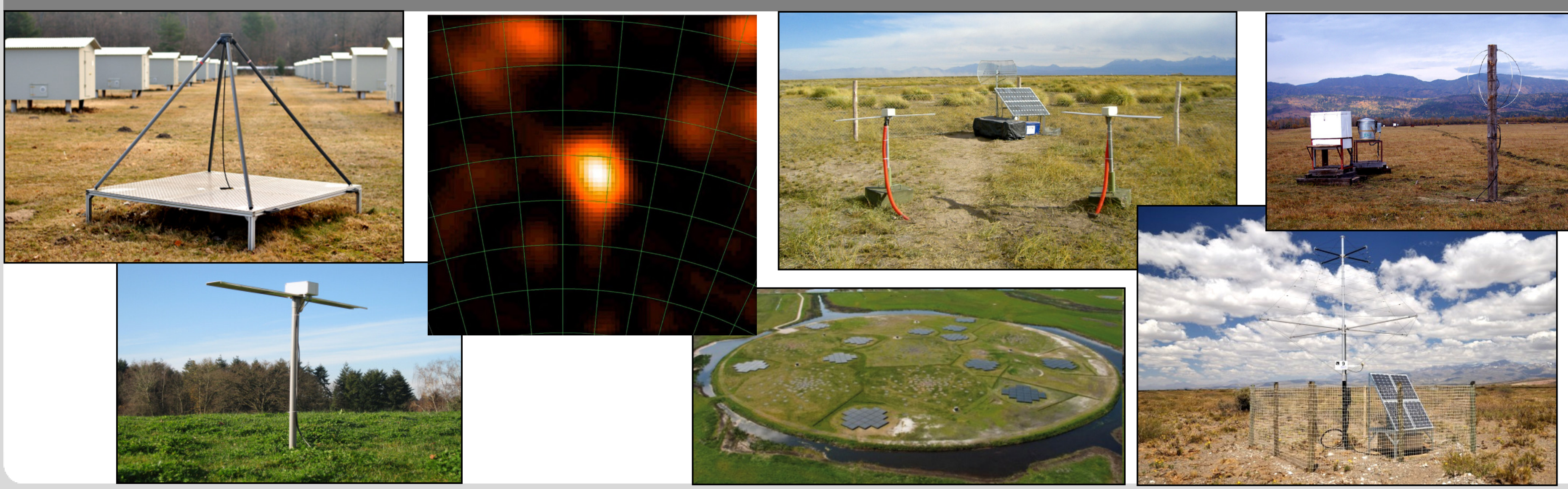
see also T. Huege,
Physics Reports 620 (2016) 1,
doi:10.1016/j.physrep.2016.02.001

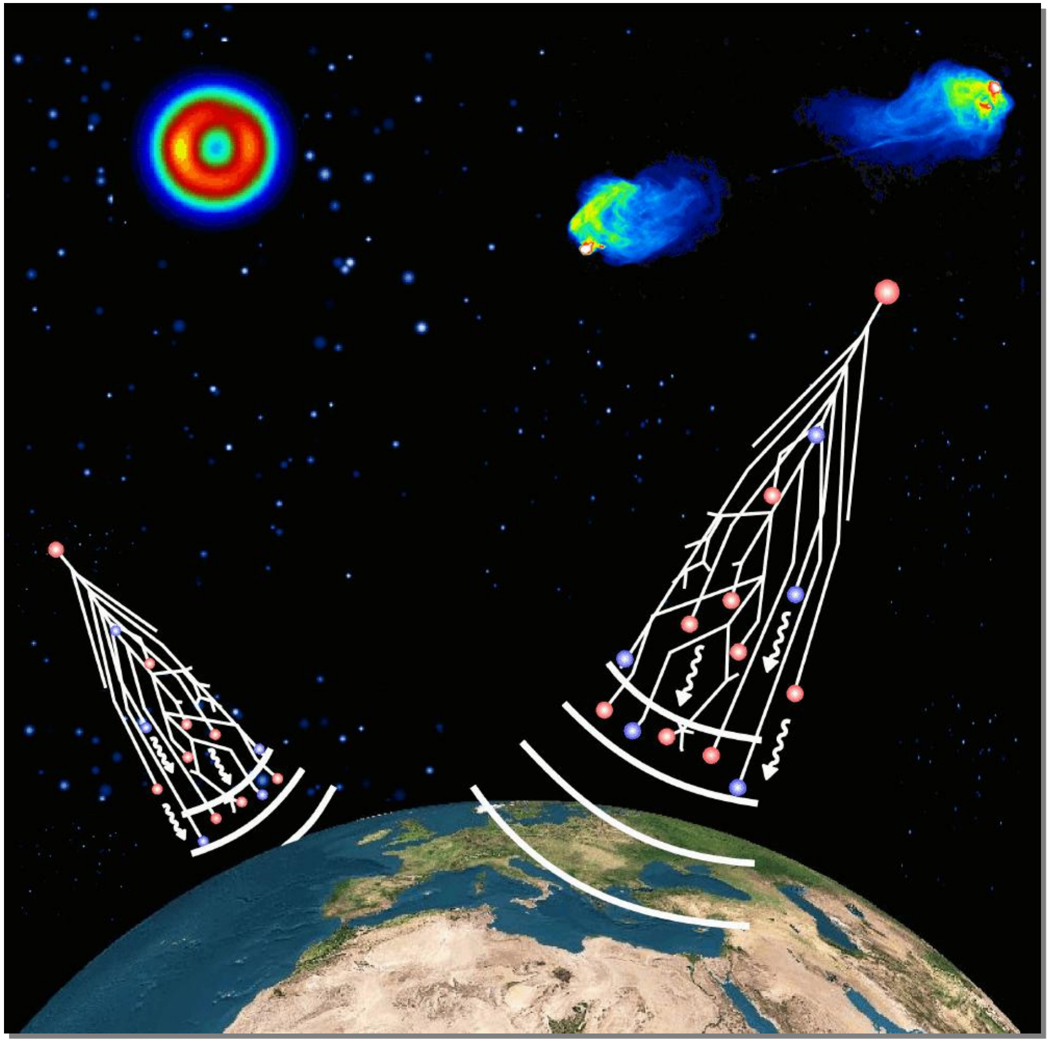
Radio detection of cosmic rays, and CoREAS

Tim Huege (Karlsruhe Institute of Technology & Vrije Universiteit Brussel)



Contents

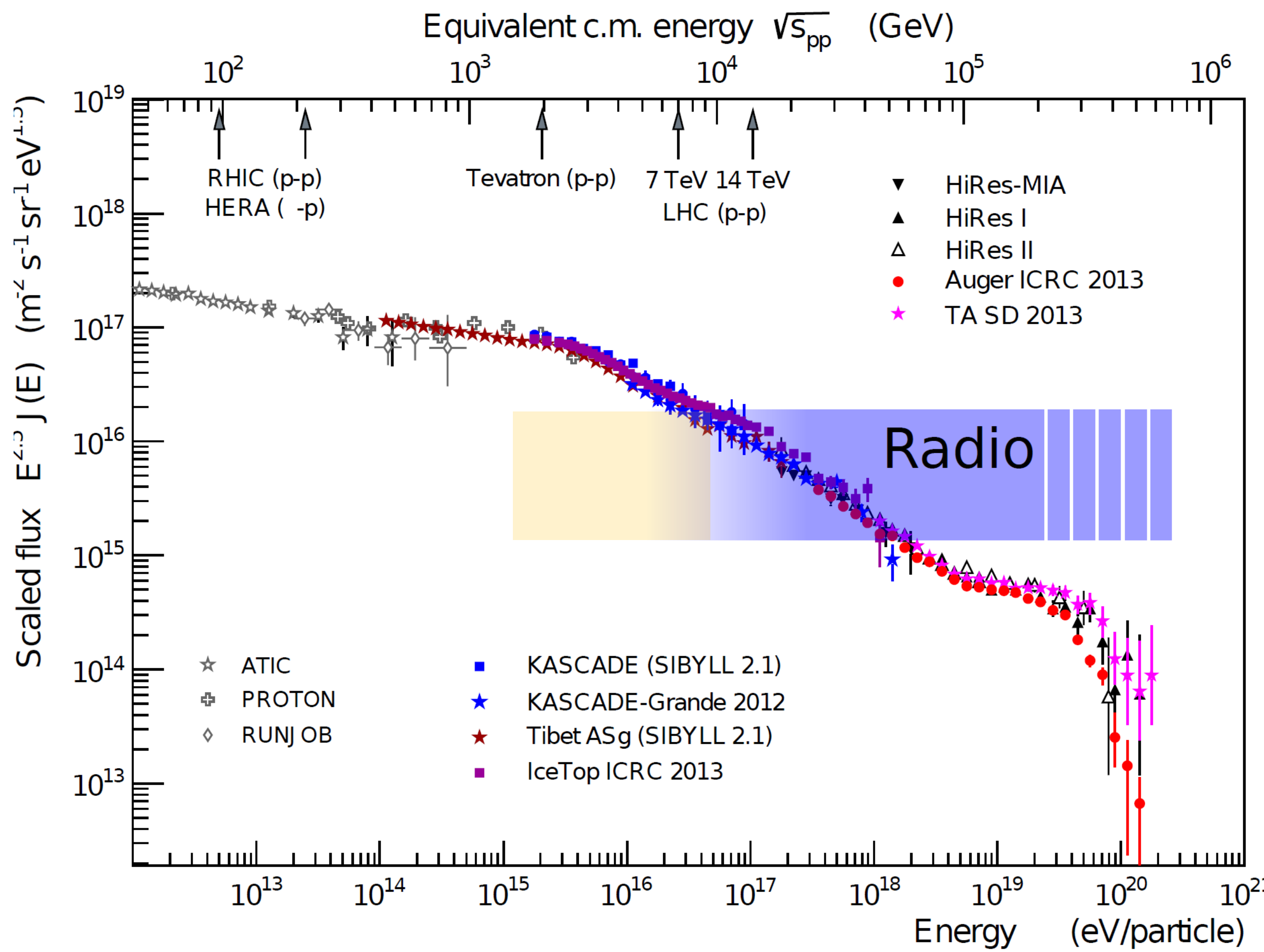
- why radio detection?
- from prototypes to maturity in 15 years
- simulating radio emission – CoREAS



To understand the sources of cosmic rays …

Karlsruhe Institute of Technology

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



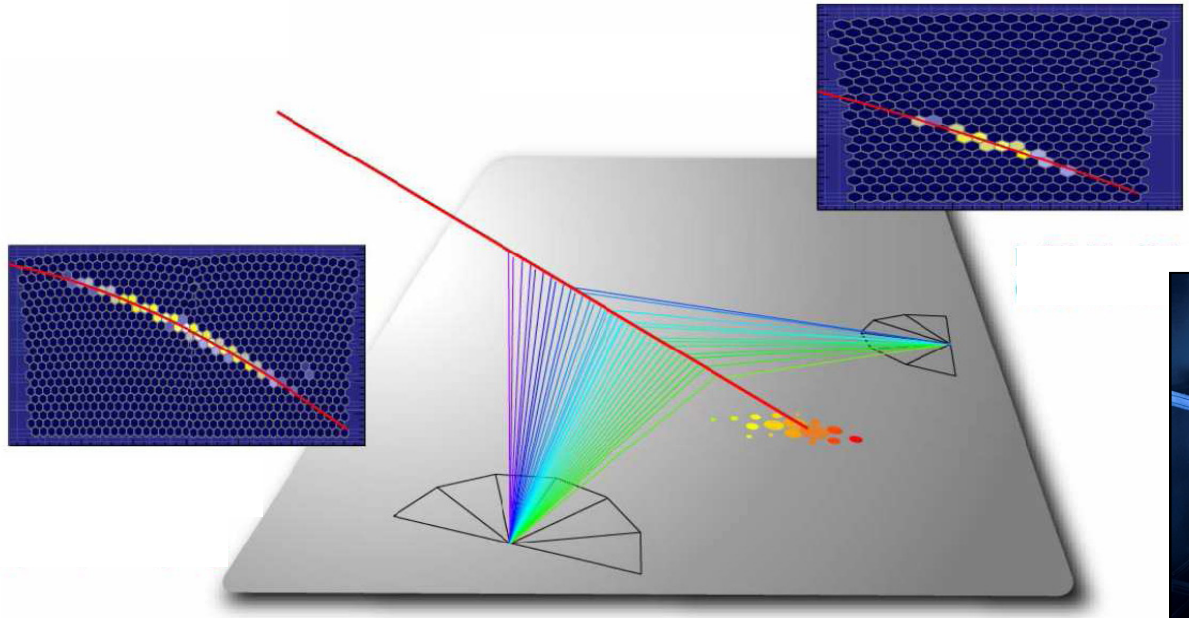
adapted from R. Engel

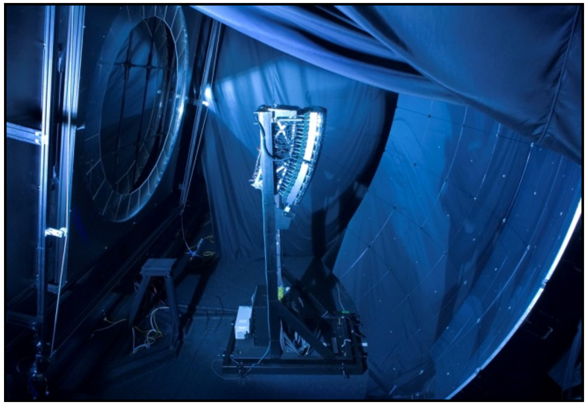
Particle detector arrays (e.g. KASCADE)

