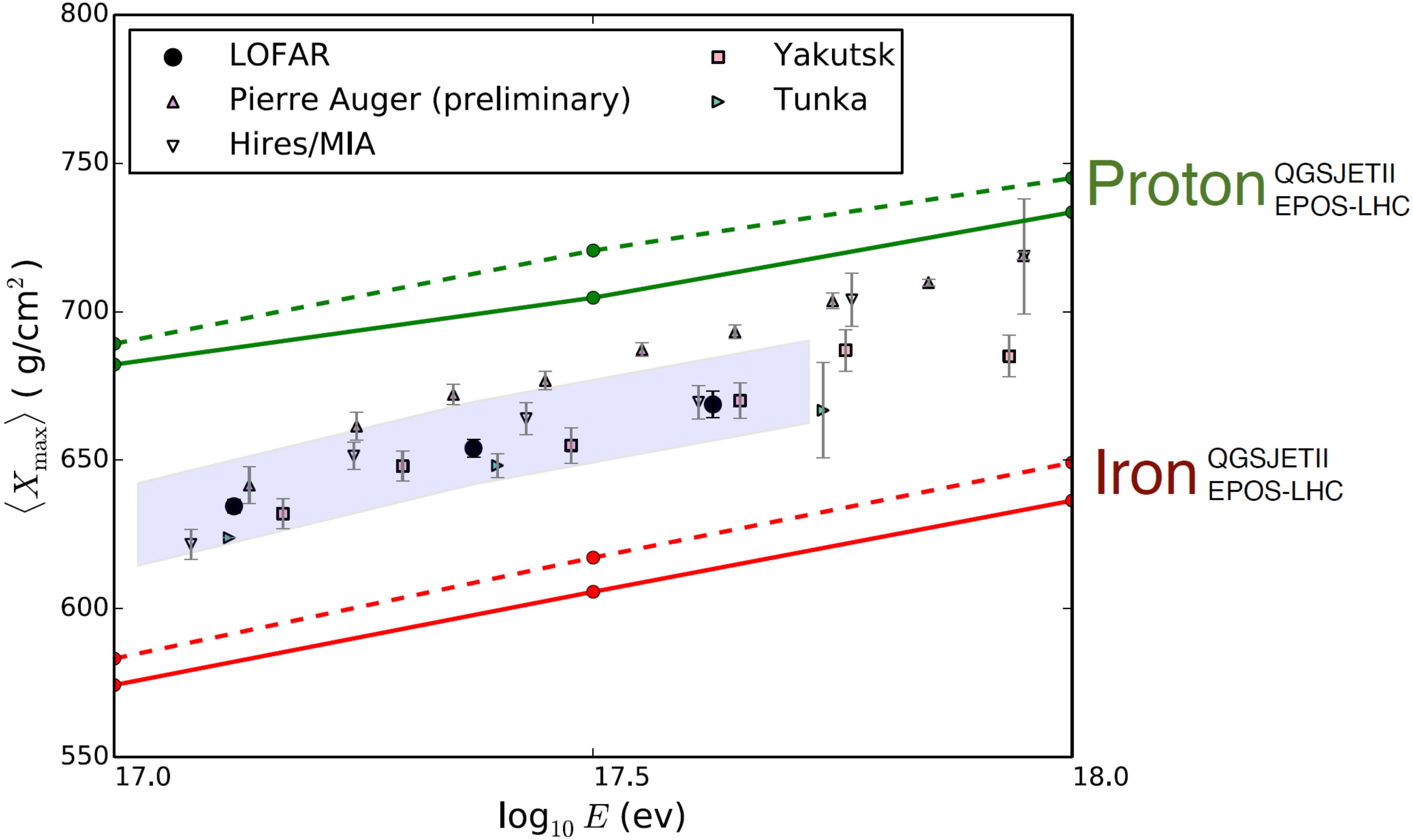
Global fit of particle and radio LDF with LOFAR



- global fit to CoREAS simulations gives Xmax to ~17 g/cm^2

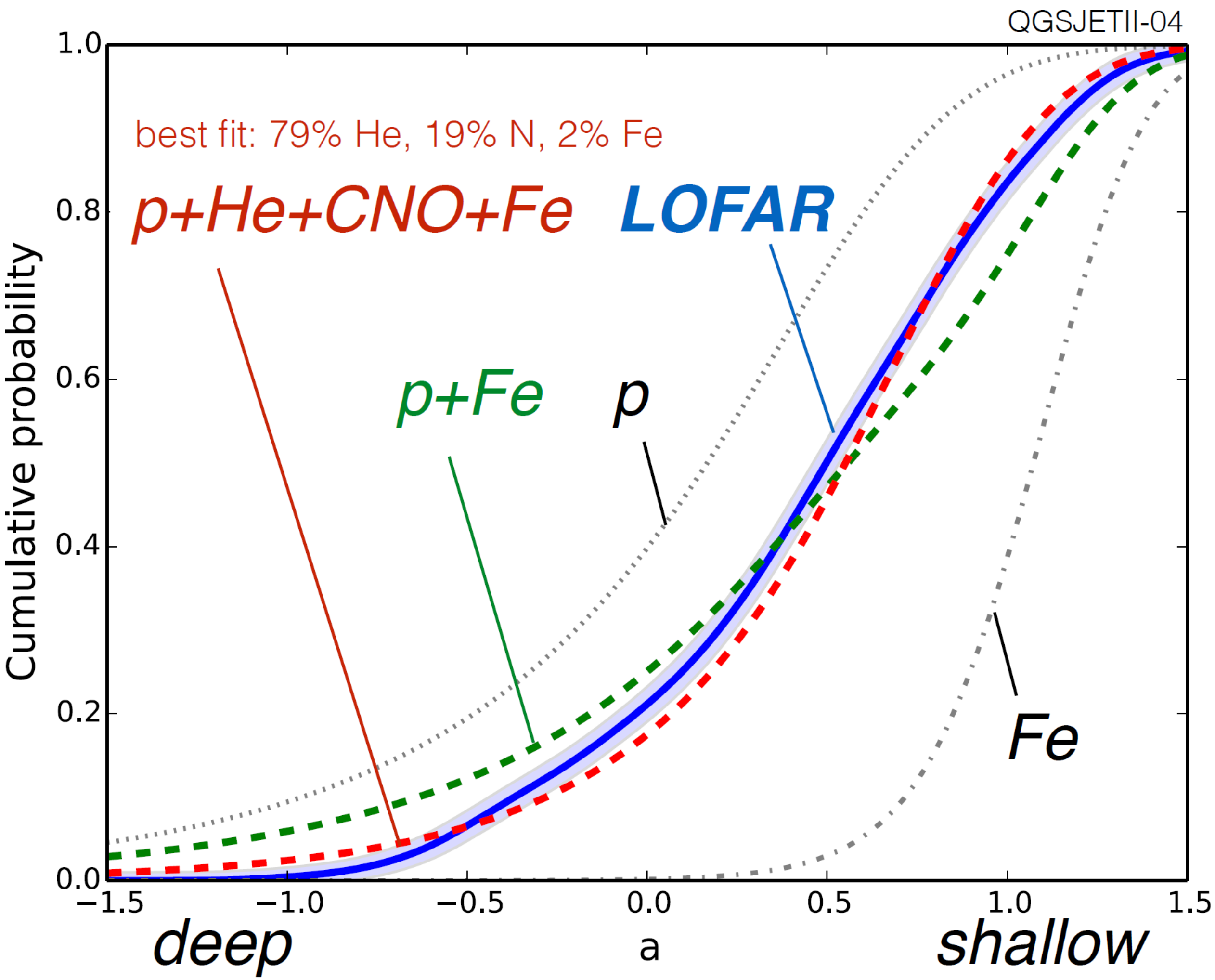
S. Buitink et al., Phys. Rev. D 90 (2014) 082003, S. Buitink et al. Nature 435 (2016) 70

Lofar <Xmax> results



S. Buitink et al. Nature 435 (2016) 70

LOFAR unbinned analysis



S. Buitink et al. Nature 435 (2016) 70

- compare measured distribution of

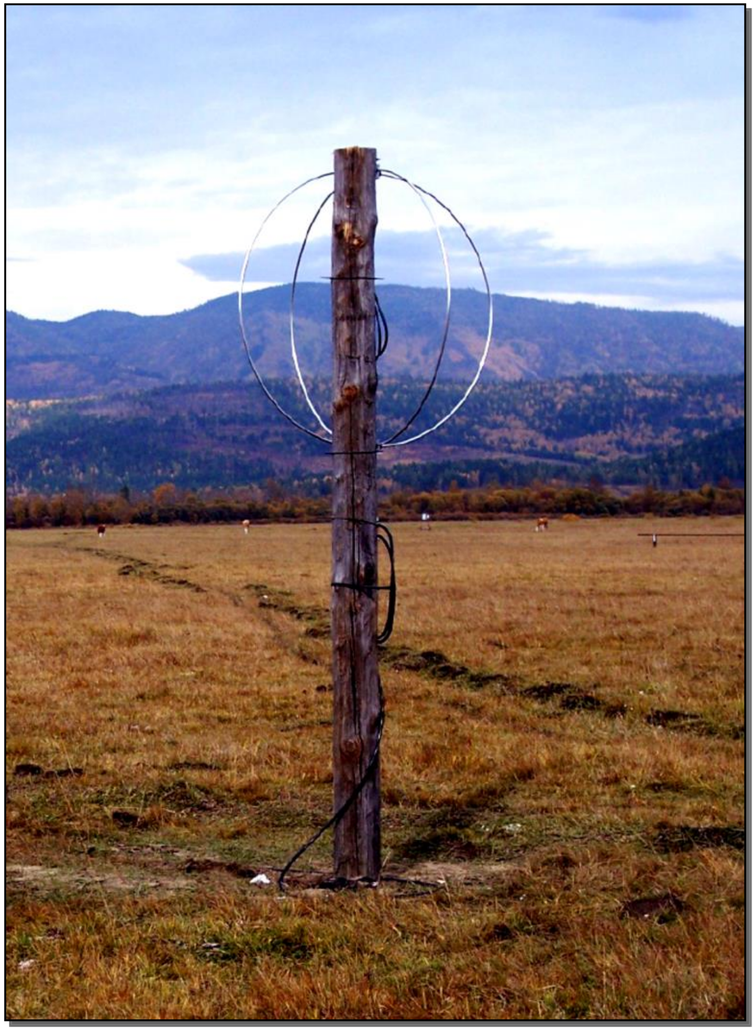
$$a = \frac{\langle X_{\text{proton}} \rangle - X_{\text{shower}}}{\langle X_{\text{proton}} \rangle - \langle X_{\text{iron}} \rangle}$$

  with simulated distributions
- result shows large fraction of light primaries at 10^{17}-$10^{17.5}$ eV

Strengths and limitations of radio detection

radio signal can be predicted from first principles	emission well-understood, can be used to set energy scale
measures pure electromagnetic shower component	direct comparison to FD, little influence of hadronic interactions
no absorption in the atmosphere, calorimetric energy measurement	$\sigma_E < 15\%$, possibly below 10%, cross-calibration between detectors
near 100% duty cycle	>95%
high angular resolution	$\sigma < 0.5°$
particle mass sensitivity	$\sigma_{Xmax} < 20$ g/cm^2 dense (< 40 sparse)
simple (cheap) detectors	
required detector spacing	
direction-dependent threshold	
radio-backgrounds	

How expensive are individual detectors?



- antenna can be cheap, SALLA antenna plus low-noise amplifier costs <500 US$
- digital electronics more expensive, but profit from Moore‘s law
- most expensive part is „infrastructure“ (power supply, communications, …)
- sub-1000$ for antenna plus digital electronics certainly seem feasible