- measure the secondary particles arriving at the ground (snapshot)
- suffer from uncertainties in hadronic interaction physics

Fluorescence detectors (e.g. in Auger)

- air shower particles excite atmospheric nitrogen
- nitrogen molecules fluoeresce in ultraviolet light
- yield very direct information on air shower evolution
- yield calorimetric energy of electromagnetic cascade
- only work during dark, clear, moonless nights (~10% of time)





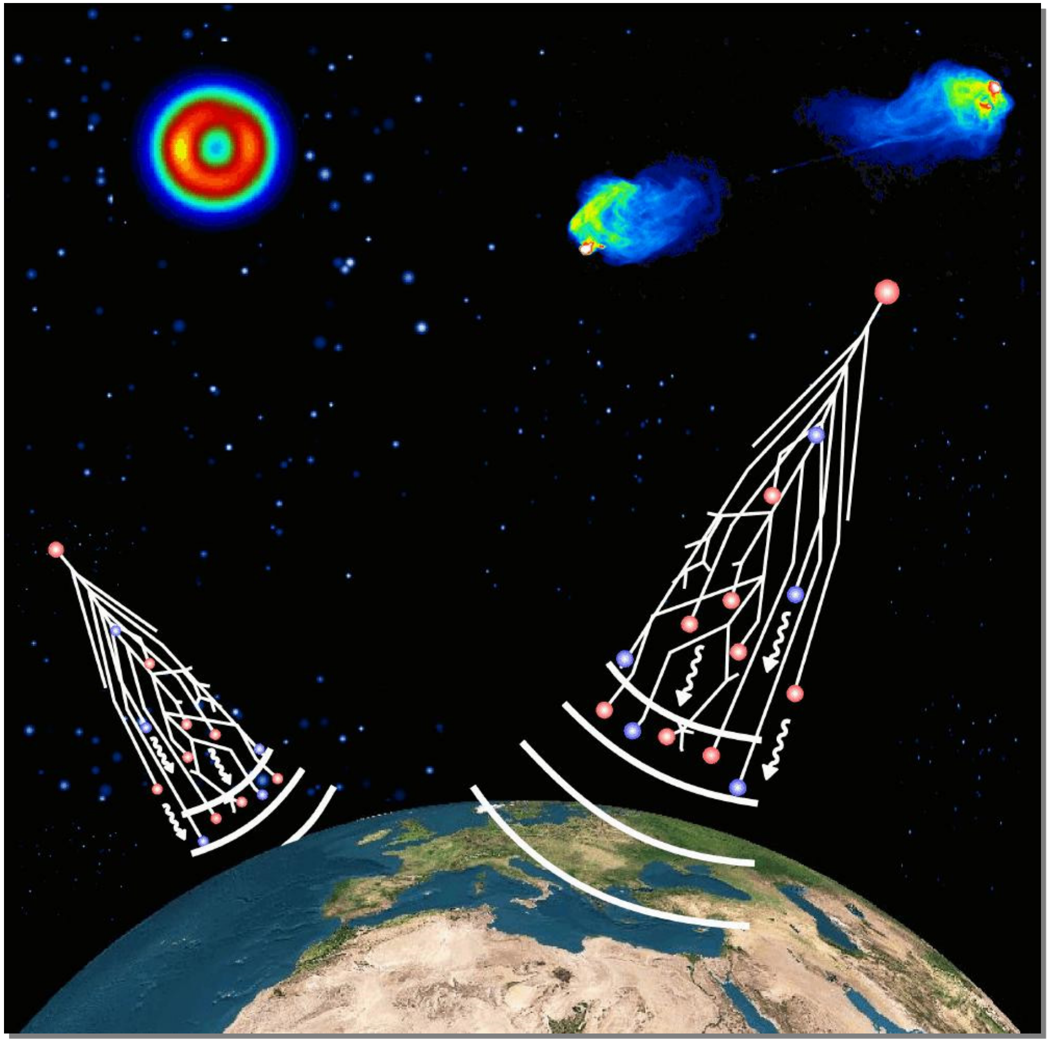
Tim Huege <tim.huege@kit.edu>

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)
- particle mass sensitivity
- high angular resolution (< 0.5°)
- simple (potentially cheap) detectors
- *how well does it all work in practice and on large scales?*

Contents

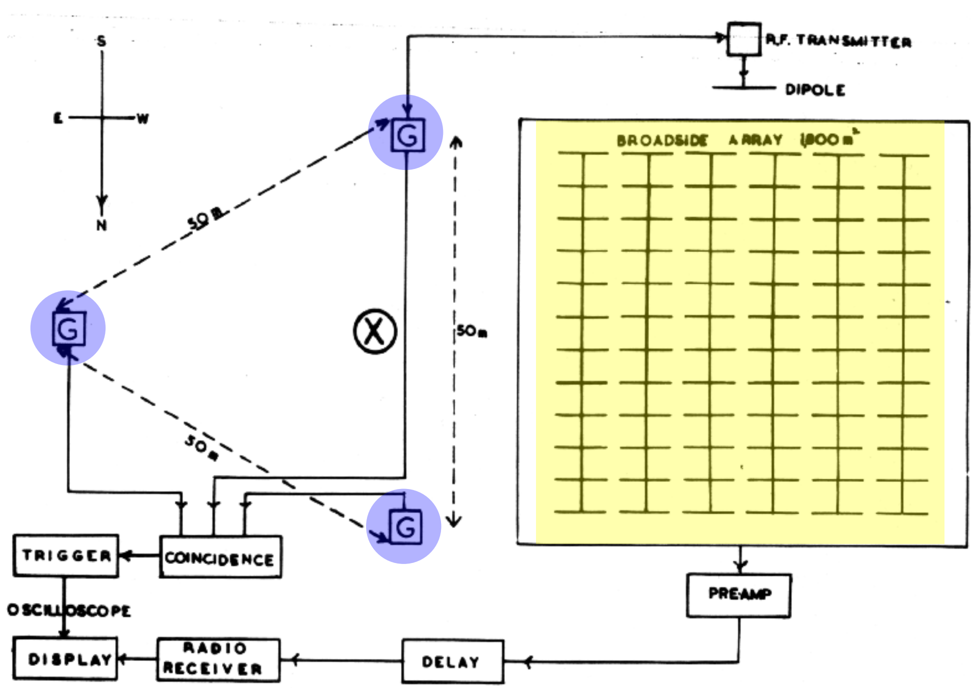
- why radio detection?
- from prototypes to maturity in 15 years
- simulating radio emission – CoREAS

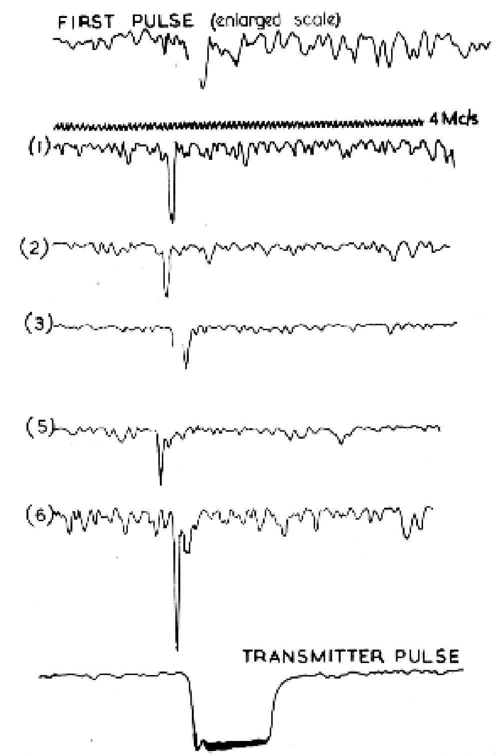


The Jodrell Bank experiment (Jelley et al.)

Karlsruhe Institute of Technology

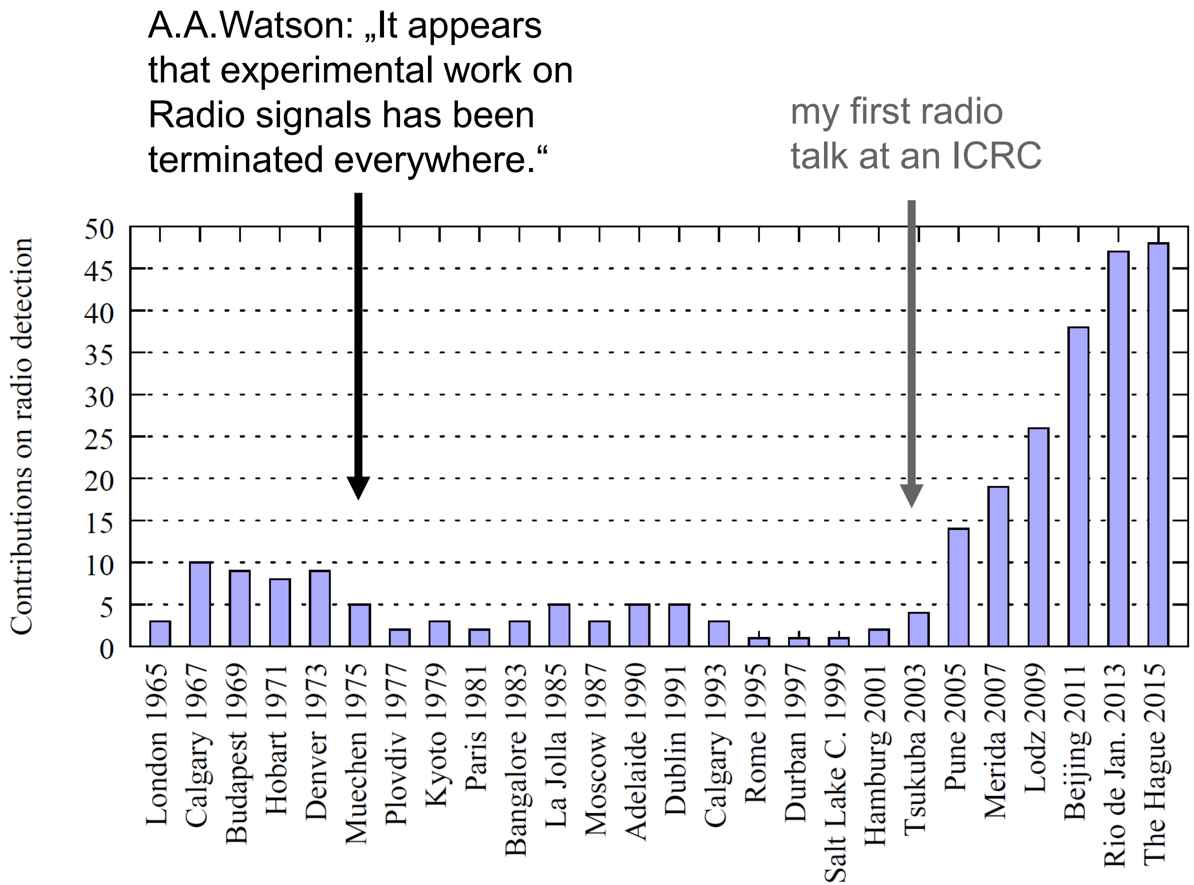
- array of dipoles with 10° FWHM beam width
- operation at 44 MHz with 2.75 MHz bandwidth
  - BBC TV channel, turned off from midnight to 9 a.m.
- Geiger counter coincidence triggers photograph of oscilloscope traces





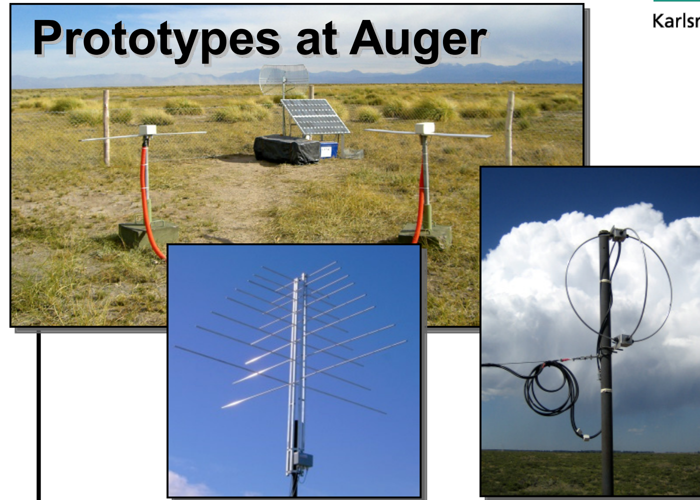
Decline and revival of radio detection

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



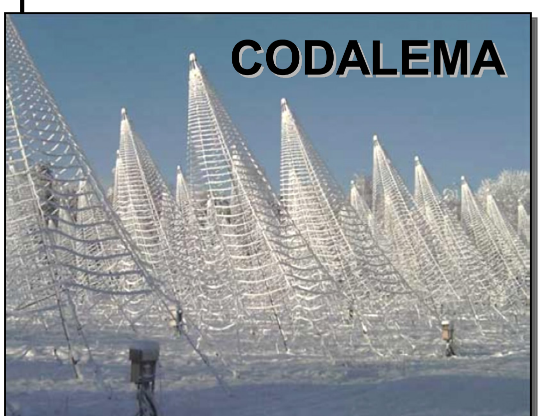
First-Generation modern MHz experiments

Karlsruhe Institute of Technology

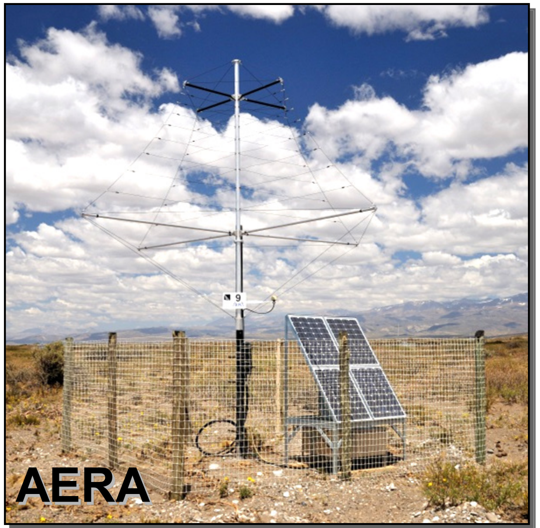


2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	…	…

Falcke & Gorham propose „geosyn-chrotron approach“

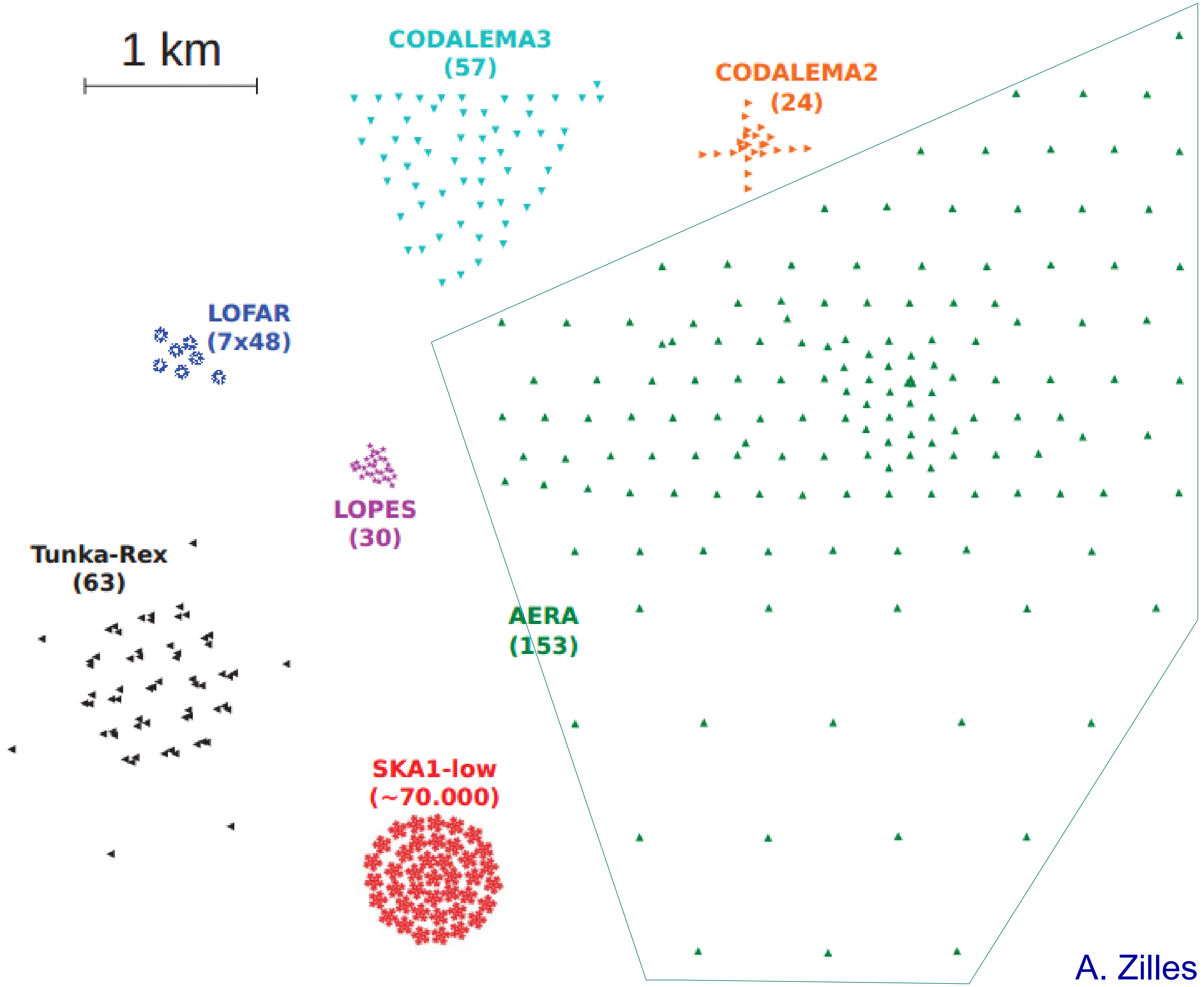


Second-Generation modern MHz experiments



2010	2011	2012	2013

Comparison of ground experiments to scale

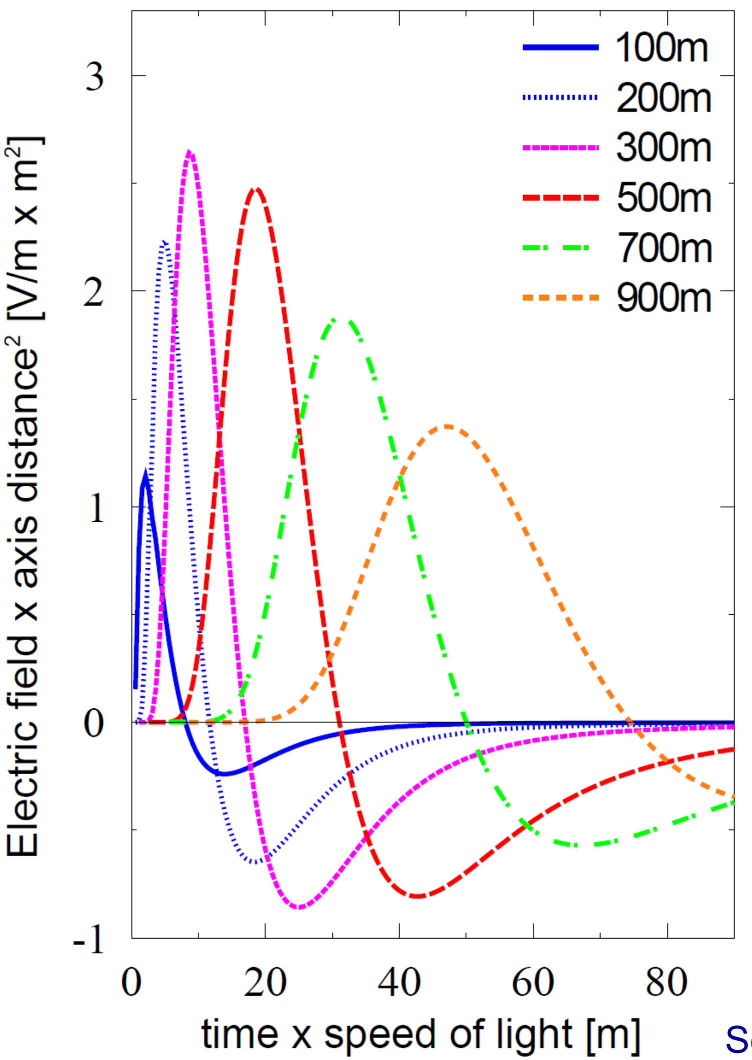


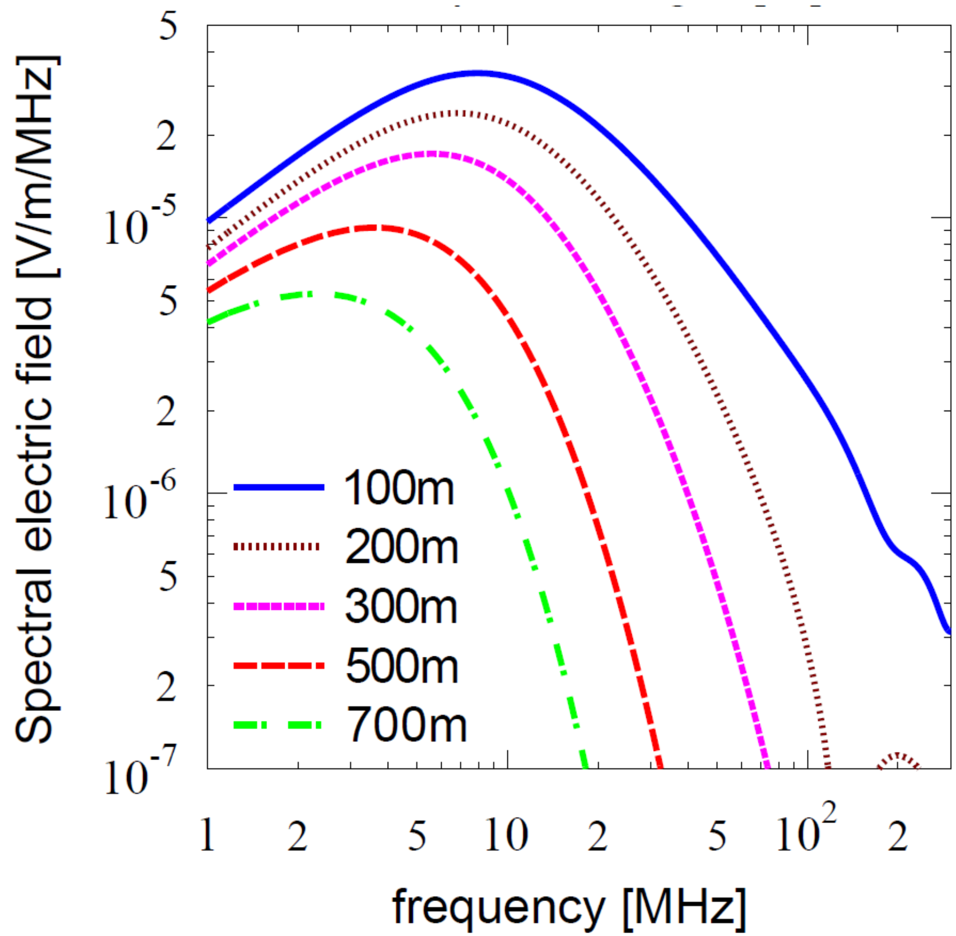
- from prototypes to large-scale experiments
- typical range 30-80 MHz, some higher
- sparse vs. dense arrays

Radio emission physics

Tim Huege <tim.huege@kit.edu>

Broad-band pulses – mostly in MHz regime





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

A decade of radio-emission modelling

Karlsruhe Institute of Technology

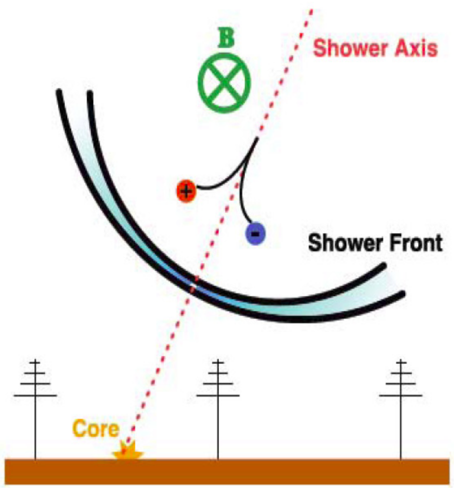
more „microscopic"

MGMR	time-domain, analytic, parametrized shower, fast, free parameters, summing up „mechanisms"
EVA & MGMR-3D	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