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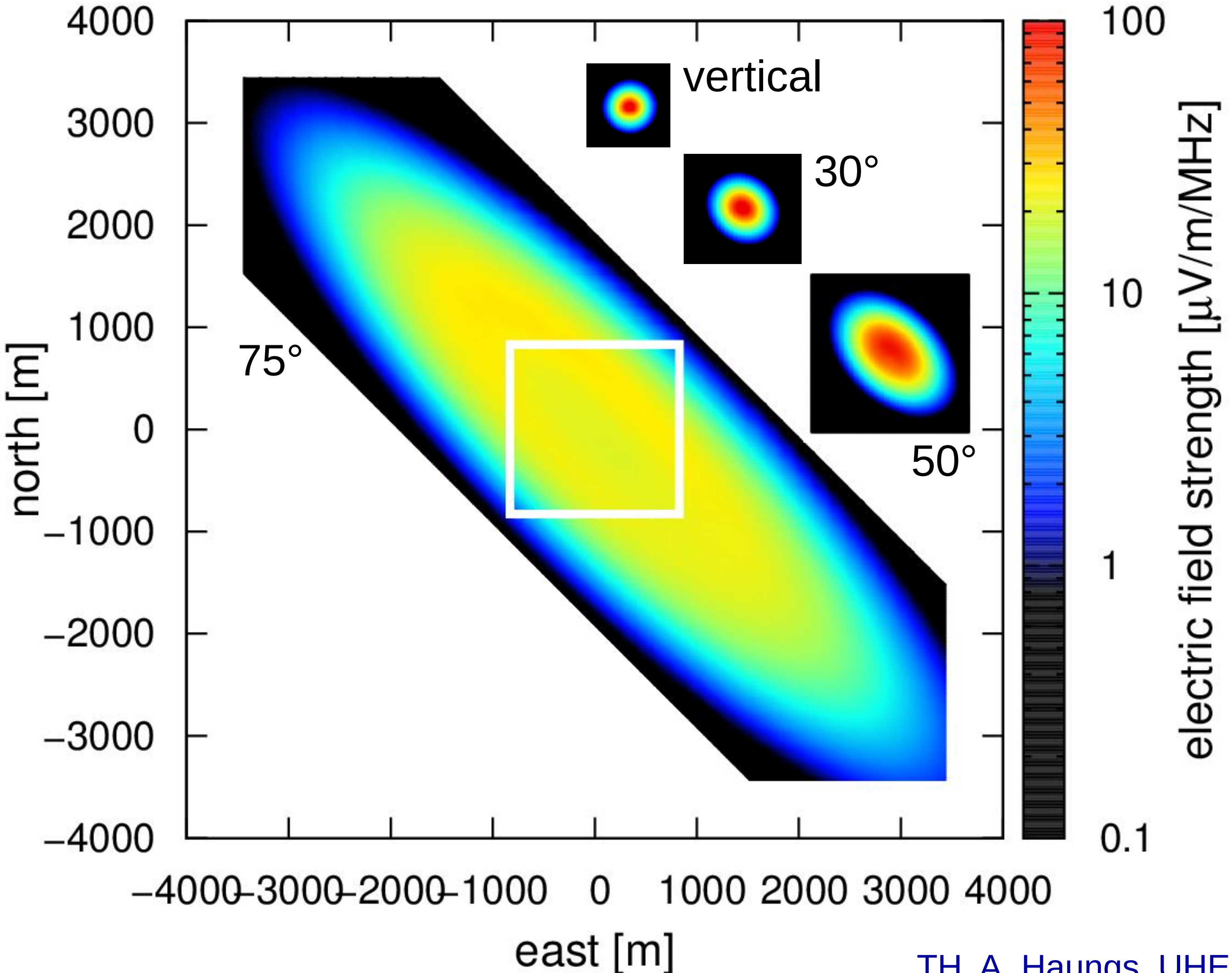
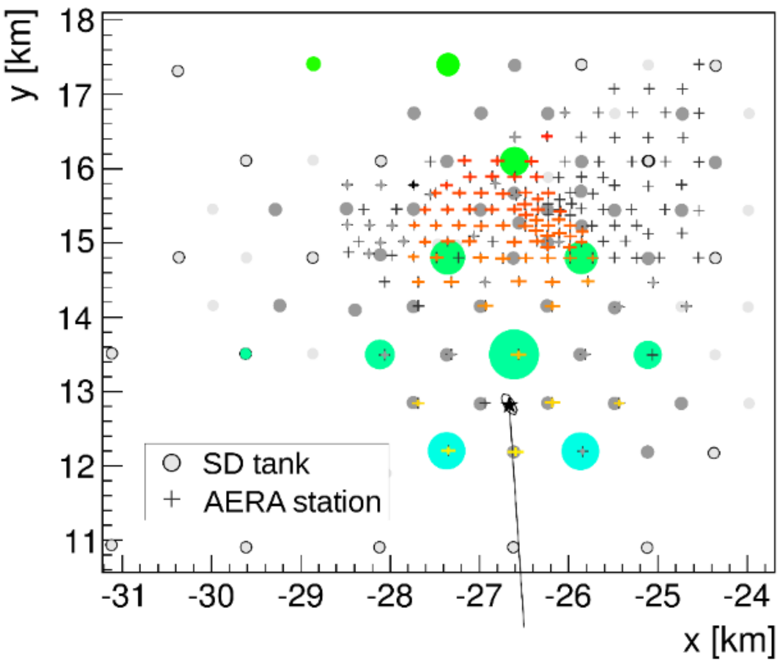
Required detector spacing – inclined showers

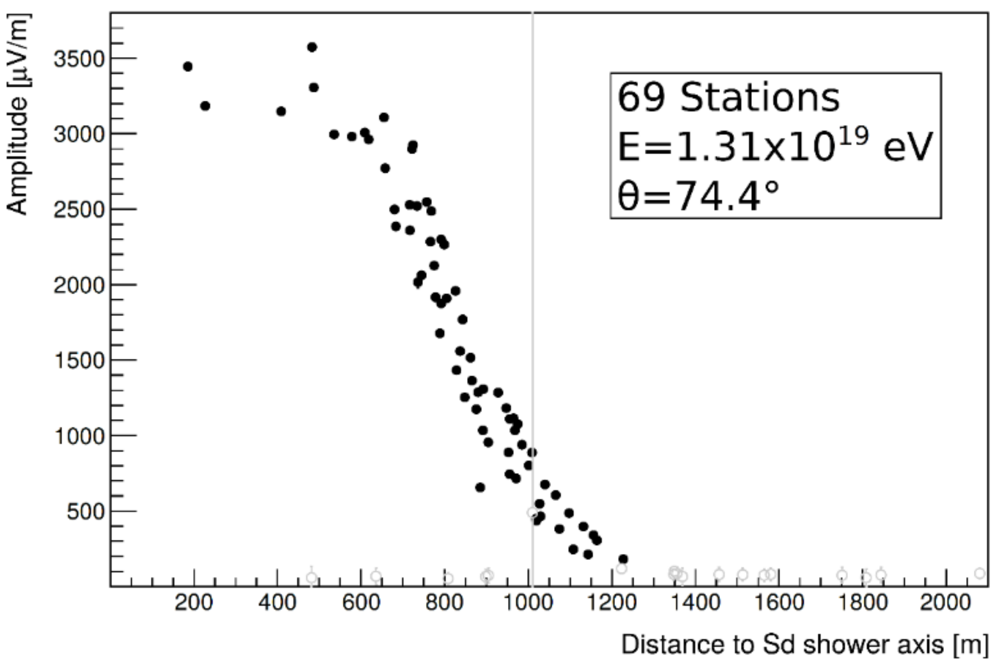


- large source distance leads to very large radio emission footprints in inclined air showers
- should be detectable with sparse arrays

TH, A. Haungs, UHECR2014, arXiv:1507.07769.

Large-scale showers measured by AERA





- air showers up to 83° zenith angle measured
- footprints with radii up to 2 km in shower plane
- detection with 1.5 km antenna grid would be sufficient

O. Kambeitz for the Pierre Auger Collaboration, ARENA2016 conference, arXiv:1609.05456

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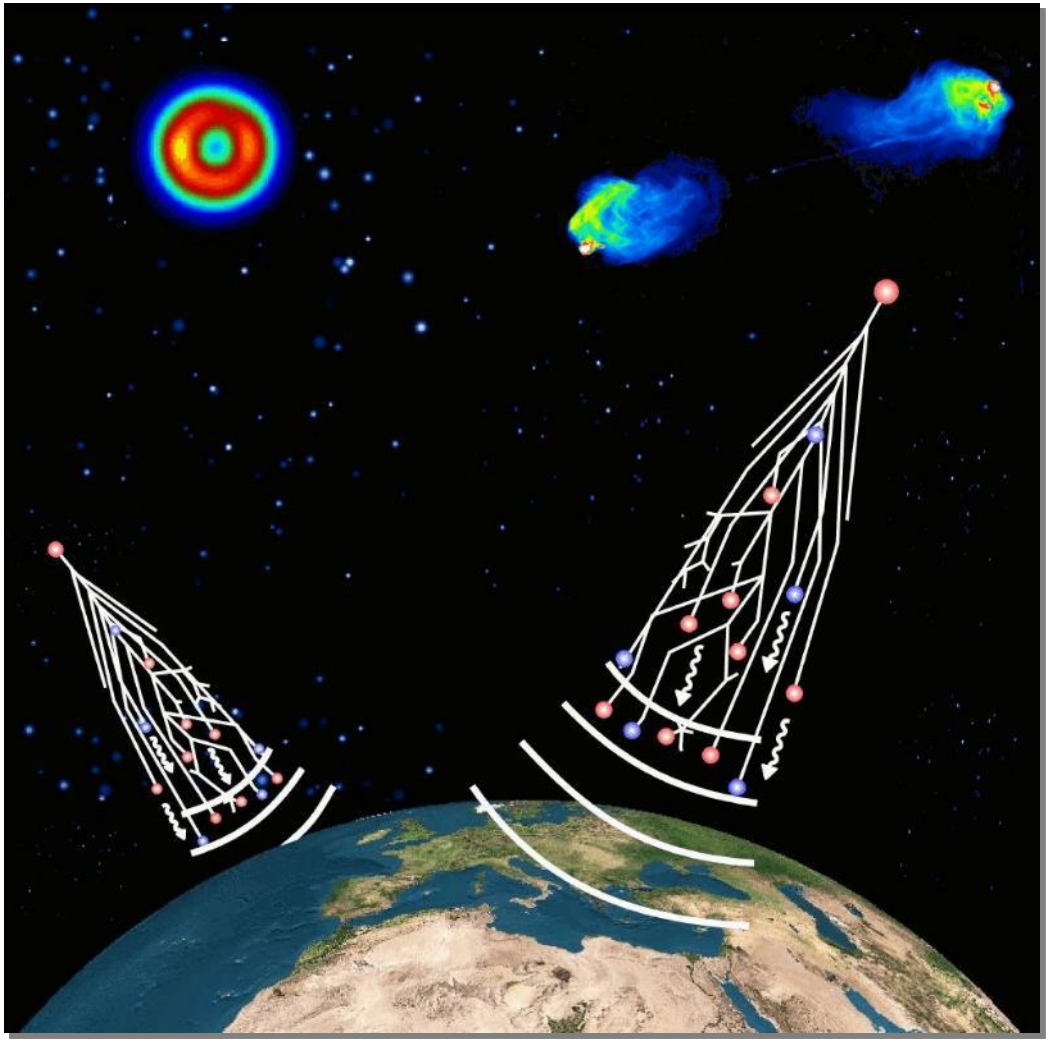
direction-dependent threshold	cut heavily or rely on simulations
radio-backgrounds	E > 10^{17} eV, exploit external triggers

Contents

- achievements of radio detection
- what can radio do for (U)HECR science



Improvement of hybrid measurements

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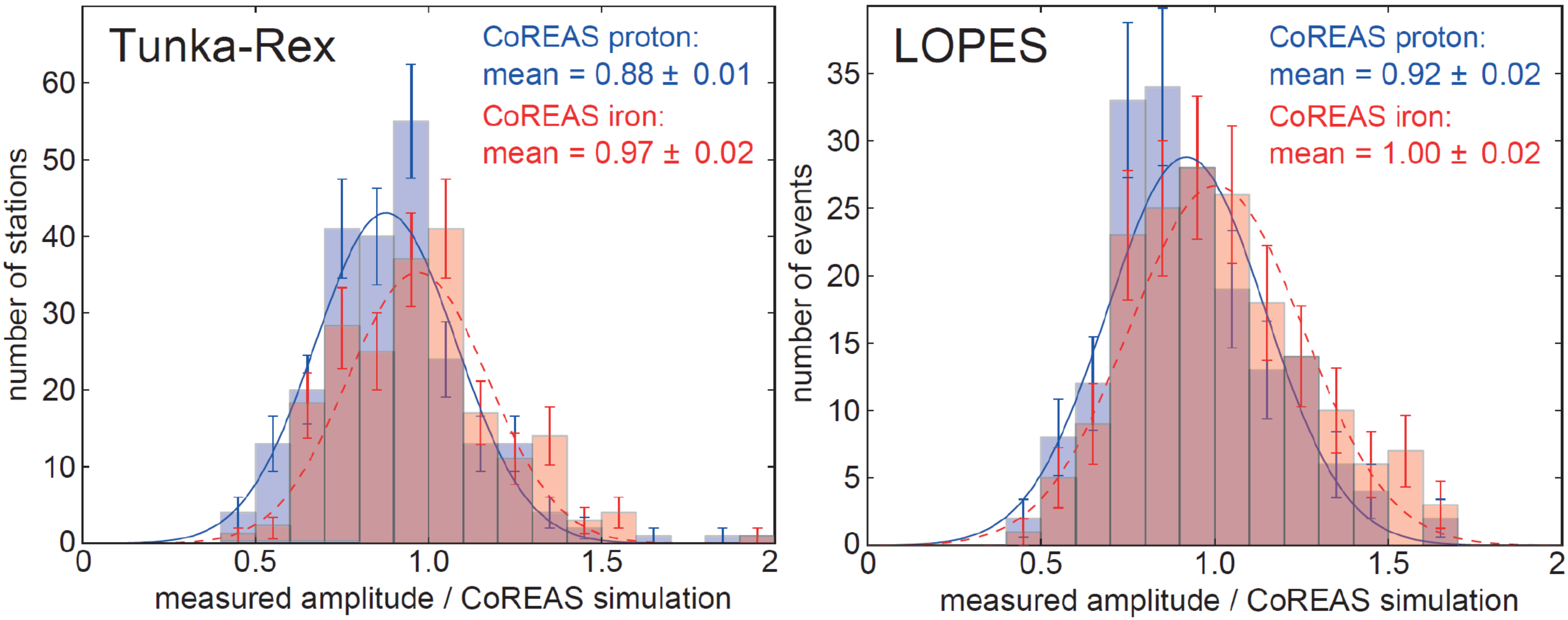
- existing cosmic-ray detectors can often be equipped with radio antennas at limited cost (re-use „infrastructure“)
- incorporation of radio detectors provides many advantages
  - pure measurement of electromagnetic component
  - good energy resolution
  - Xmax measurements with 100% duty cycle
  - generally different systematic uncertainties
- caveat: for non-inclined showers detector spacing of ~200-300 m required, so interesting in energy range 10^{17} to few times 10^{18} eV

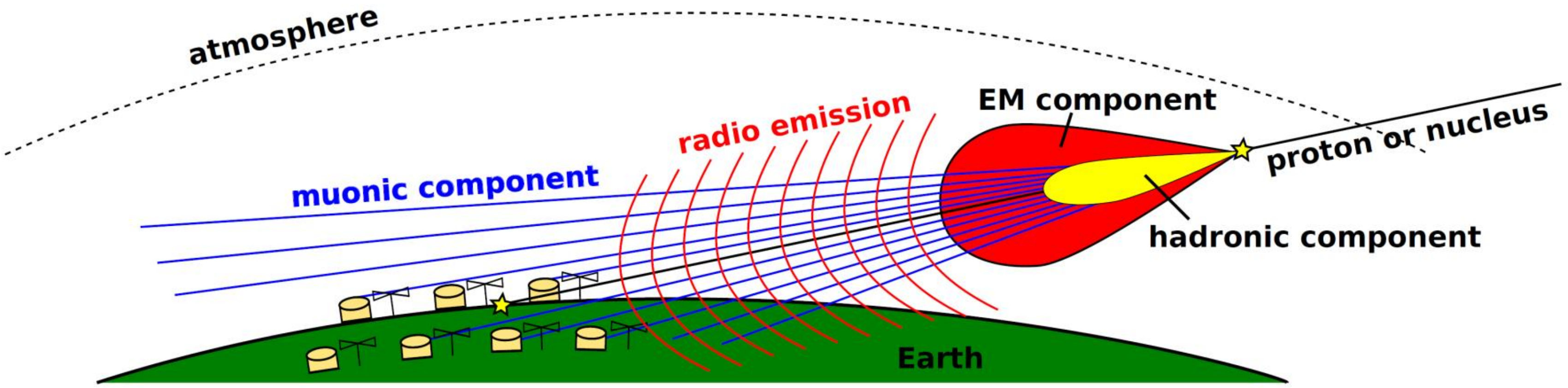
(Cross-)calibration of the energy scale

- many uncertainties in data interpretation are related to uncertainties of the absolute energy scale
- measuring radio emission allows calibrating the energy scale
  - among different experiments (e.g., Auger‘s radiation energy@10^{18} eV)
  - against first-principle calculations (within 10% seems feasible)



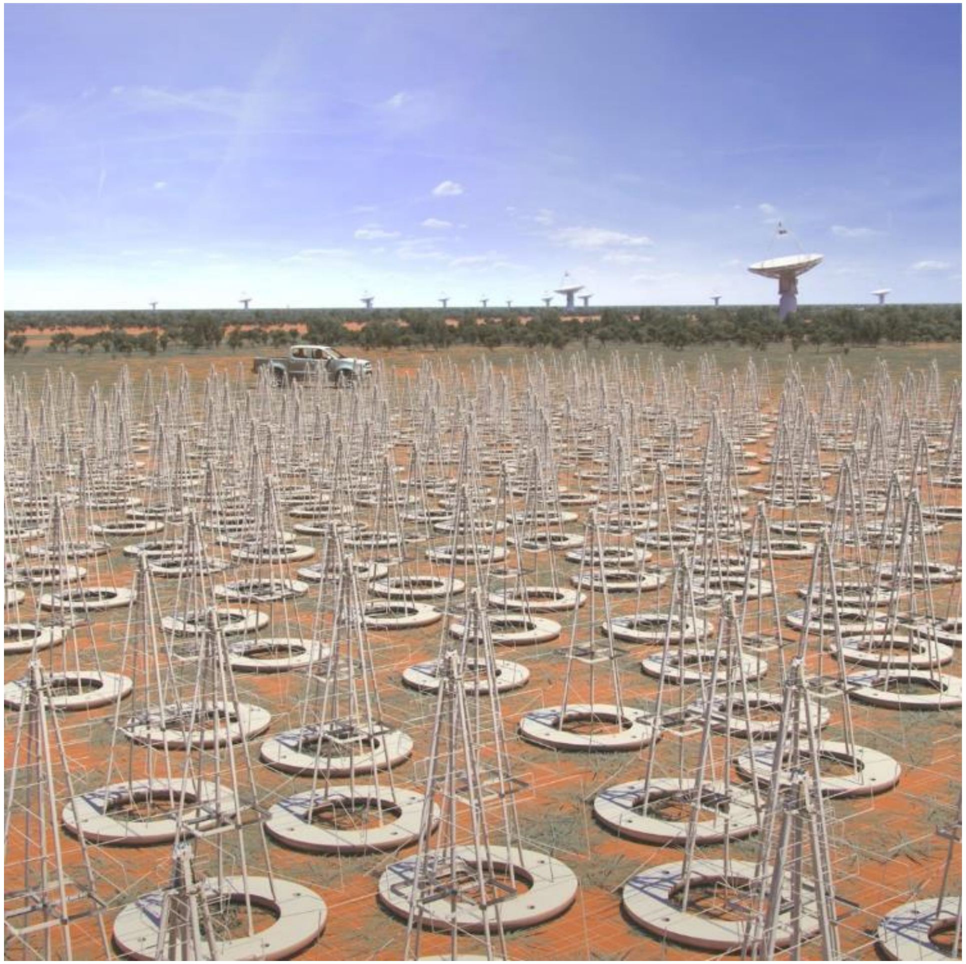
Tunka-Rex & LOPES Collaborations, ARENA 2016 and submitted to PLB

Radio measurements of inclined showers



- combined measurements of inclined showers with particle detectors and radio antennas are an attractive option
  - particle detectors measure muons, radio detectors measure em component
  - range >~ 10^{18} eV will be above Galactic noise
  - common detector grid spacing – can share infrastructure – lower cost
  - useful also as veto for neutrino-induced air showers (small footprint)
- radio detection generally seems to be the most favorable technique to measure the electromagnetic component of inclined air showers
- see also plans for GRAND experiment for detection of neutrinos

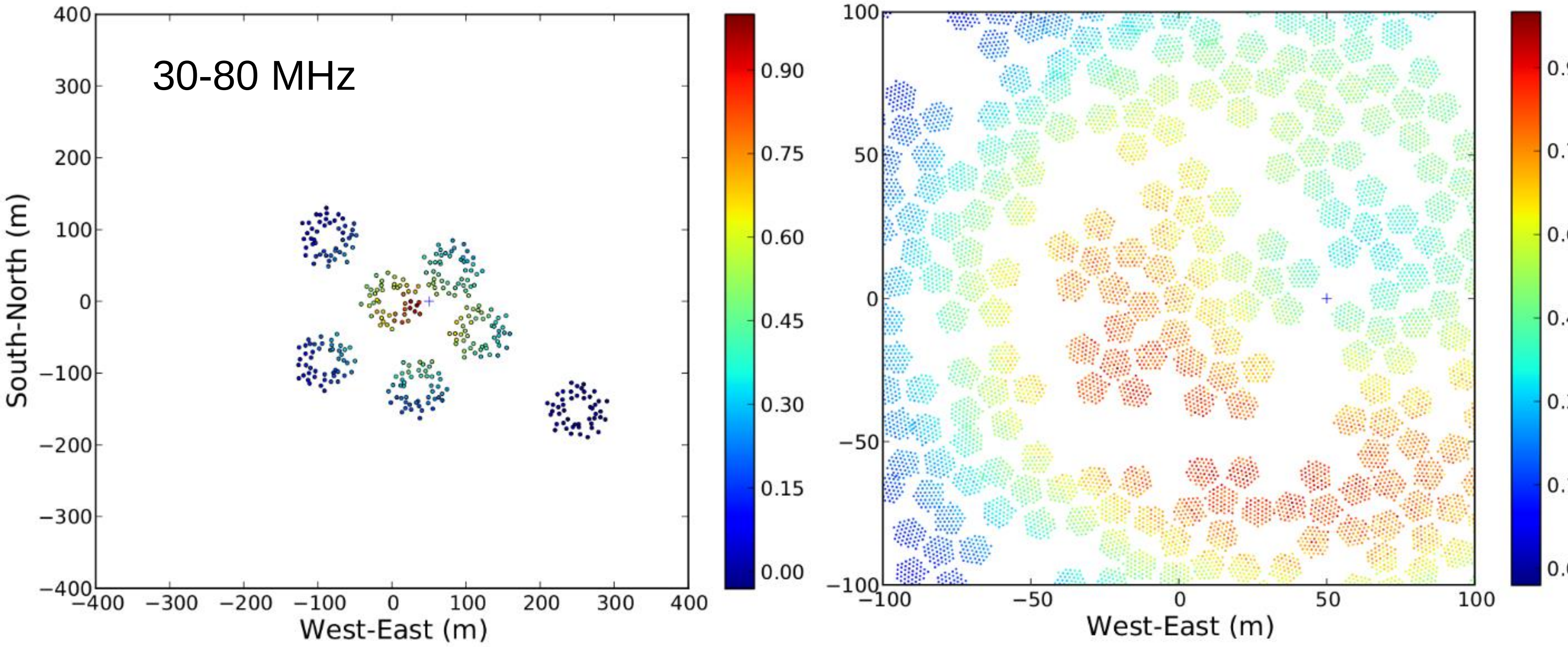
Very dense arrays - Square Kilometre Array



- in the final design stages
- to be built in western Australia
- first science 2020
- planned completion 2023
- >60,000 dual-polarized antennas within 750 m diameter
- bandwidth 50-350 MHz
- can be used for air shower detection with minor additions
- precision measurements in energy range of ~$10^{16.5}$ to $10^{18.5}$

TH et al., ARENA2016 conference, arXiv:1608.08869

SKA will provide precision measurements



- **Xmax determination with well below 10 g/cm² resolution predicted by simulation study based on LOFAR reconstruction approaches**

A. Zilles et al., ARENA2016 conference

Summary and conclusions

- radio detection of CRs has boomed and matured in the last decade
- we have clearly established
  - detailed understanding of complex radio emission physics (within 10%)
  - determination of arrival direction (well below 0.5°)
  - determination of air shower energy (~15%, room for improvement)
  - radio signal sensitivity to Xmax (<20 g/cm^2 for dense arrays and 40 g/cm^2 for sparse arrays, but with significant room for improvement)
- potential for application
  - high-duty-cycle energy & mass reconstruction in hybrid arrays
  - cross-calibration of the energy scale of cosmic-ray detectors
  - independent calibration of energy scale from first principle calculations
  - air shower physics via measurement of purely electromagnetic cascade

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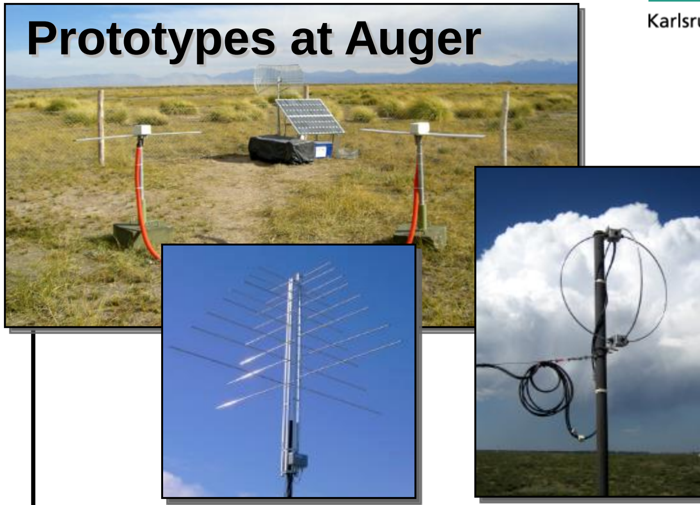
Backup slides

First-Generation modern MHz experiments



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

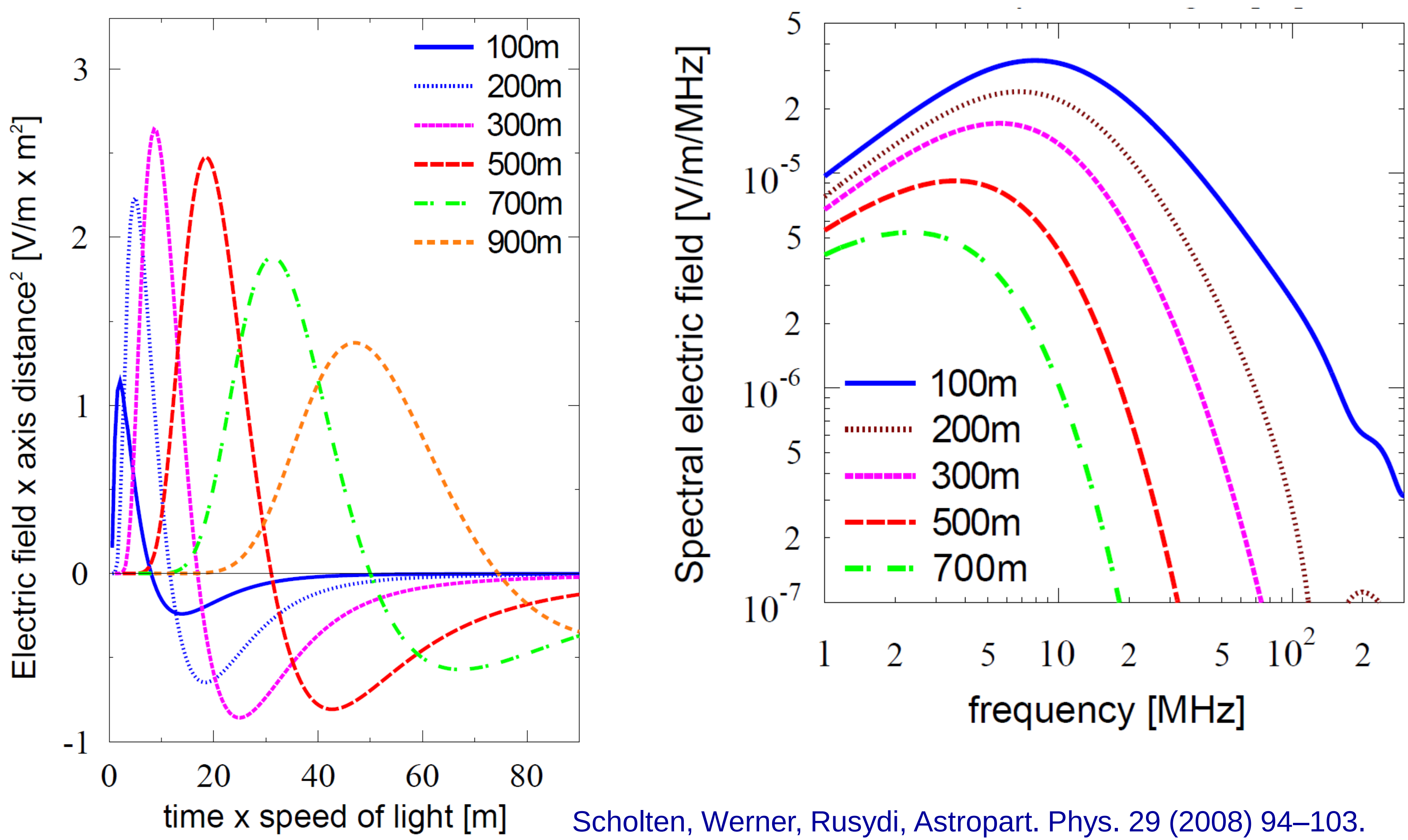
Falcke & Gorham propose „geosyn-chrotron approach“