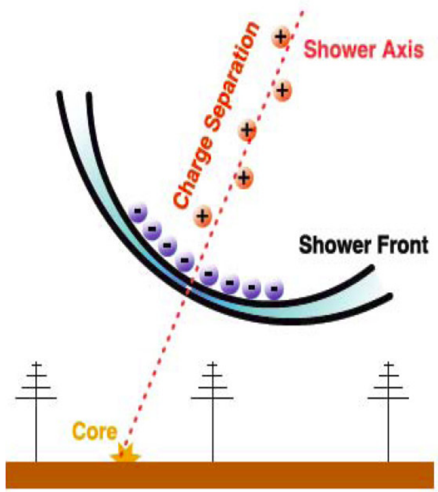
Tim Huege <tim.huege@kit.edu>

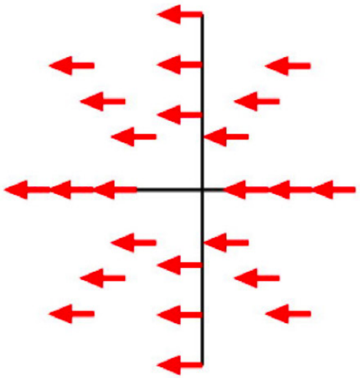
Radio emission physics as predicted by theory



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

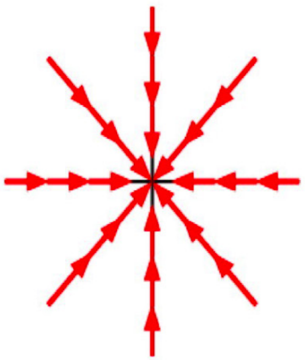
Kahn & Lerche (1967)





Askaryan (1962,1965)

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

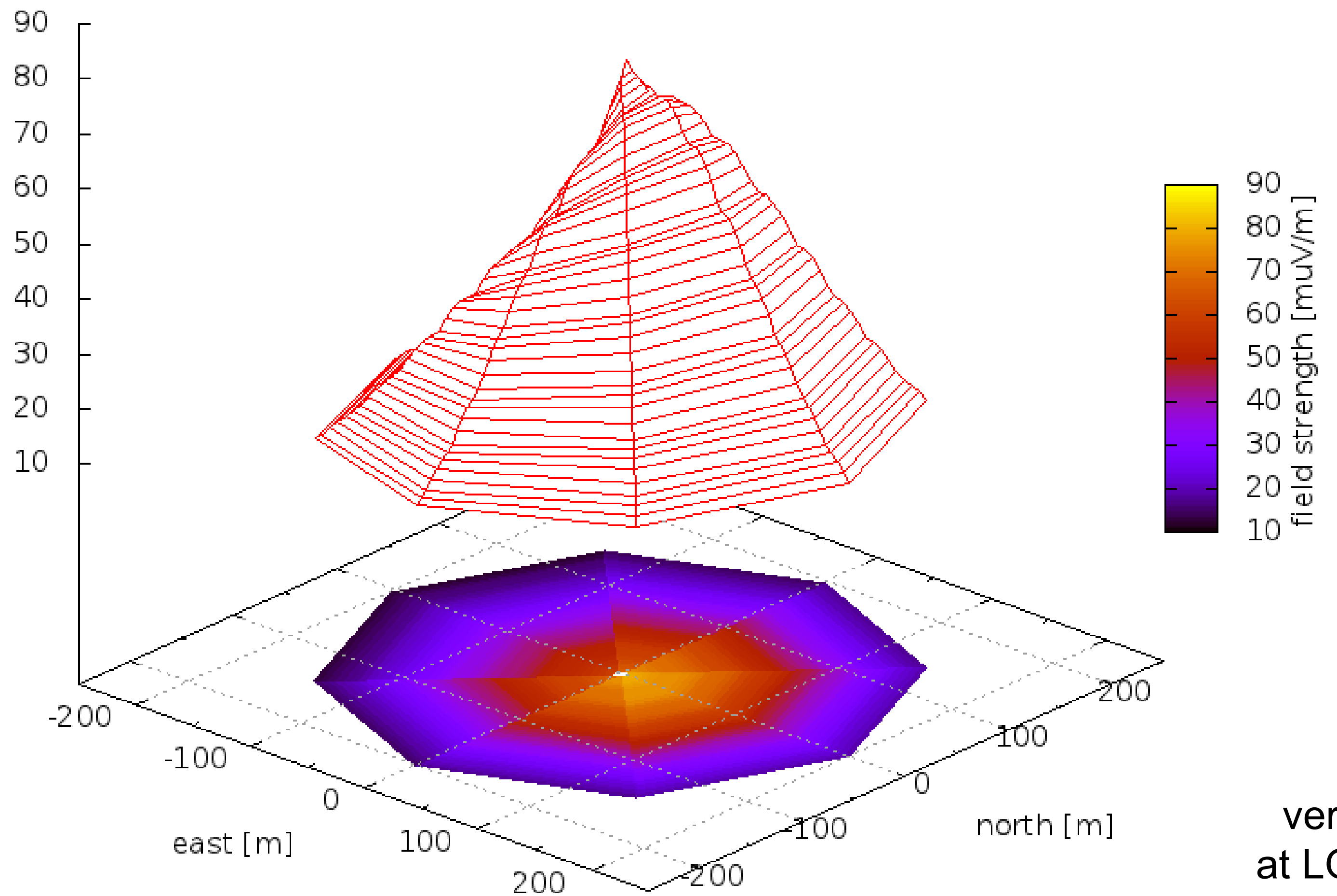


„**v x B**"

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

„**radial**"

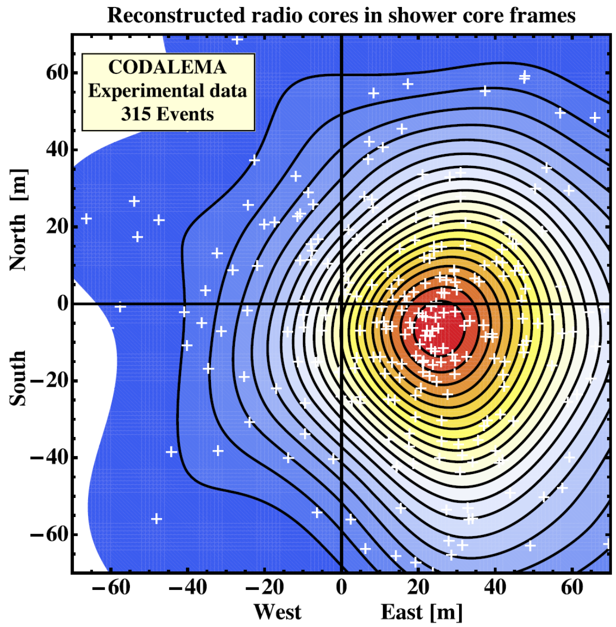
Complexity of radio LDF



vertical iron shower
at LOPES frequencies
simulated with CoREAS

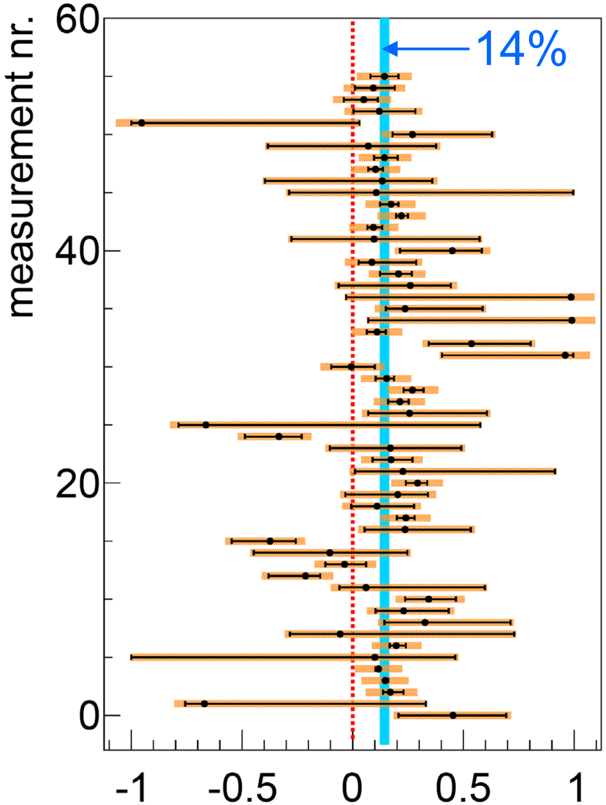
TH et al., ARENA2012

Geomagnetic seen by all – but charge excess?



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

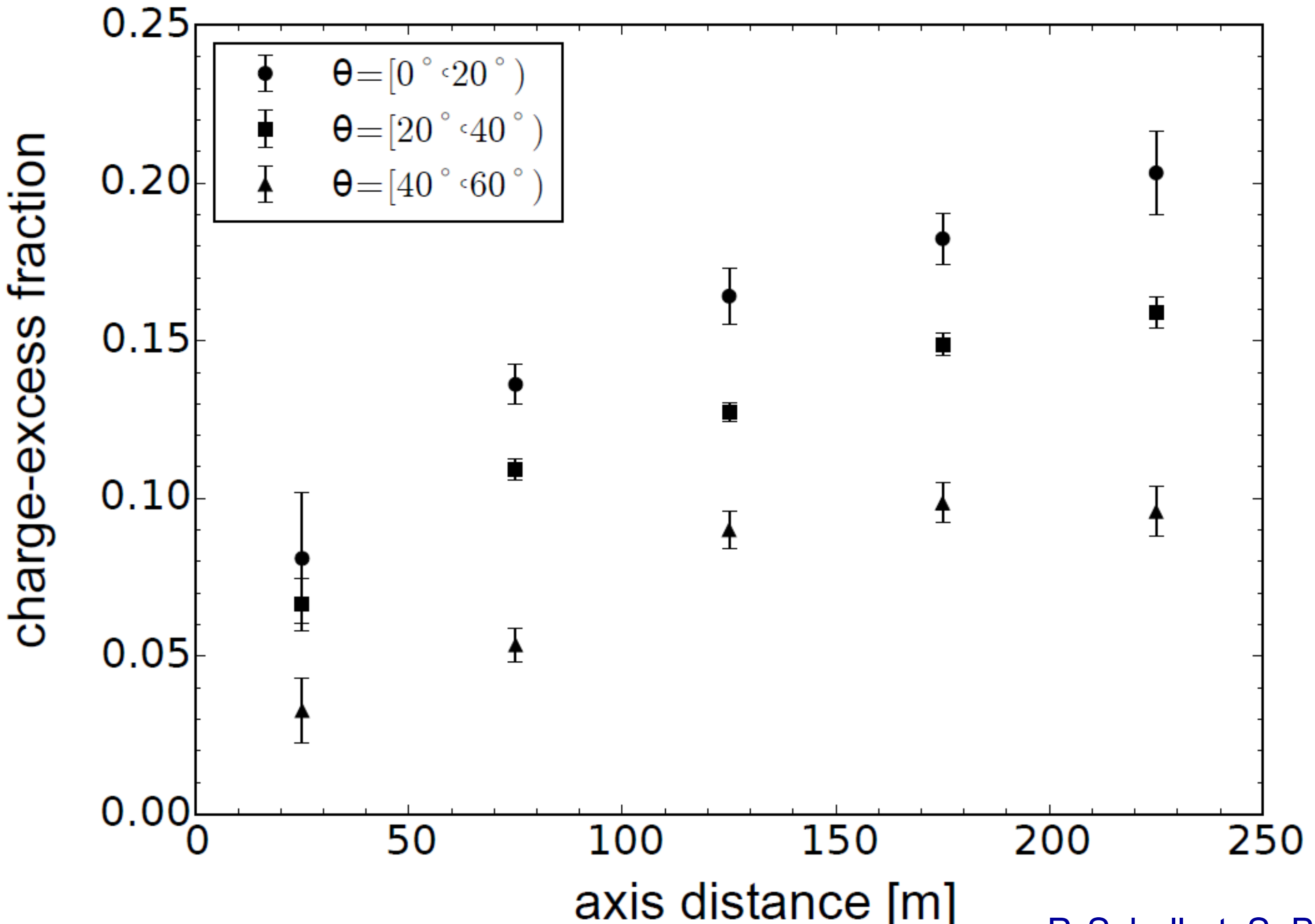
CODALEMA Coll., Astropart. Phys. 69 (2015) 50–60.