Second-Generation modern MHz experiments

Karlsruhe Institute of Technology

2010 | 2011 | 2012 | 2013

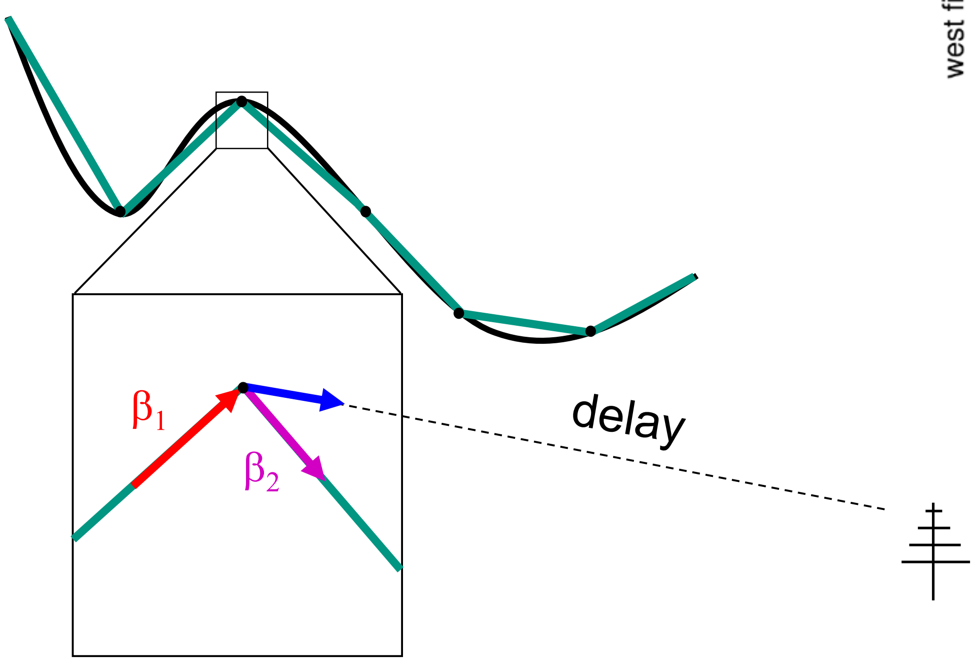
Broad-band pulses – mostly in MHz regime

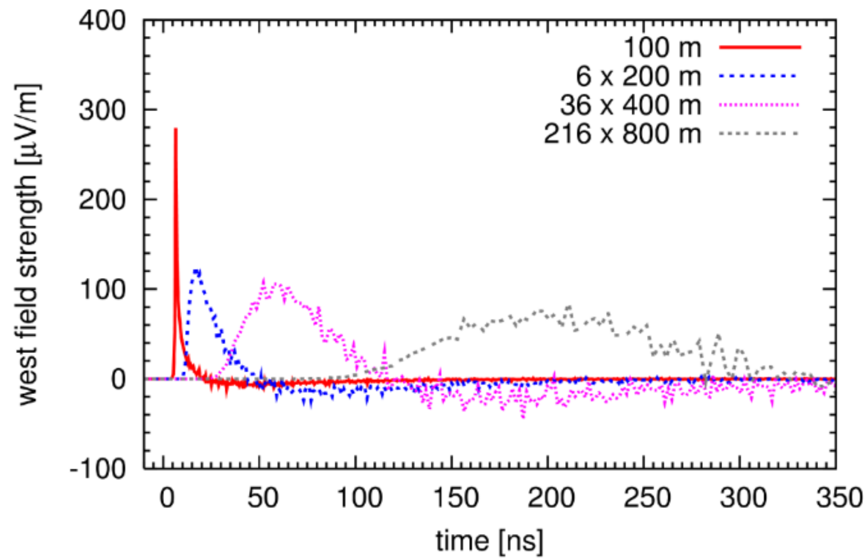


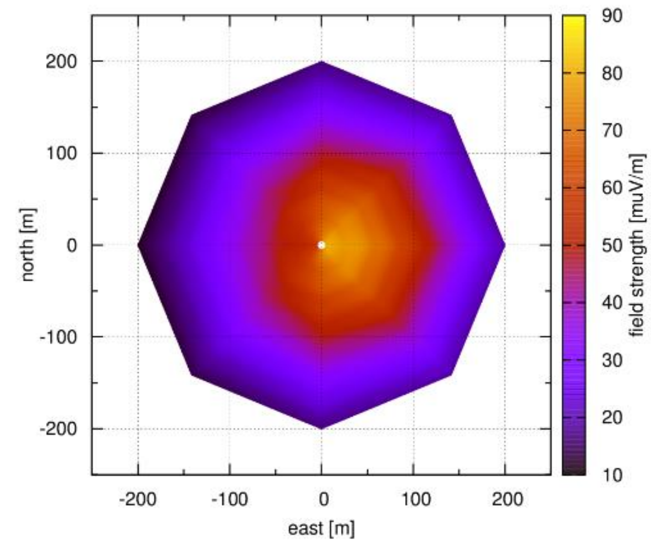
Scholten, Werner, Rusydi, Astropart. Phys. 29 (2008) 94–103.

Radio emission simulations – a vital tool

- full-scale air shower Monte Carlo
- „endpoint formalism“ for the calculation of radio emission
- codes CoREAS and ZHAireS







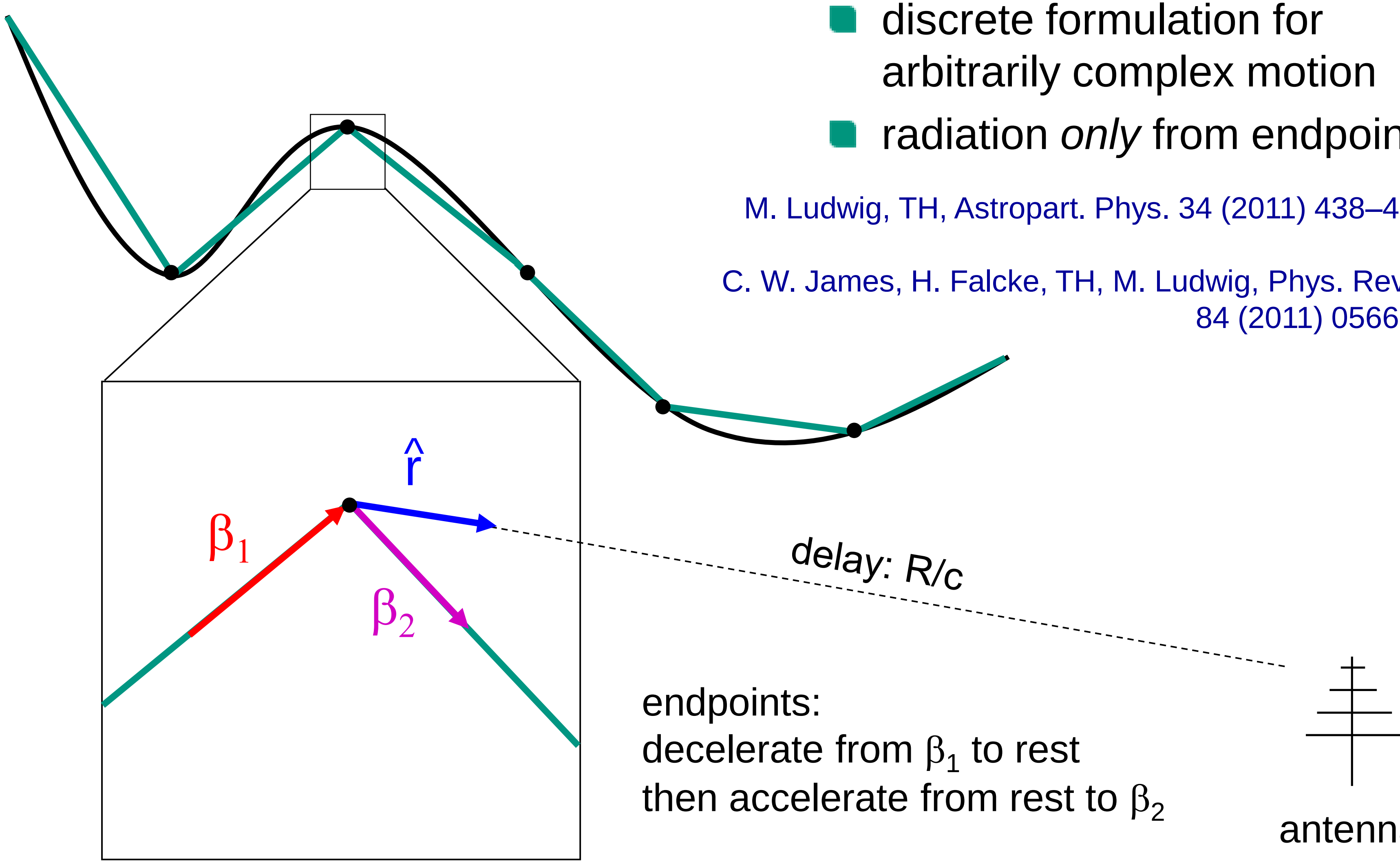
James, Falcke, Huege, Ludwig, Phys. Rev. E. 84, 056602
Ludwig & Huege, Astrop. Physics 34, 438-446

CoREAS: endpoint formalism plus shower sim

- discrete formulation for arbitrarily complex motion
- radiation *only* from endpoints

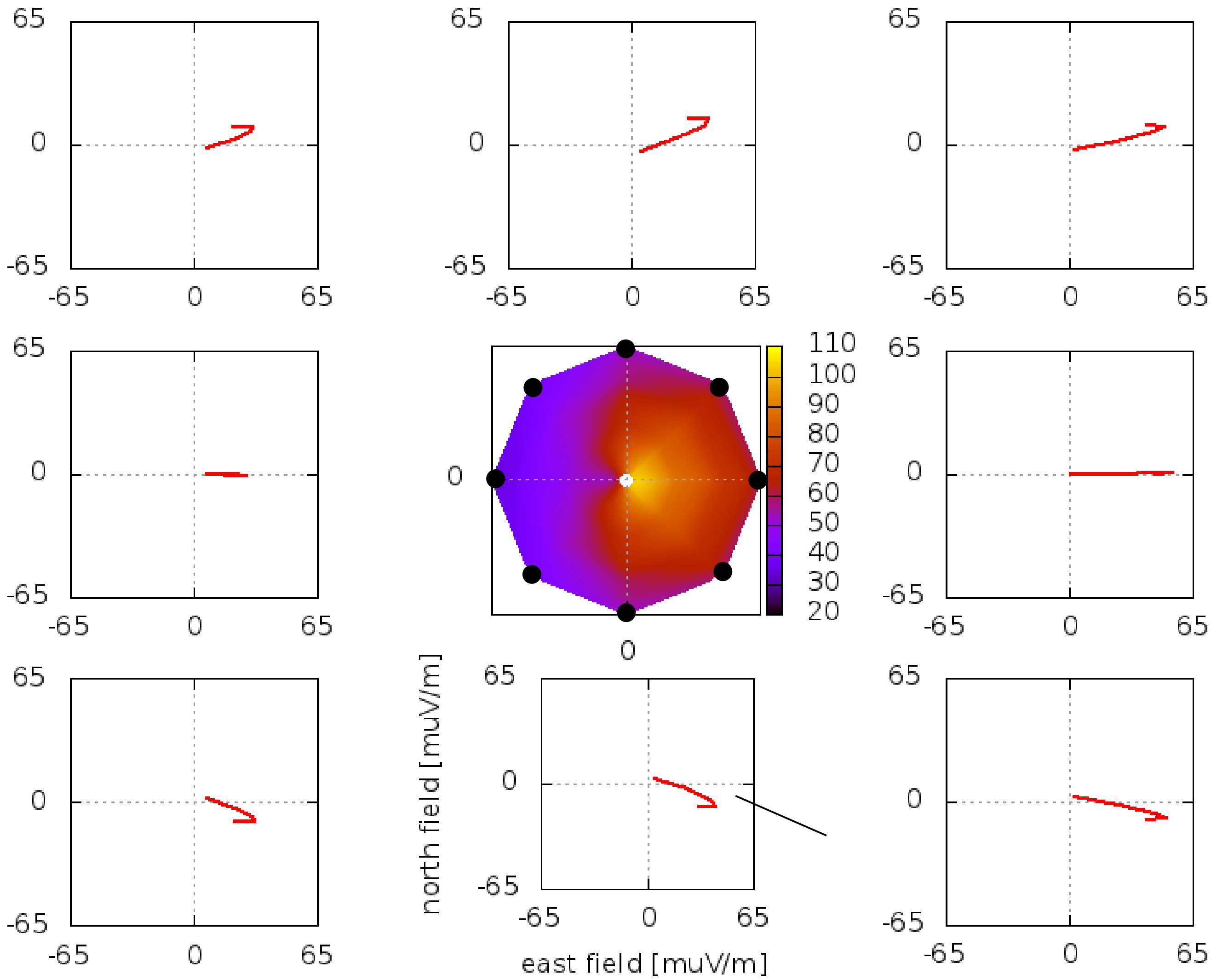
M. Ludwig, TH, Astropart. Phys. 34 (2011) 438–446.