- AERA quantifies radial component to 14 ± 2%

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

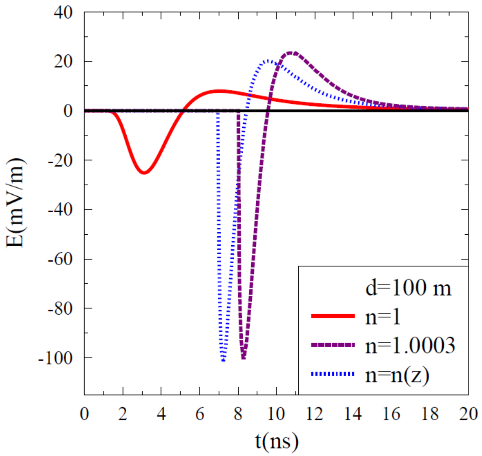
Charge excess fraction is not a constant



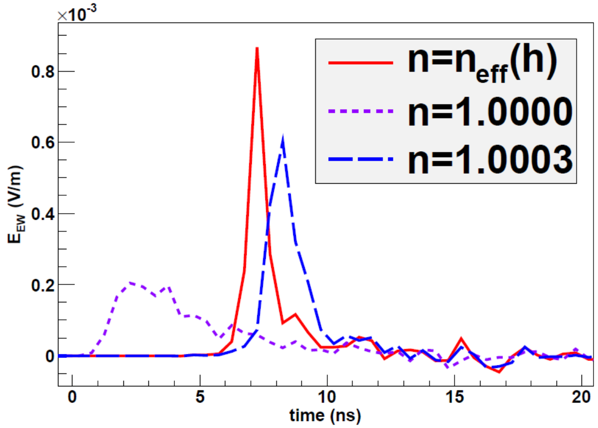
- depends on shower azimuth angle and observer lateral distance

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

Refractive index effects

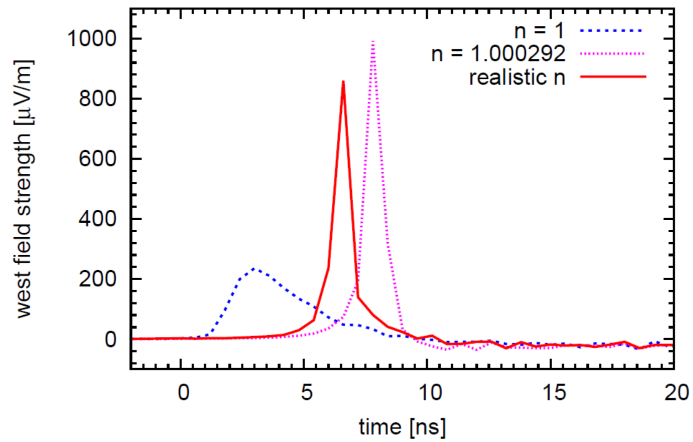


K.D. de Vries et al, PRD (2010)

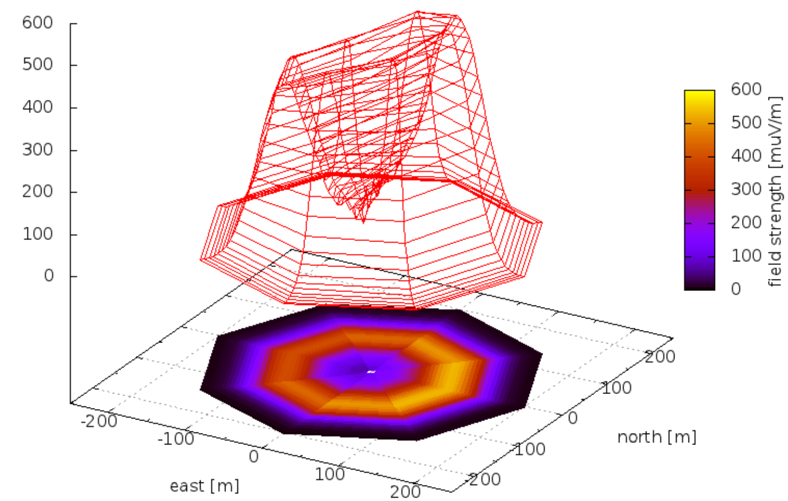


Alvarez-Muniz et al., Astrop. Phys. (2011)

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

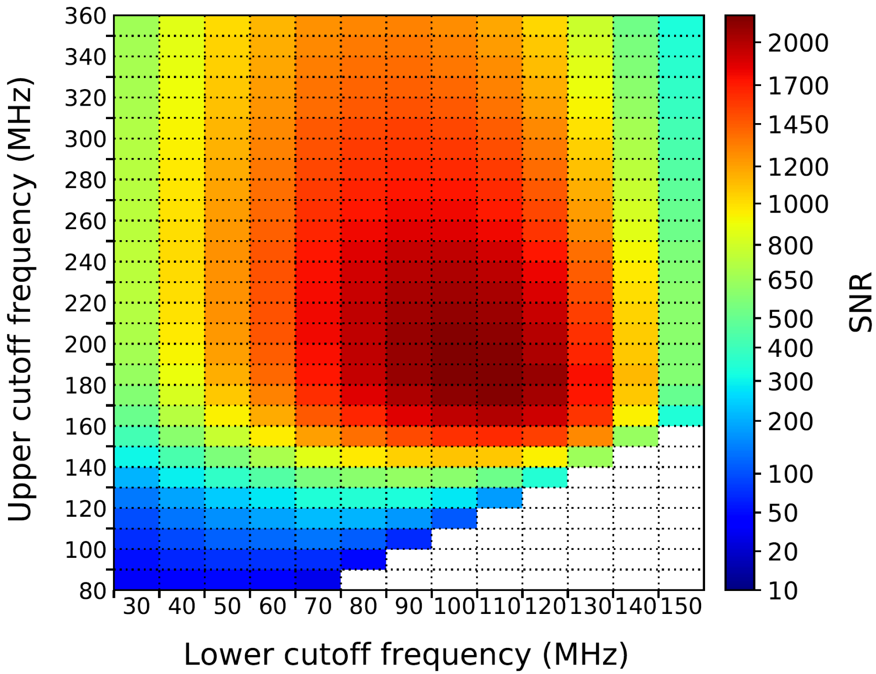


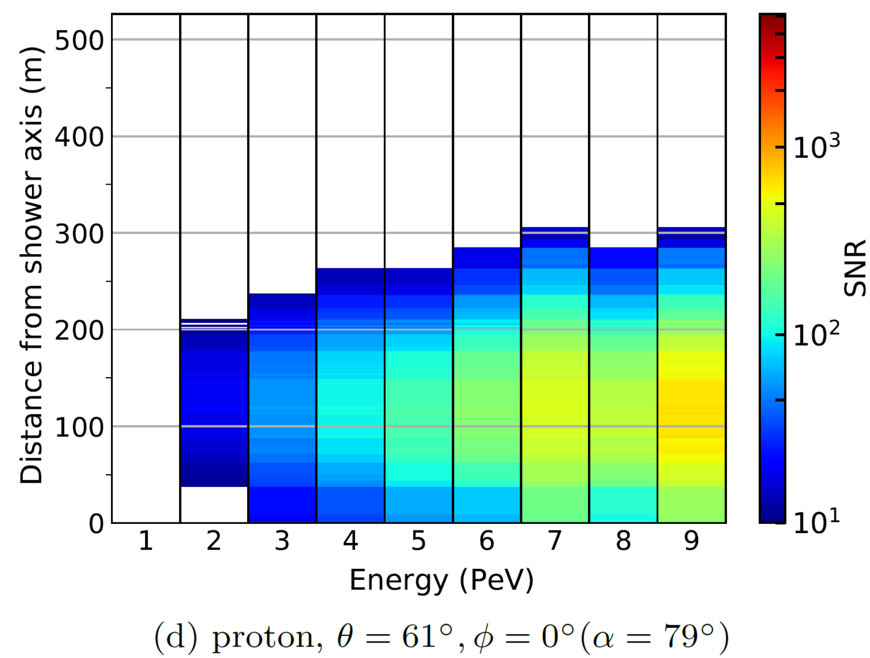
TH et al., ARENA2012

300-1200 MHz

Energy threshold for radio detection

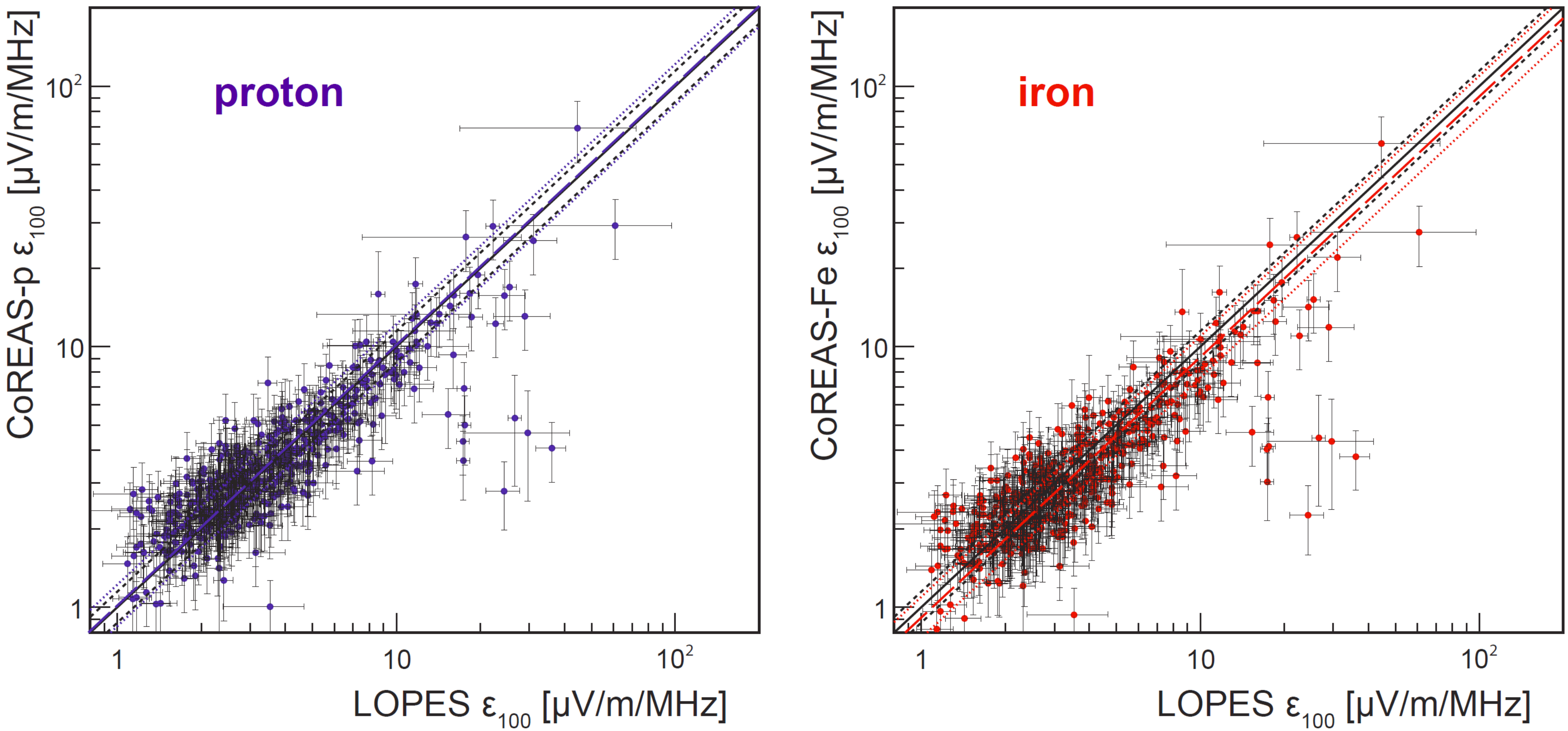
- previously, in 30-80 MHz band ~10^{17} eV (LOFAR few times 10^{16} eV)
- simulation studies show that at higher frequencies, detection possible down to few times 10^{15} eV (Galactic noise drops off)





Balagopal et al., EPJ C 78 (2018) 111

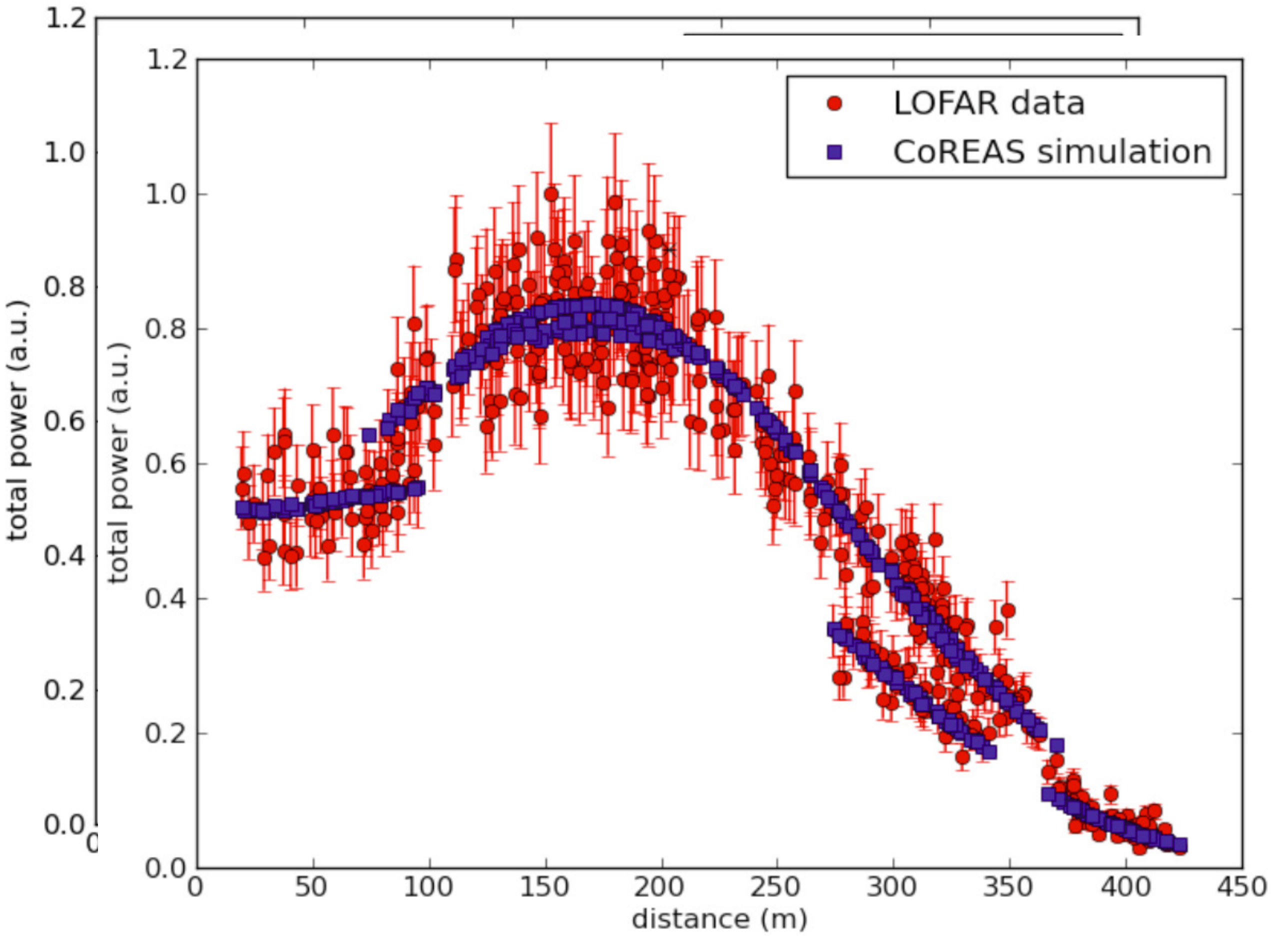
Comparison of simulations with LOPES data