C. W. James, H. Falcke, TH, M. Ludwig, Phys. Rev. E 84 (2011) 056602.



endpoints:
decelerate from β_1 to rest
then accelerate from rest to β_2

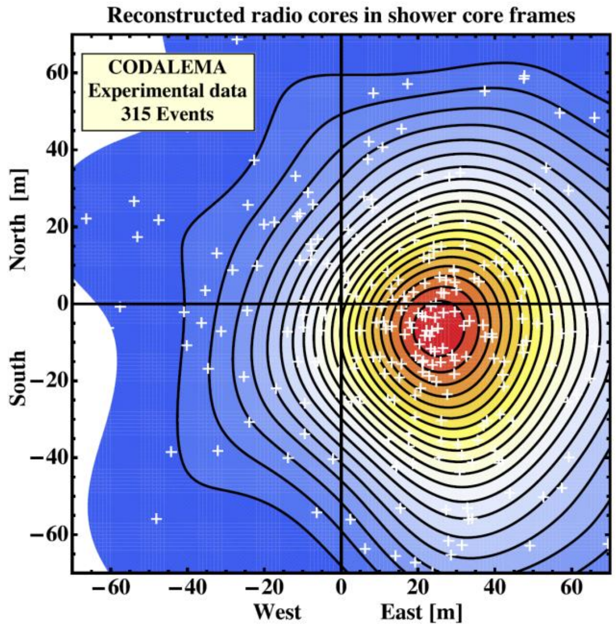
Complexity of signal polarization



- complex time evolution of electric field vector
- superposition of geomag-netic and charge excess emission

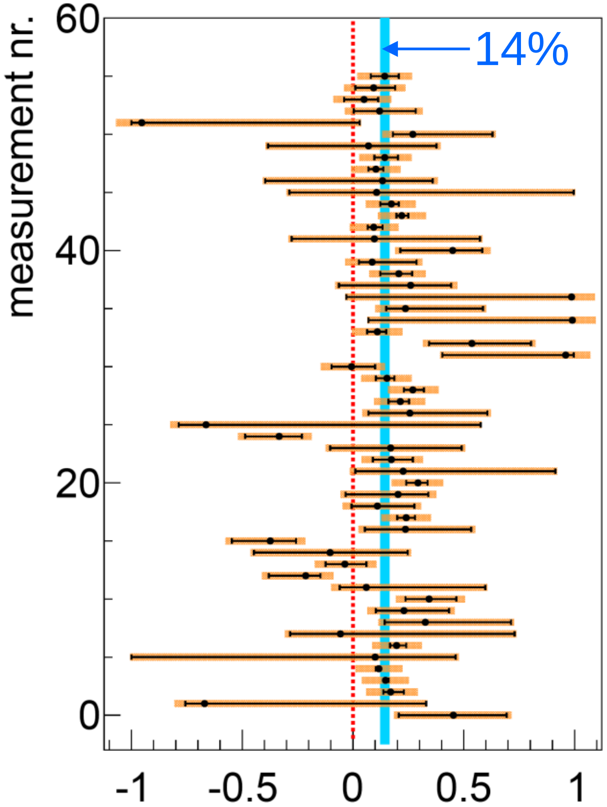
CoREAS simulations, TH et al., see id 548

Geomagnetic seen by all – but charge excess?



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

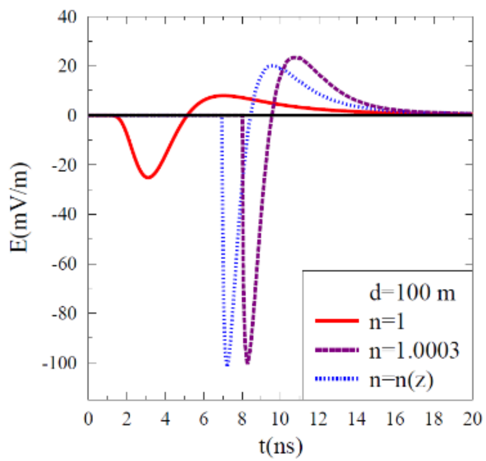
CODALEMA Coll., Astropart. Phys. 69 (2015) 50–60.



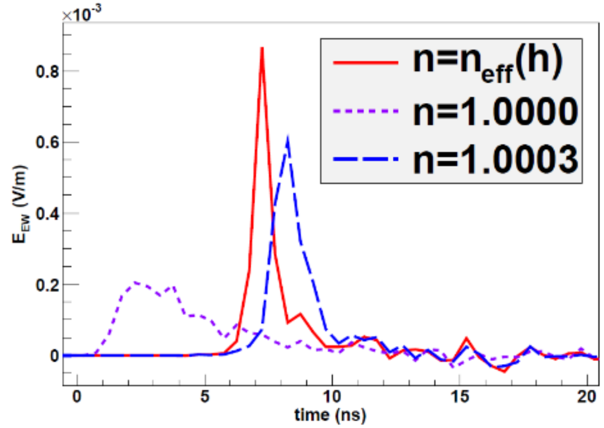
- AERA quantifies radial component to 14 ± 2%

Pierre Auger Coll., Phys. Rev. D 89 (2014) 052002.

Refractive index effects

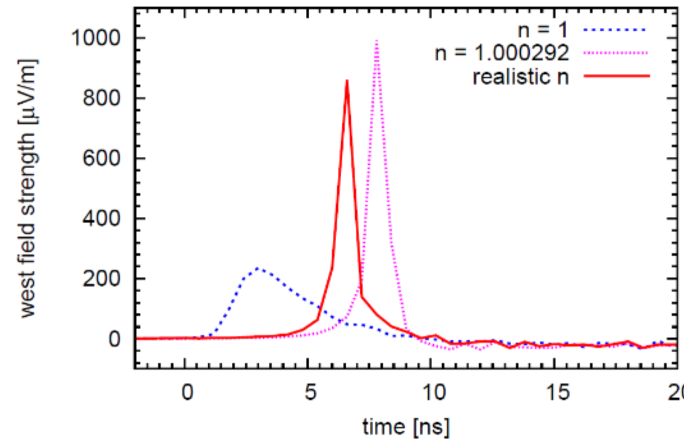


K.D. de Vries et al,
PRD (2010)

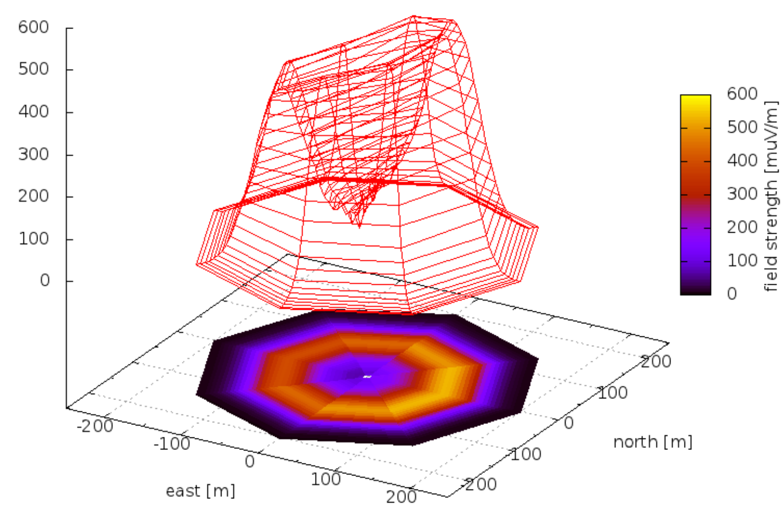


Alvarez-Muniz et al.,
Astrop. Phys. (2011)

M. Ludwig et al., ICRC 2011



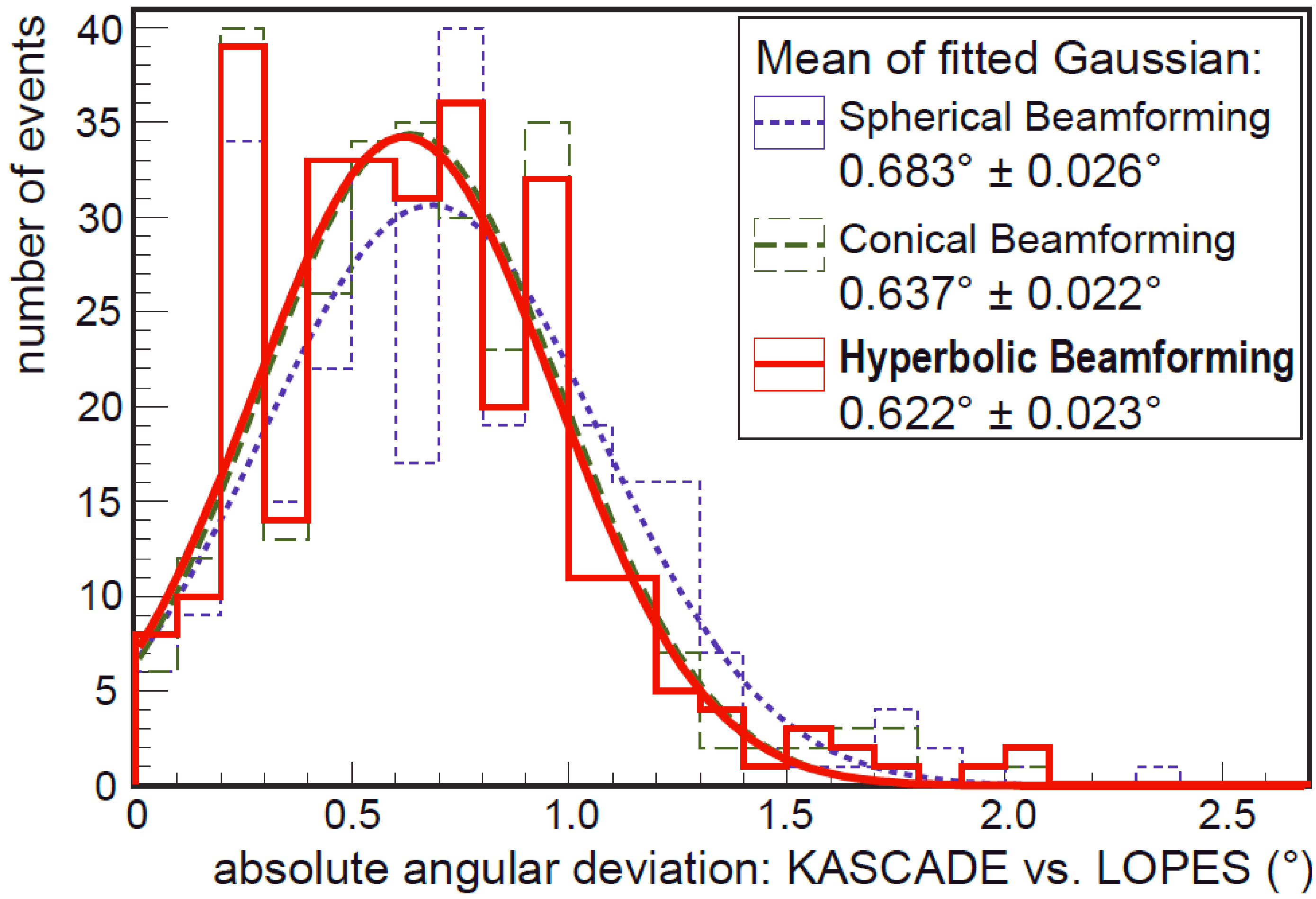
- time compression of radio pulses along the Cherenkov angle
  - power at high frequencies, up to several GHz
  - Cherenkov ring arises