- 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

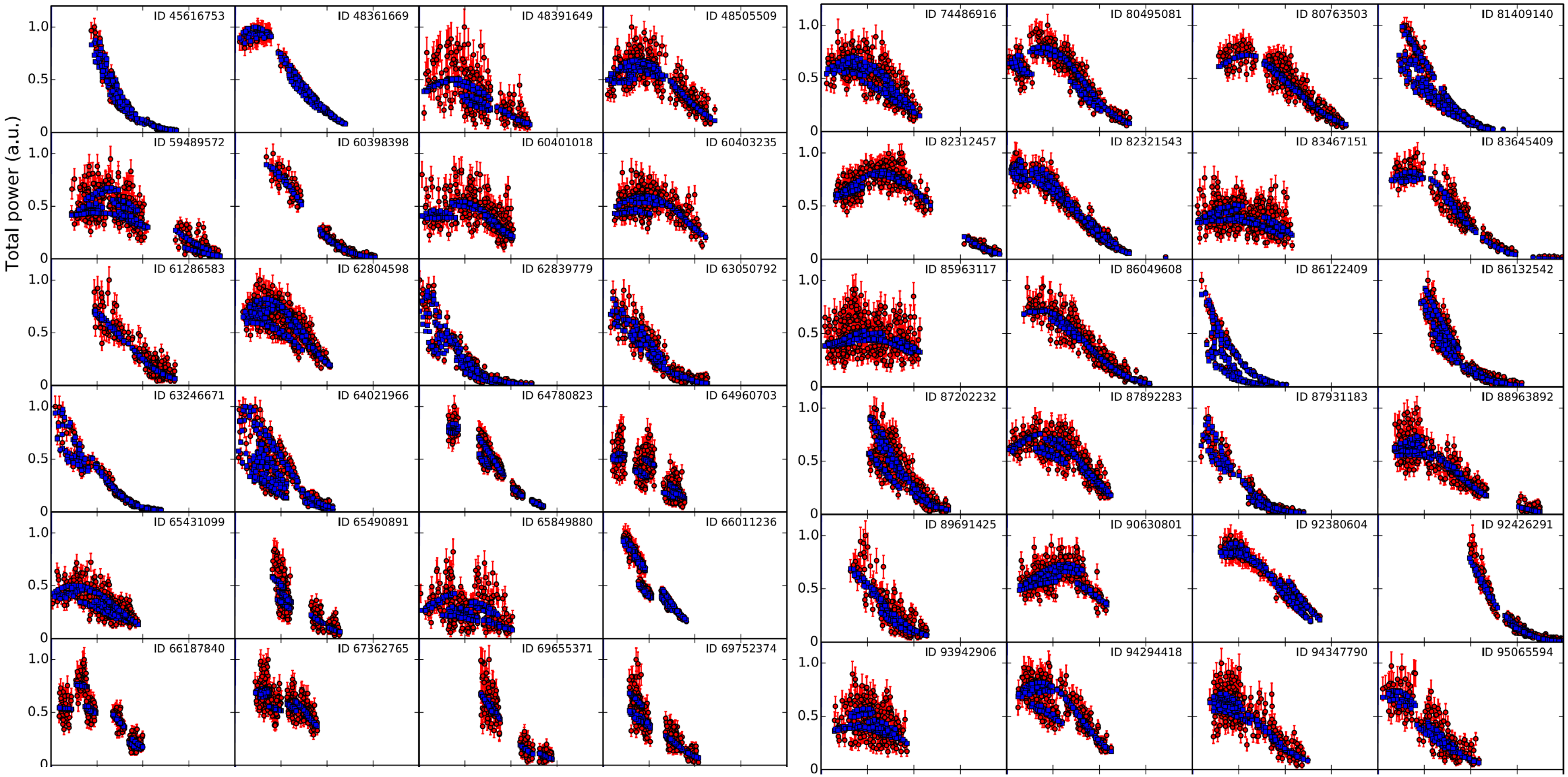


- measurement of individual shower with extreme level of detail
- data can be reproduced by simulations
- see geomagn., charge excess and Cherenkov effects
- but: here absolute scale arbitrary

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

Many LOFAR events

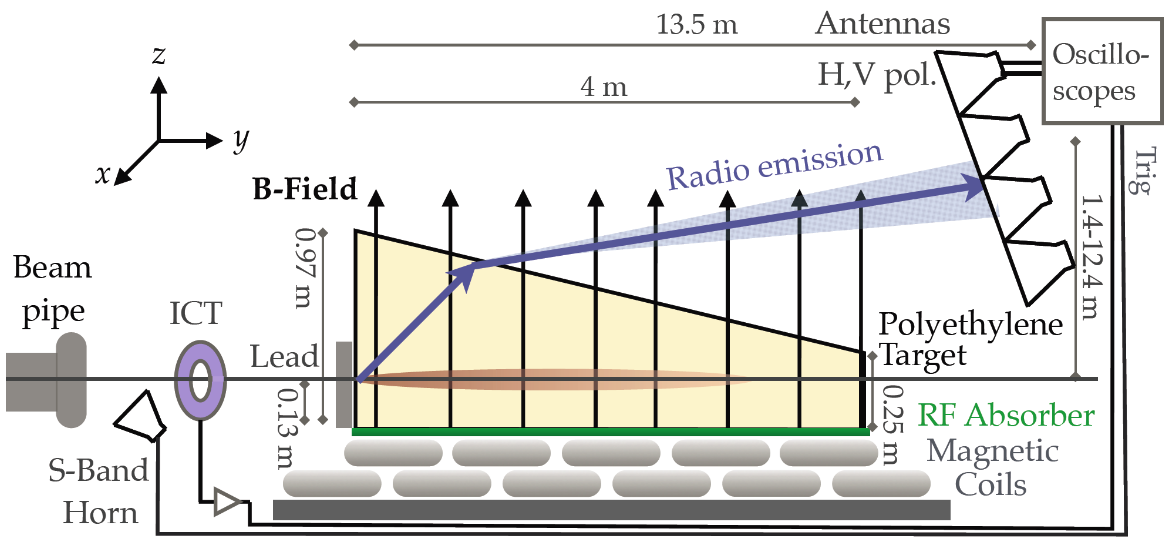
Karlsruhe Institute of Technology

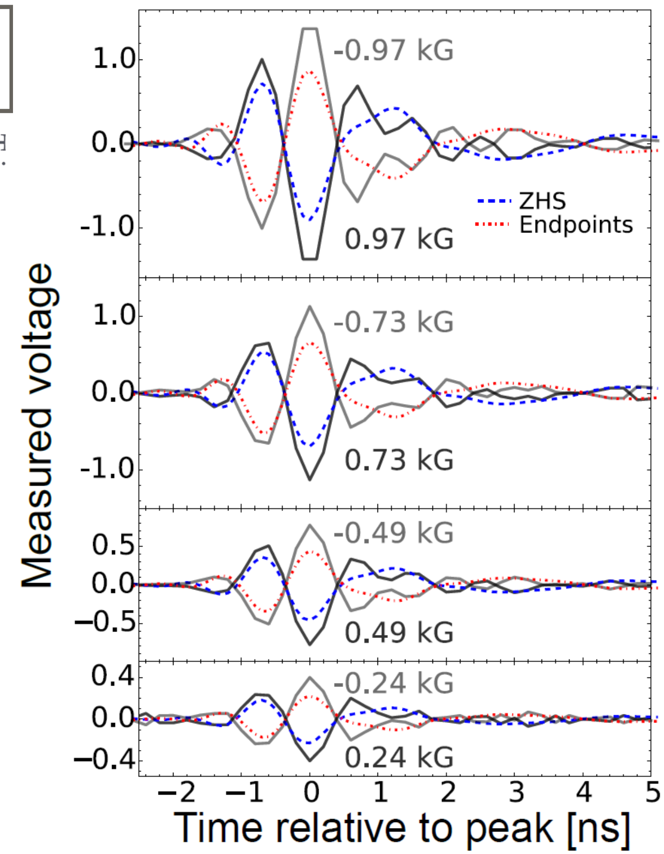


- all LOFAR events are described very well

Lab-Experiment: SLAC T-510

Karlsruhe Institute of Technology





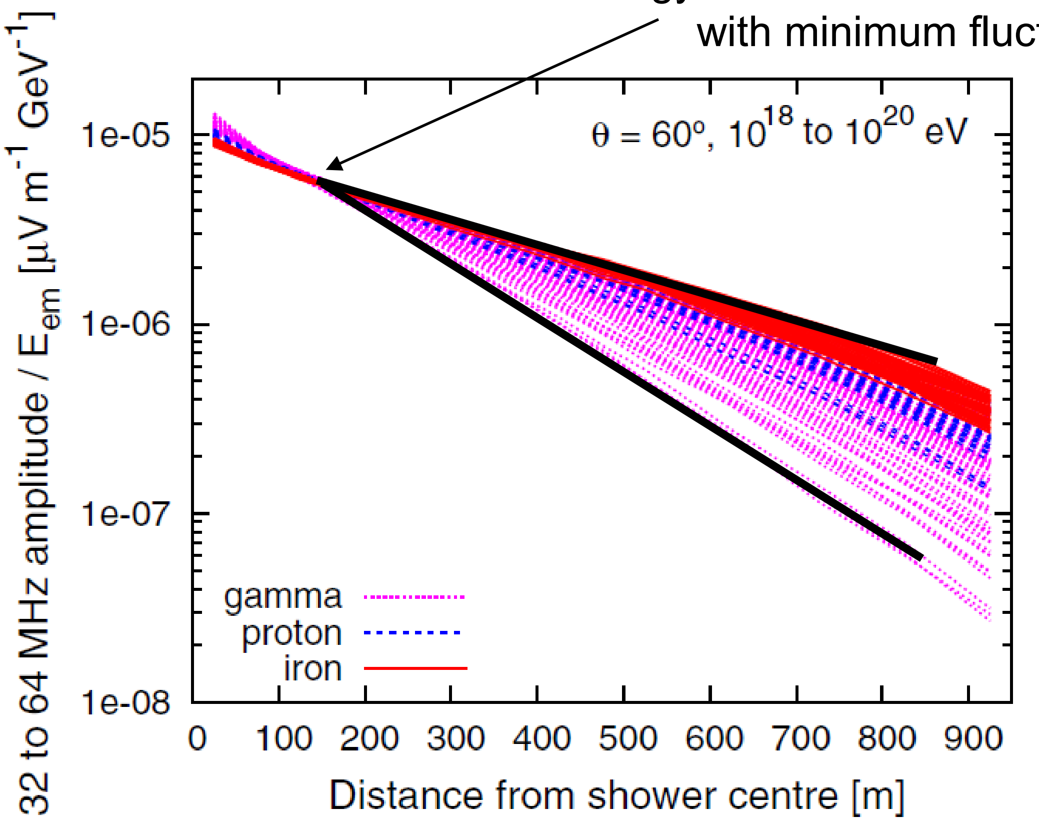
- electromagnetic particle shower in strong magnetic field, controlled conditions
- cross-check first-principle calculations
  - agree within systematic uncertainties

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

Energy reconstruction

Expected energy sensitivity of radio detection

energy determination at distance
with minimum fluctuations

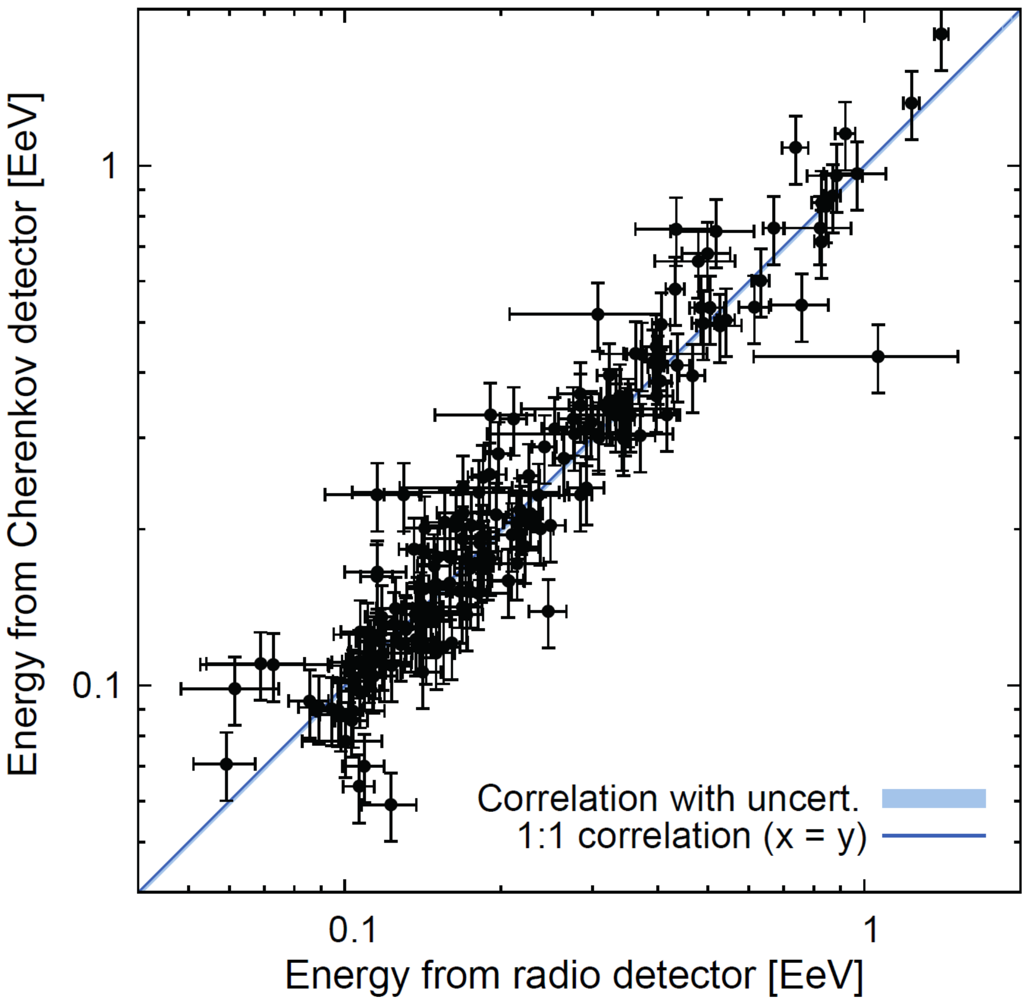


Fe – flat
p – steeper, fluctuating
γ – steepest, fluctuating

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

- linear scaling & characteristic distance for best energy estimate

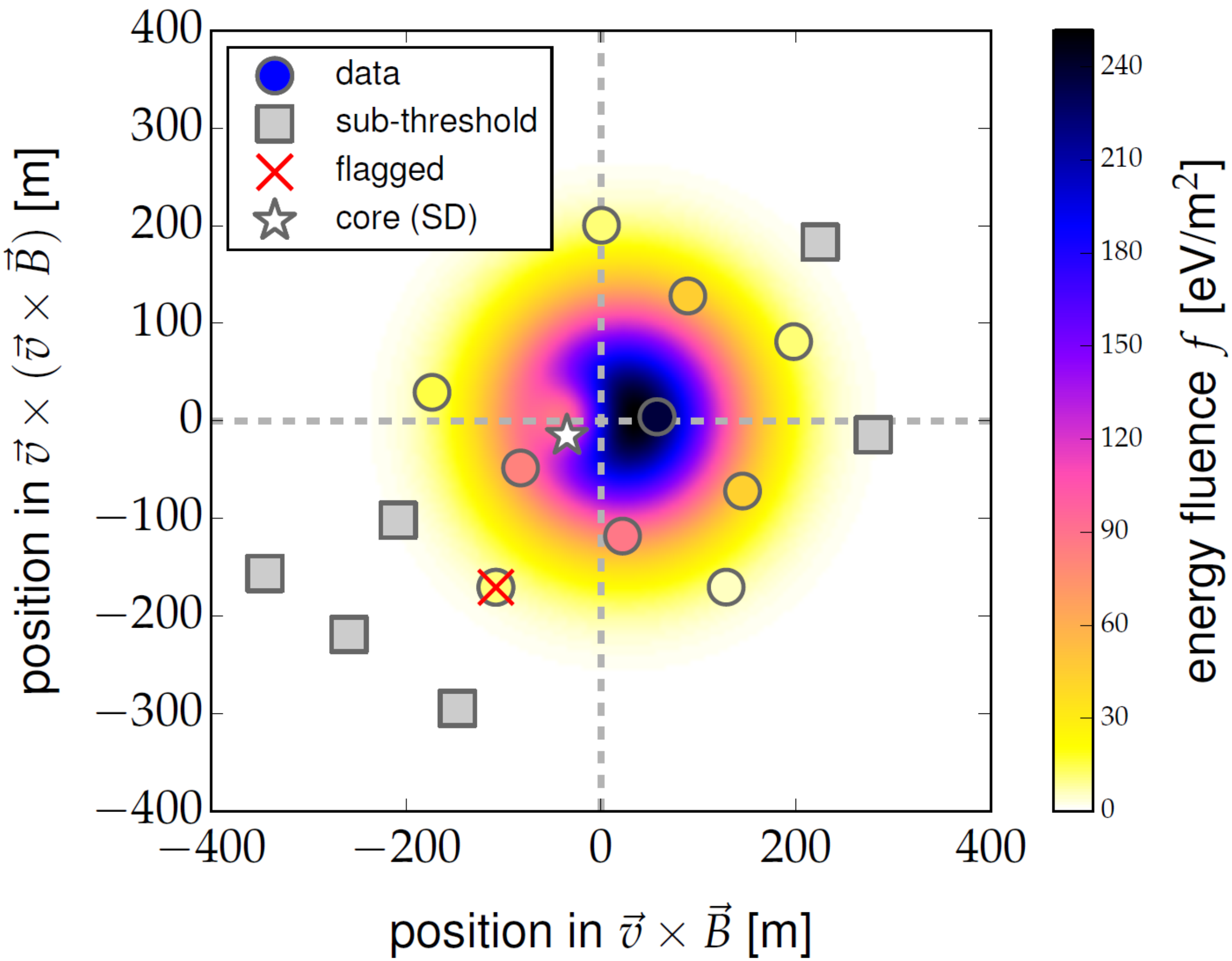
Tunka-Rex energy reconstruction



- very good energy reconstruction
  - 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.

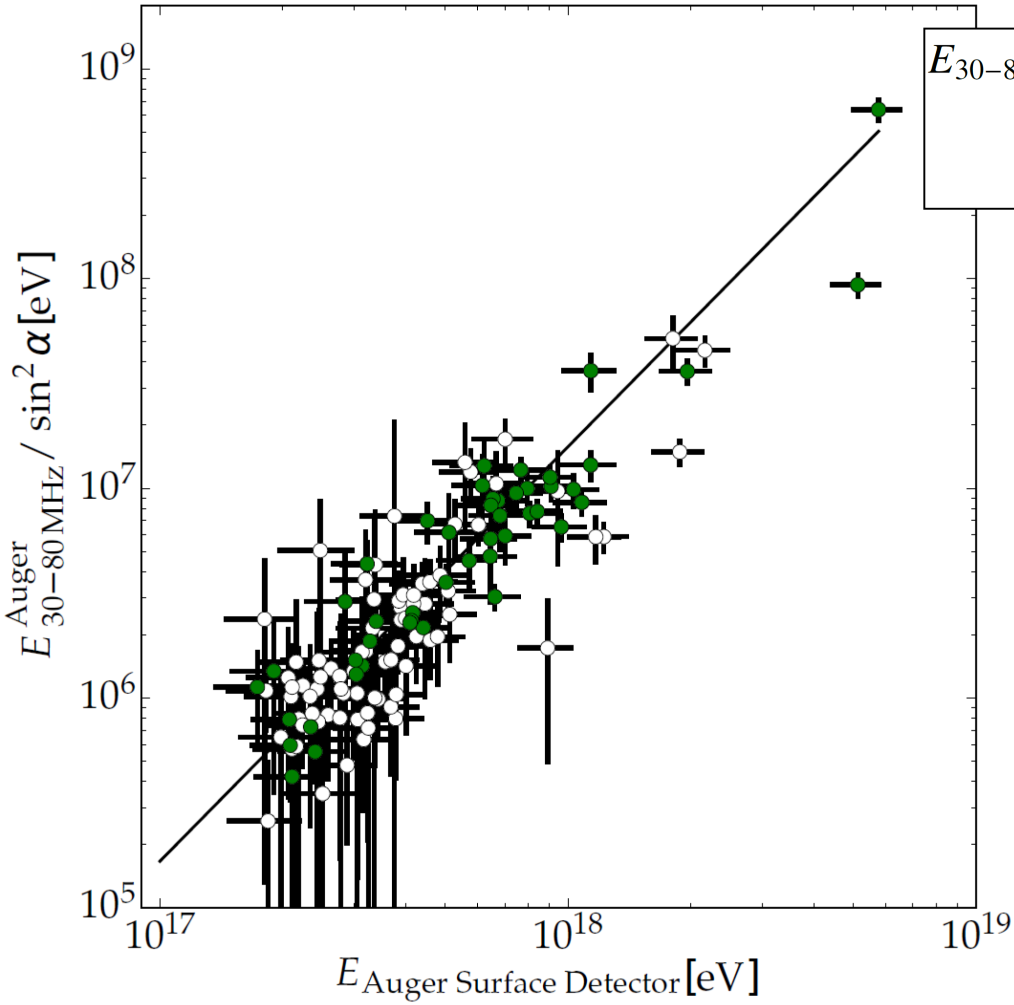
AERA energy reconstruction – radiation energy



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.