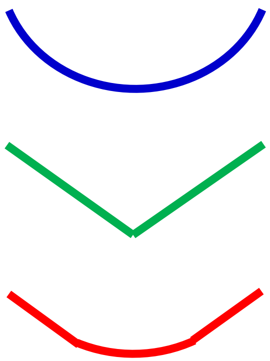


TH et al., ARENA2012

300-1200 MHz

Accuracy of direction reconstruction

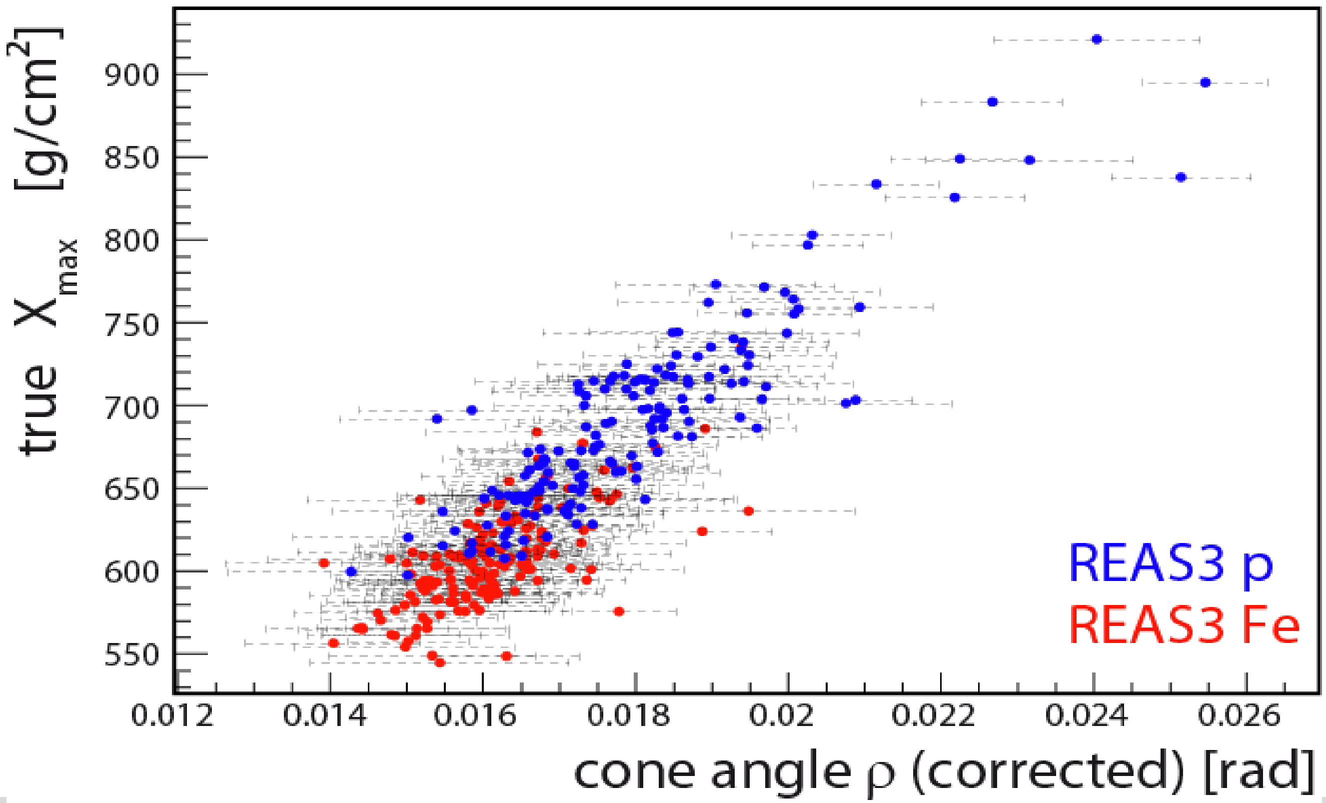




- from simulations: LOPES alone better than 0.1°

X_{max} reconstruction with cone angle

- X_{max} proportional to ρ after correction for zenith angle
  - precision: ~30 g/cm² for REAS3 simulations without noise
  - precision: ~200 g/cm² for LOPES measurements



LOPES,
ICRC 2011

Tim Huege <tim.huege@kit.edu> frank.schroeder@kit.edu
Institut für Kernphysik, KIT Campus North

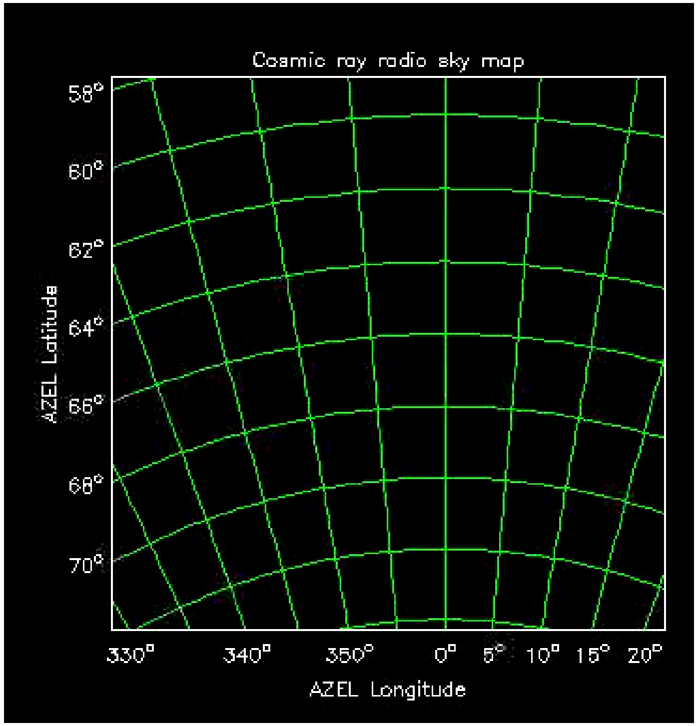
External versus self-triggering

- 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?

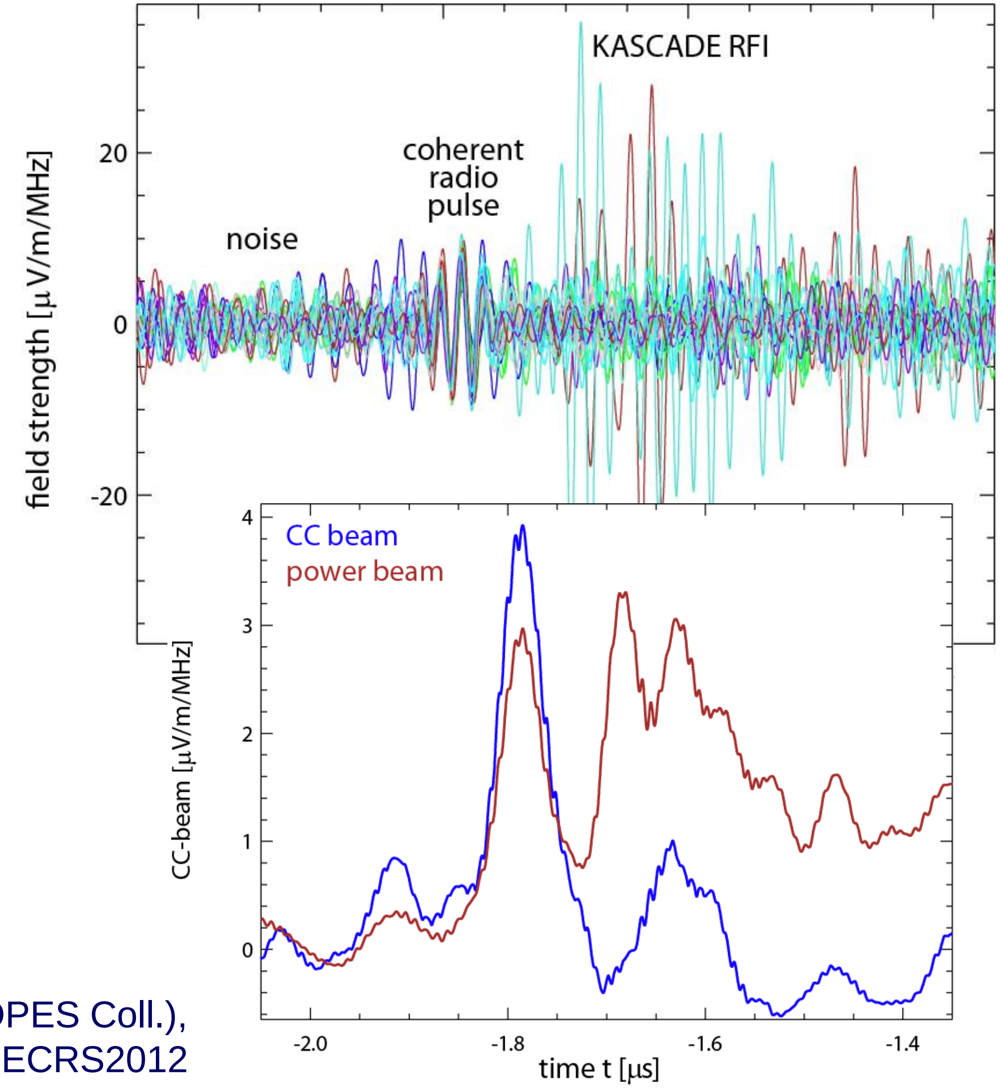
- self-triggering is very challenging
  - transient noise (RFI)
- it has been done successfully
  - TREND
  - AERA prototype and AERA
  - CODALEMA-III
- but: radio trigger purity is very low
  - need coincidence with other detector for clear identification
  - or need to use many details of radio signal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

Direction reconstruction with interferometry



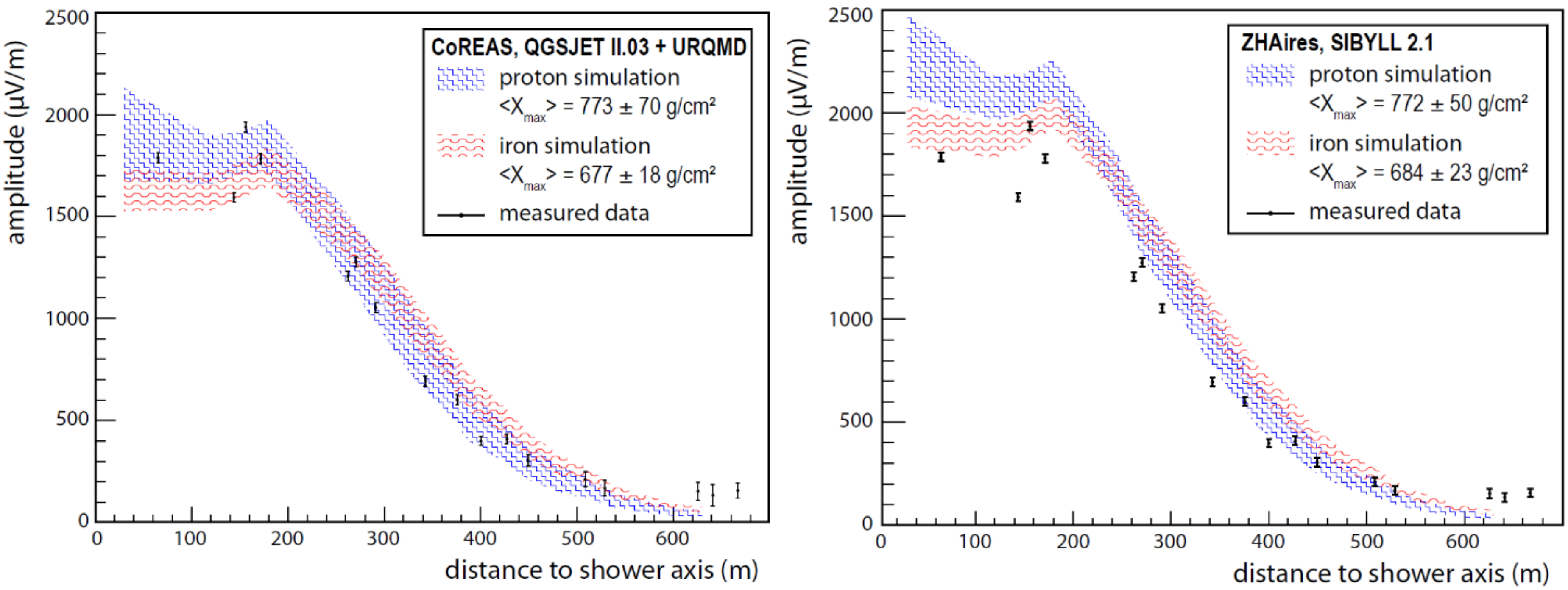
Sky map of a cosmic ray radio flash

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



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

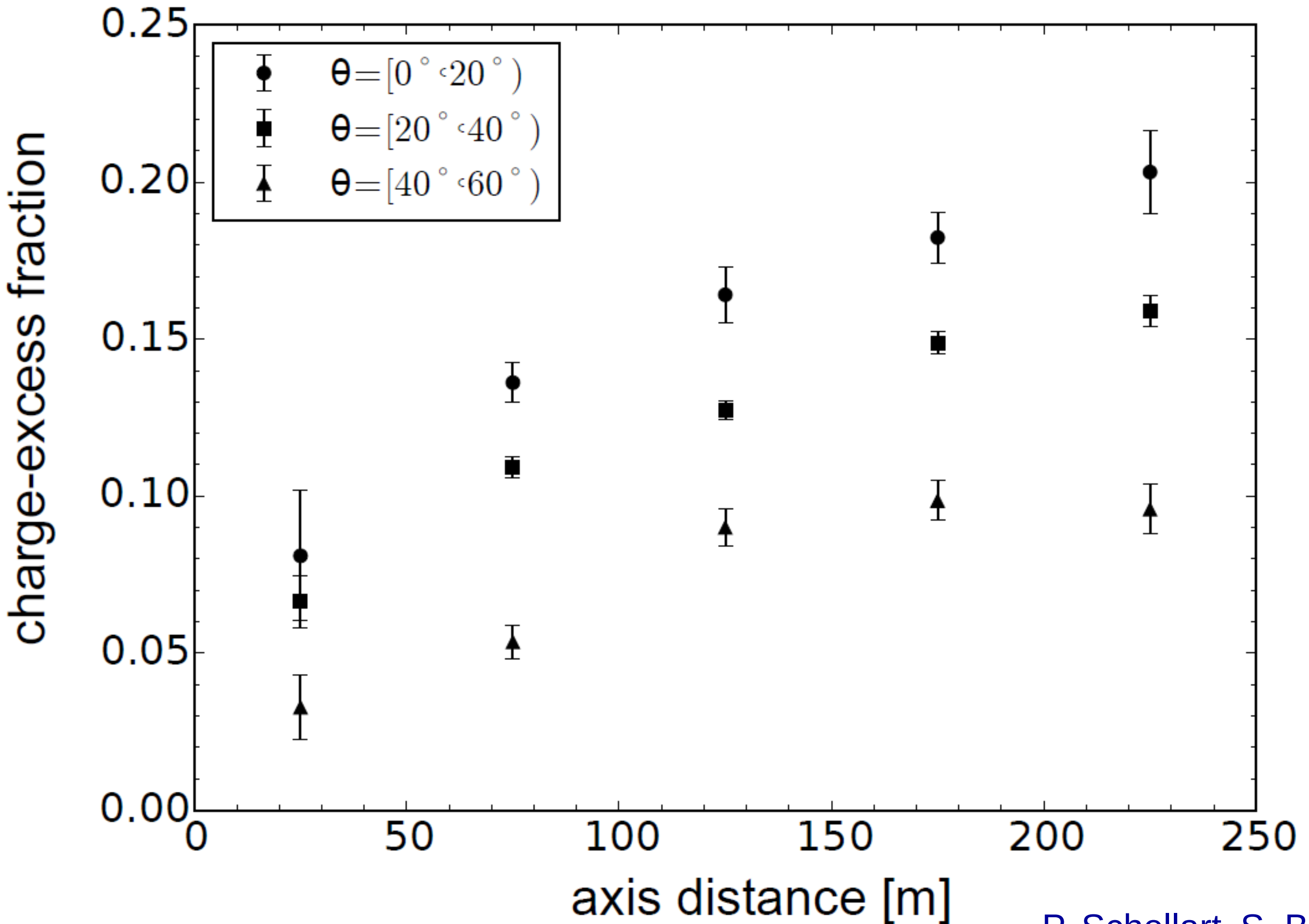
Comparison of simulations with AERA data



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

Pierre Auger Collaboration, ICRC2013, id #899

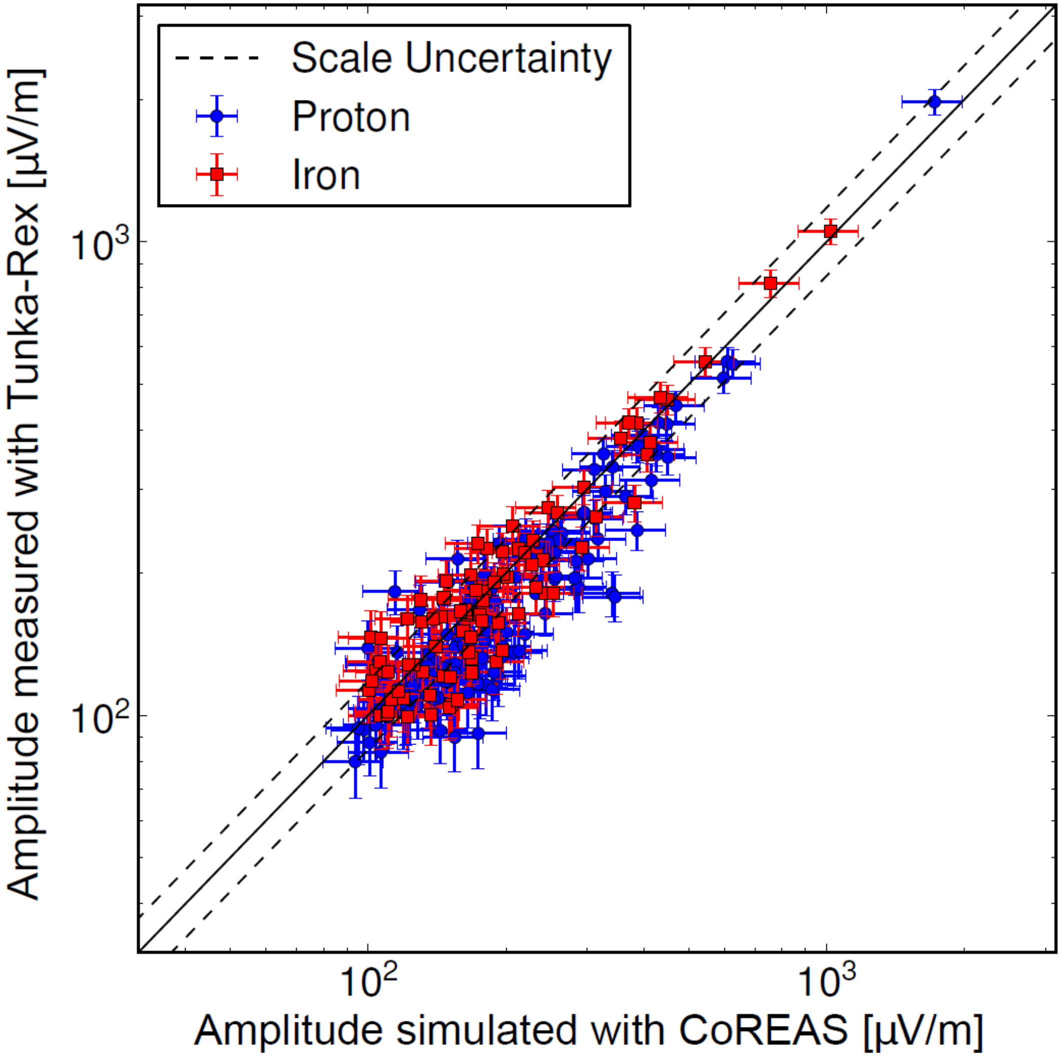
Charge excess contribution is not a constant



- depends on shower azimuth angle and observer lateral distance

P. Schellart, S. Buitink, A. Corstanje, et al., JCAP 10 (2014) 14.

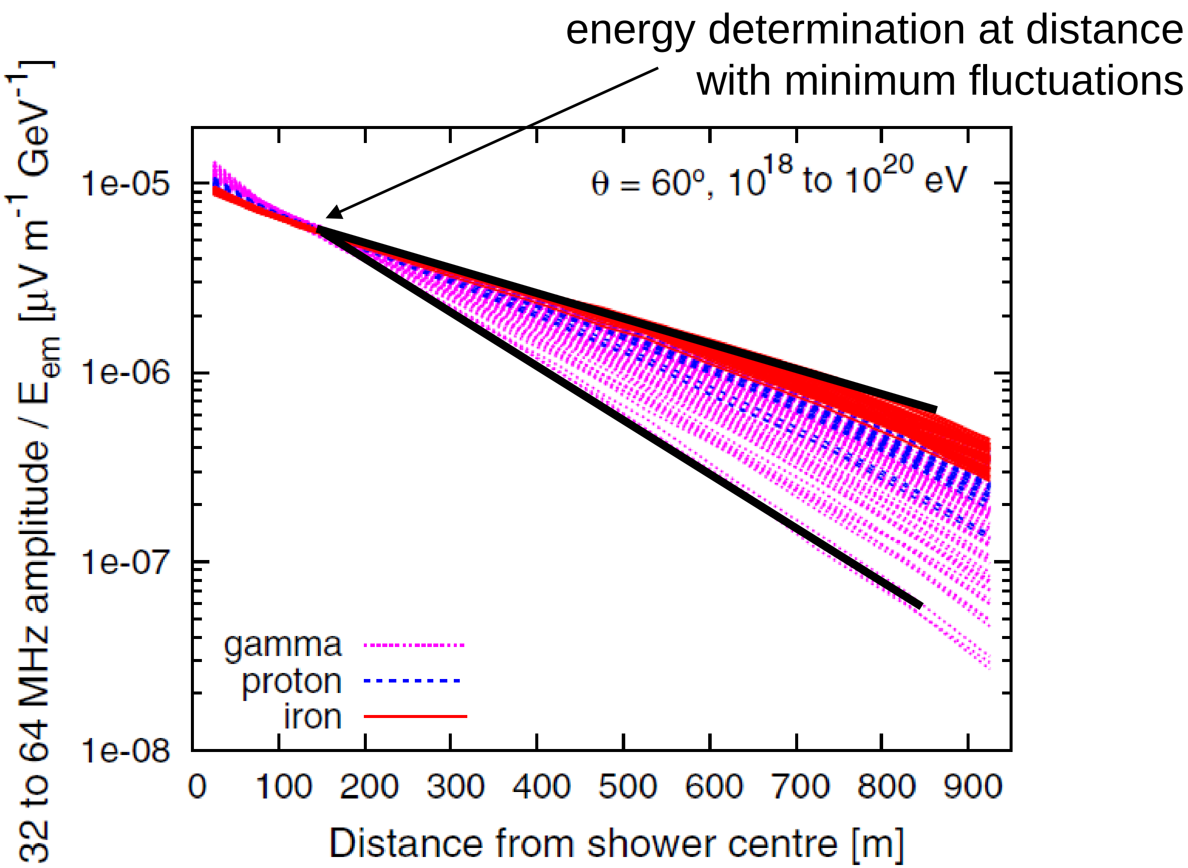
Comparison of simulations with Tunka-Rex data



- very good agreement between CoREAS simulations and Tunka-Rex data

Tunka-Rex Coll., Nucl. Instr. Meth. A 802 (2015) 89–96.

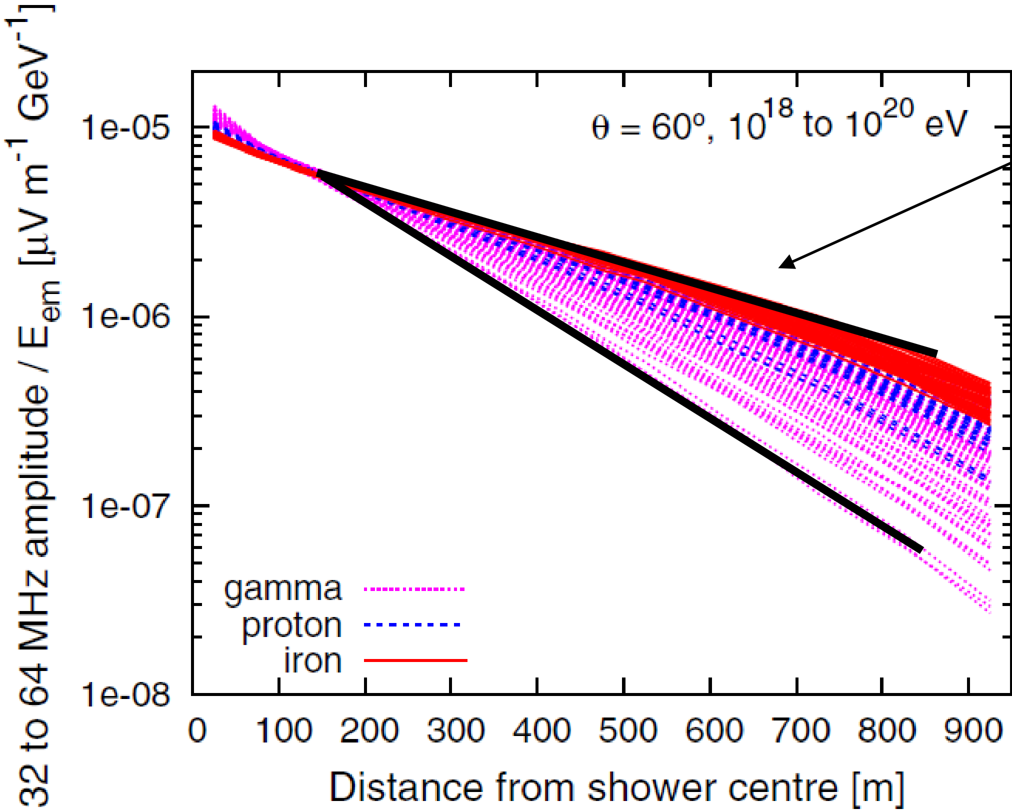
Expected energy sensitivity of radio detection



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

- linear scaling & characteristic distance for best energy estimate

Expected energy sensitivity of radio detection

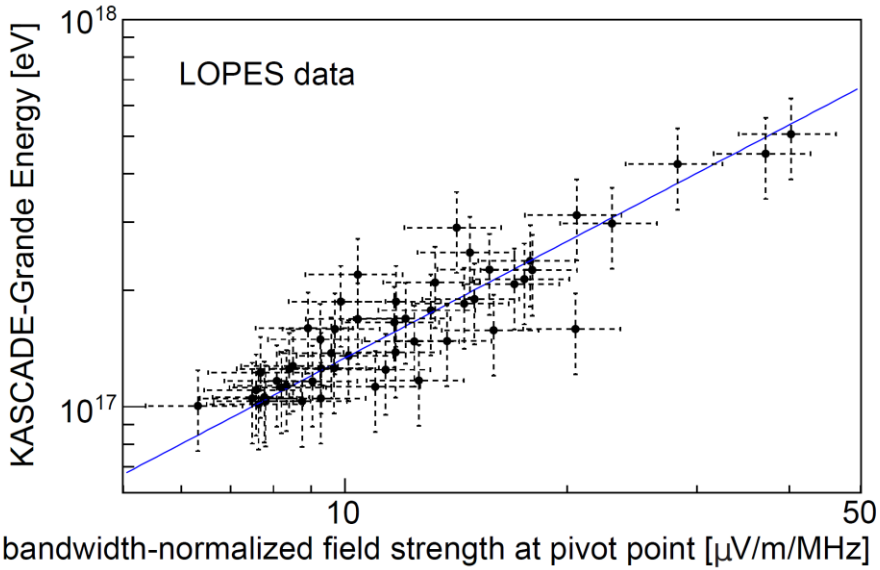


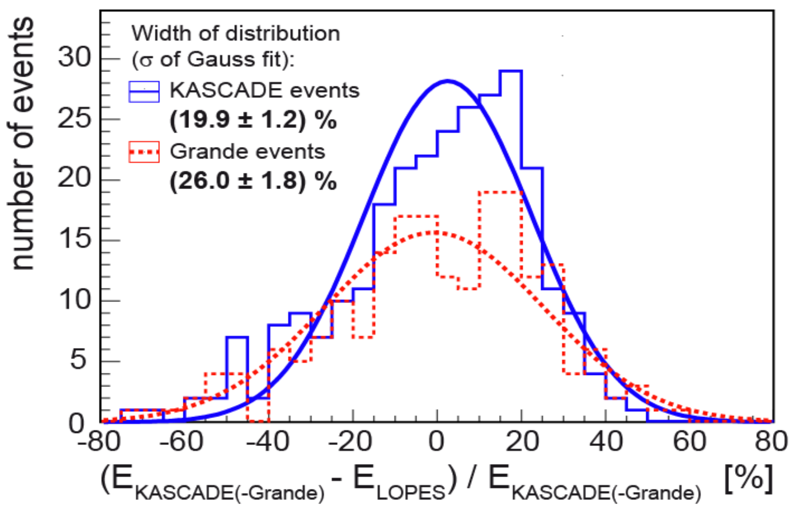
Xmax determination from slope of radio-LDF (better 2D signal distribution function)

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

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

LOPES energy reconstruction





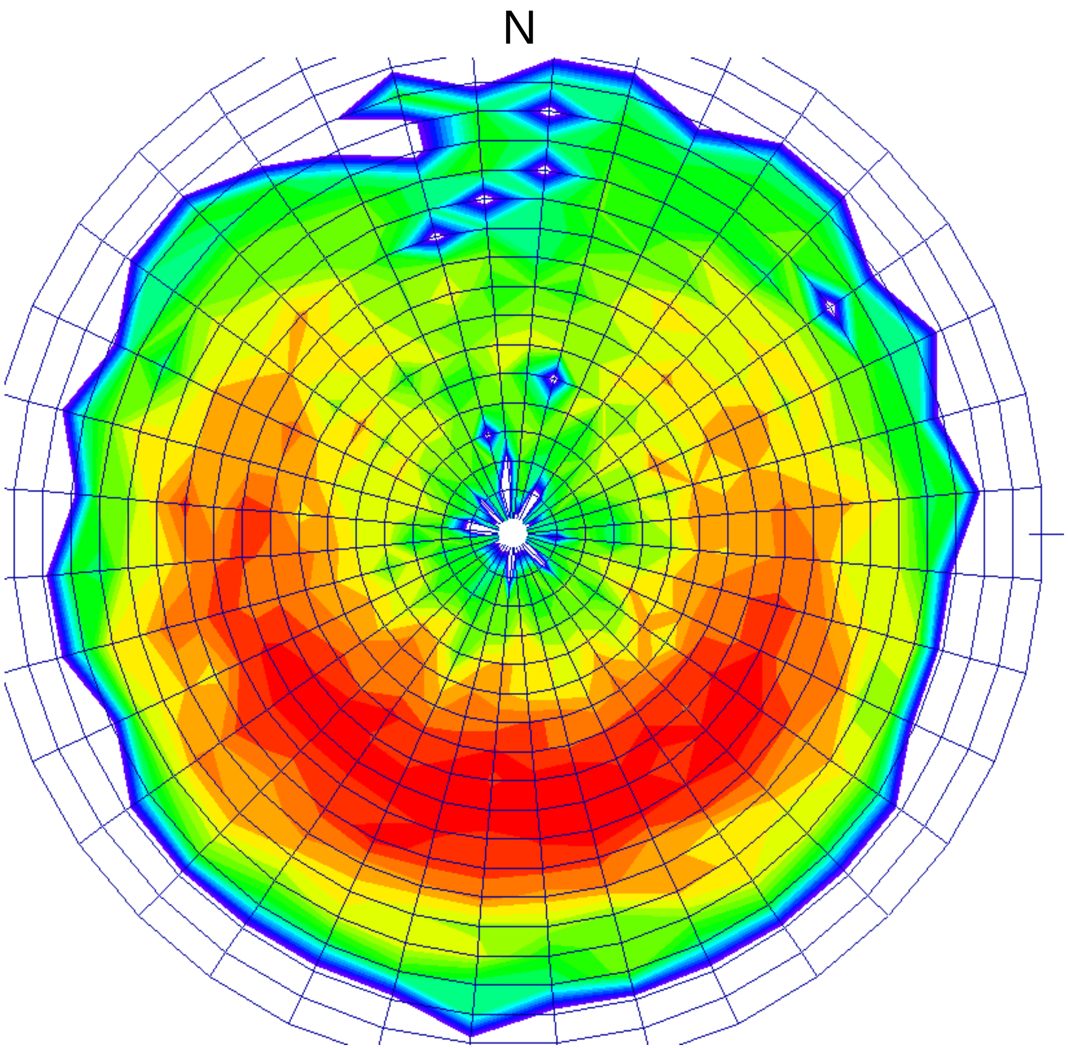
- linear correlation with 20-25% combined LOPES-KASCADE-Grande energy resolution
  - radio probably better, limited by KASCADE-Grande energy uncertainty of ~20%
  - simulations: ~8% intrinsic

LOPES Coll., Phys. Rev. D 90 (2014) 062001.

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

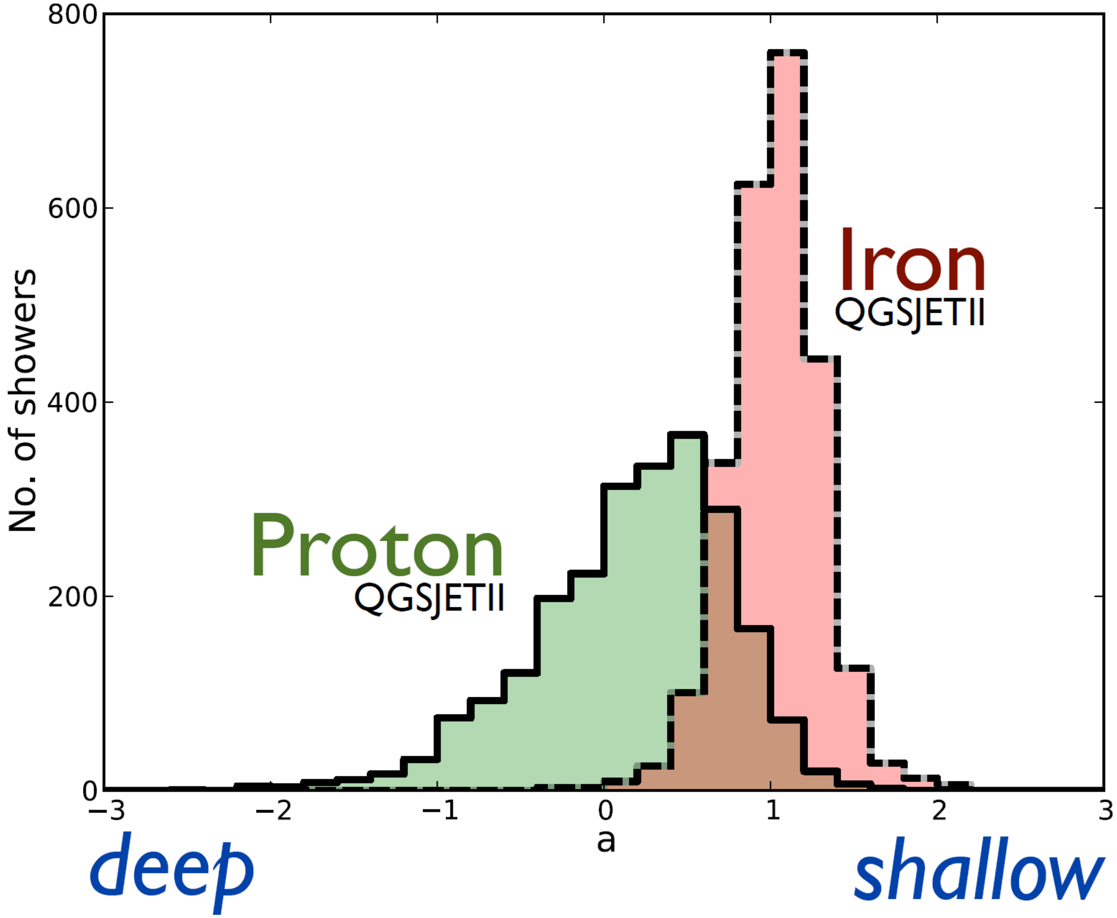
F.G. Schröder et al. (LOPES Coll.), ARENA2012

Direction-dependence of geomagnetic emission



- the dominant emission contribution scales with sin(geomagnetic angle)
- this leads to direction-dependent threshold – but with a well-defined characteristic

LOFAR unbinned analysis



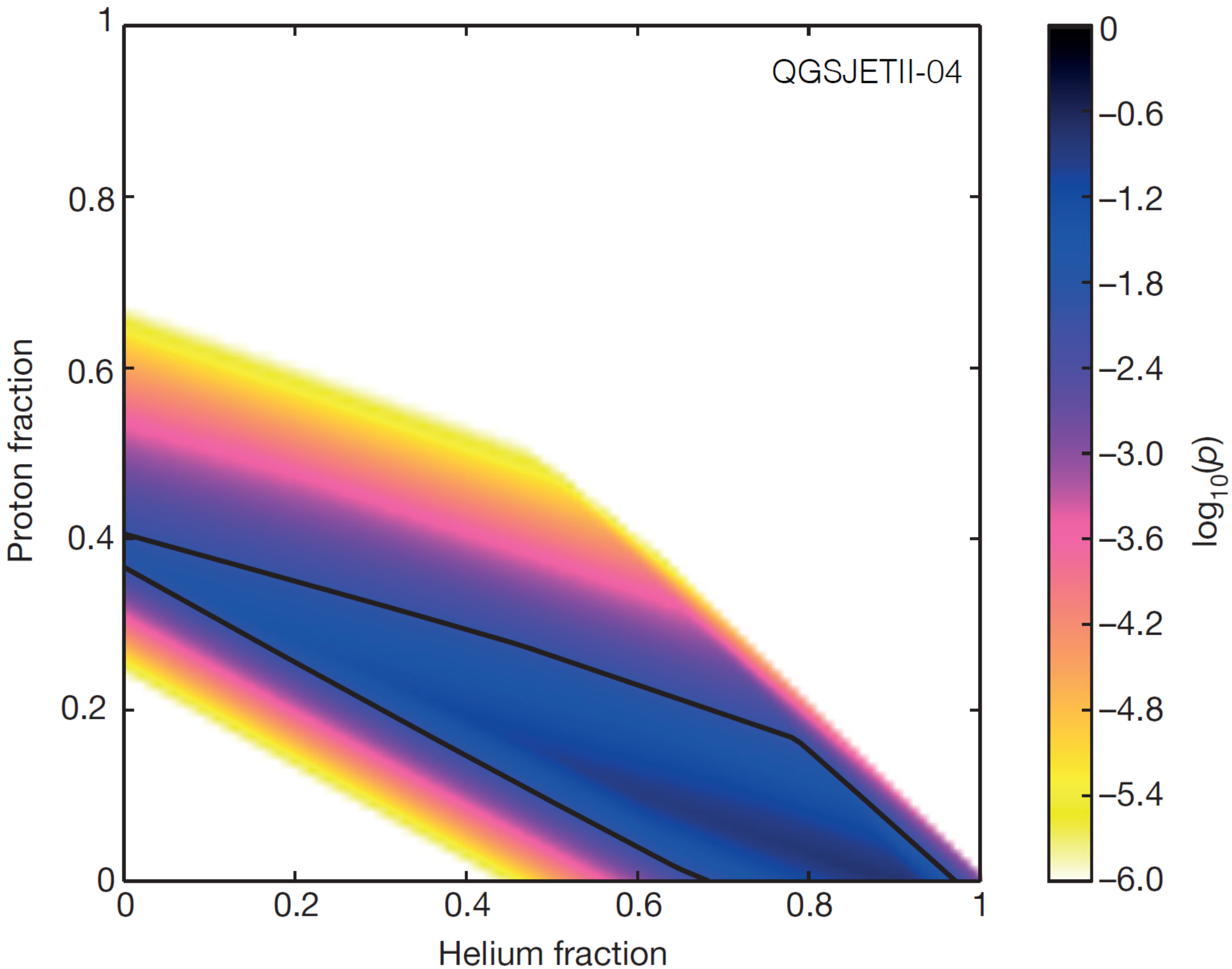
- use Xmax distribution rather than just mean
- for each shower determine value

$$a = \frac{\langle X_{\mathrm{proton}} \rangle - X_{\mathrm{shower}}}{\langle X_{\mathrm{proton}} \rangle - \langle X_{\mathrm{iron}} \rangle}$$

- compare cumulative a-distribution with simulations based on various composition assumptions

S. Buitink et al. Nature 435 (2016) 70

LOFAR four-component model scan



Total fraction of light elements (p+He) in [0.38,0.98] at 99% C.L.