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

- 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

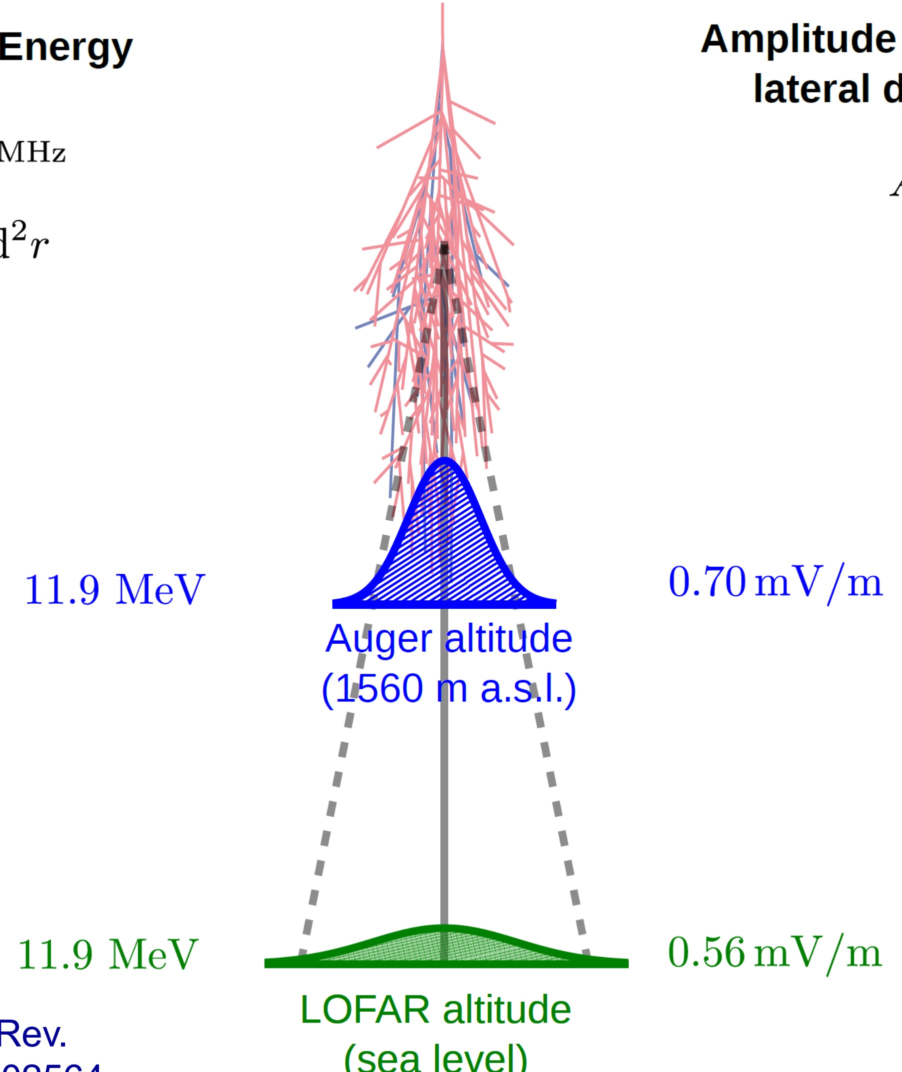
$$E_{30-80\,\mathrm{MHz}}$$

$$\propto \int A^2 \mathrm{d}^2 r$$

Amplitude at optimal lateral distance

$$A$$

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

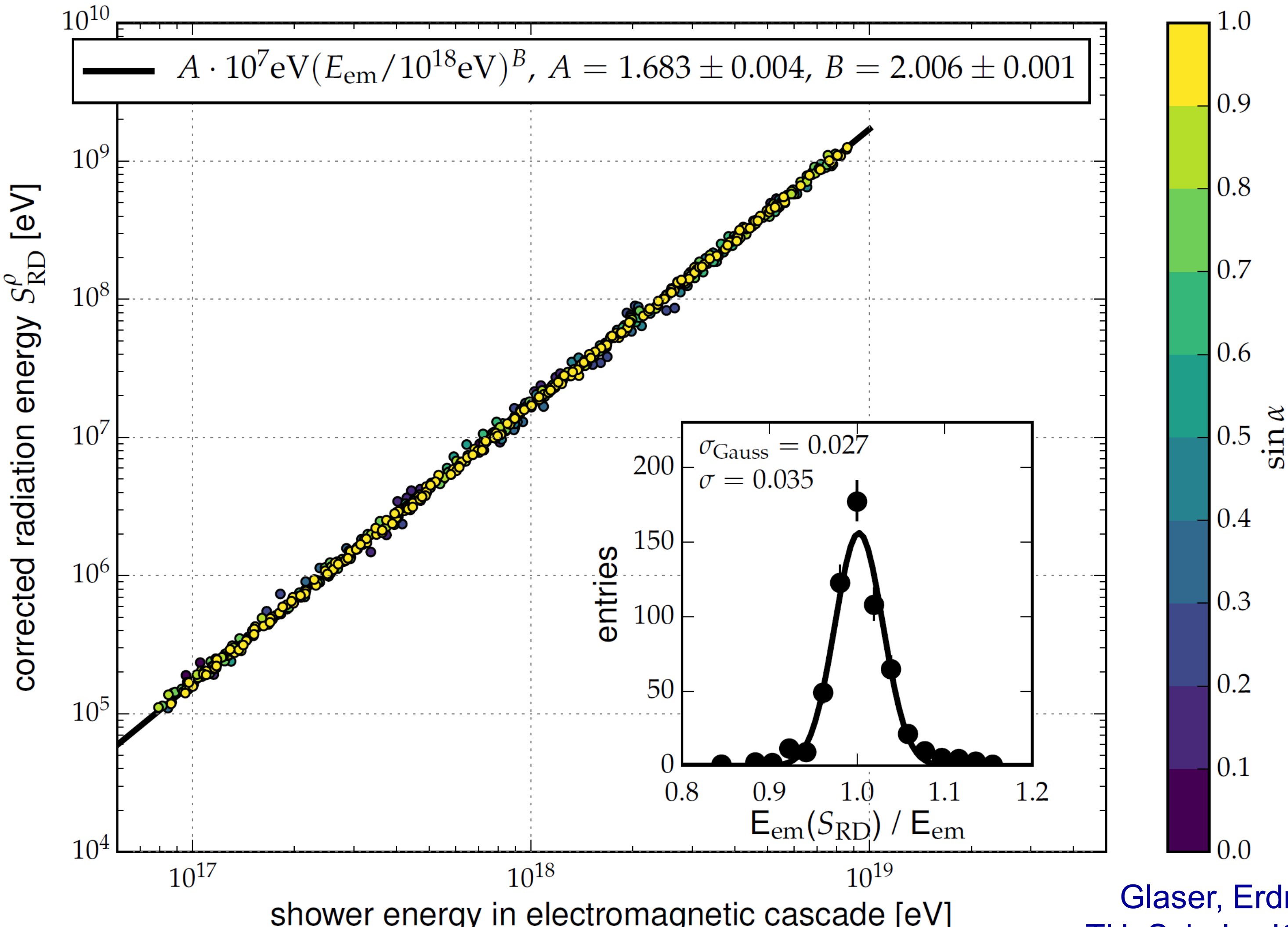


The optimal lateral distance and the amplitude measured there vary with observation altitude (even after charge-excess and zenith-angle correction).

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

Tim Huege <tim.huege@kit.edu>

Radiation energy and electromagnetic energy



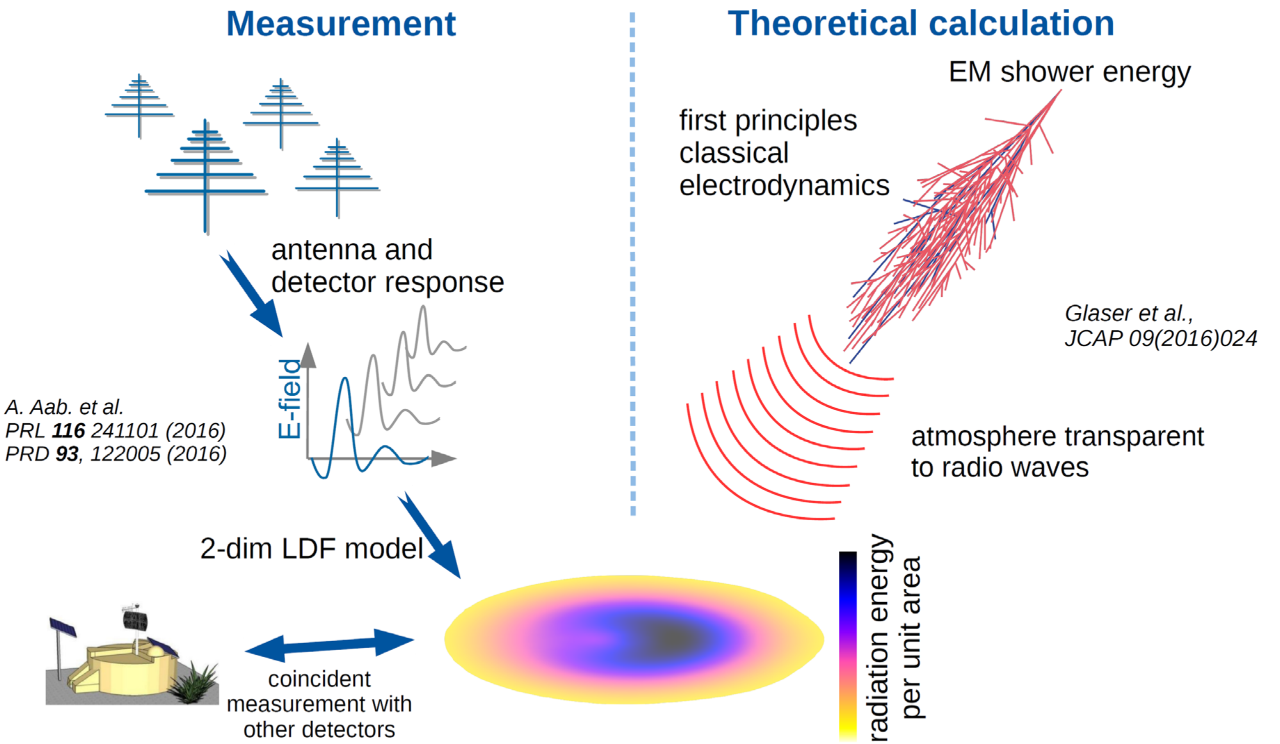
- radiation energy has been studied in detail
- very good correlation with electromagnetic energy, less than 5% intrinsic scatter

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

Energy scale from first principles

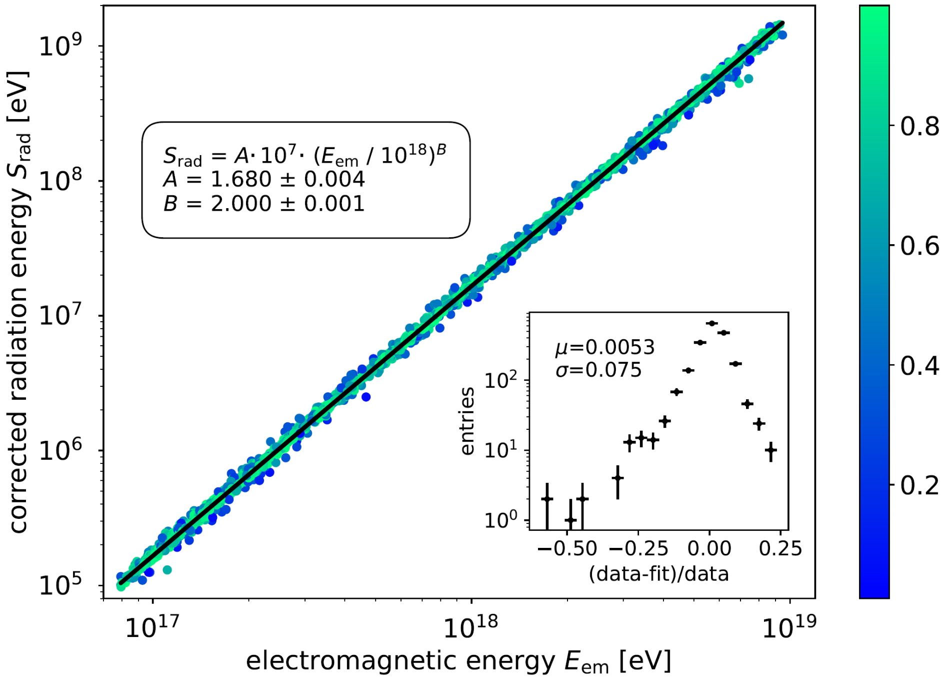
- the radio signal can be predicted from pure electrodynamics and the well-known physics of the elcectromagnetic cascade in air showers
- there is no absorption or scattering in the atmosphere
- antenna arrays can be calibrated precisely

- using radio signals, the energy scales of particle detector arrays (which usually rely on hadronic inter-action simulations) can be calibrated from first principles!



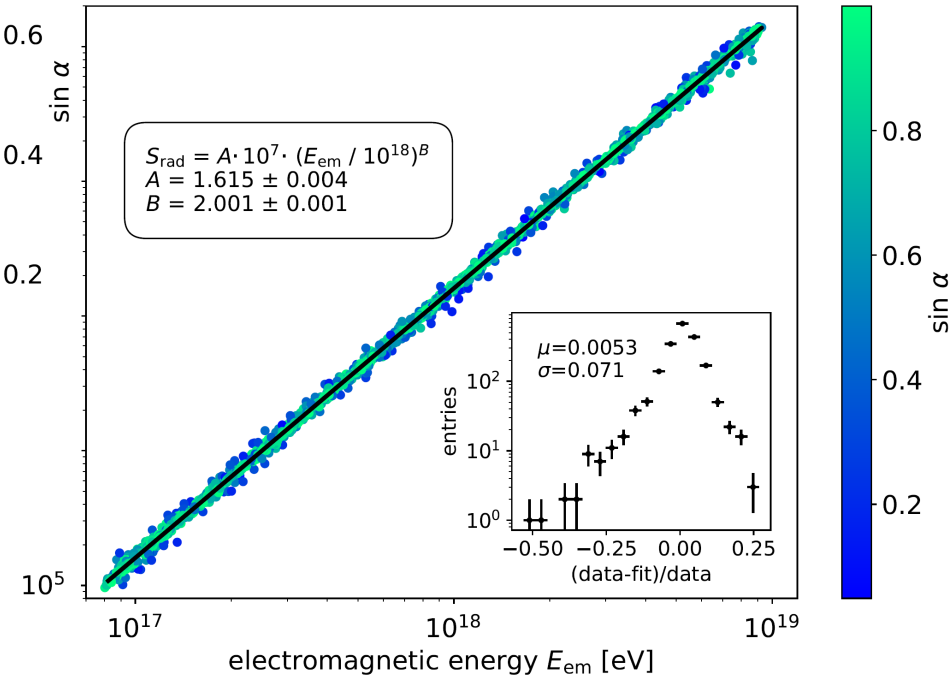
Tim Huege <tim.huege@kit.edu>

Comparison of CoREAS and ZHAireS



ZHAireS, **16.15 MeV** radiation @ 10^{18} eV electromagnetic energy

CoREAS, **16.8 MeV** radiation @ 10^{18} eV electromagnetic energy

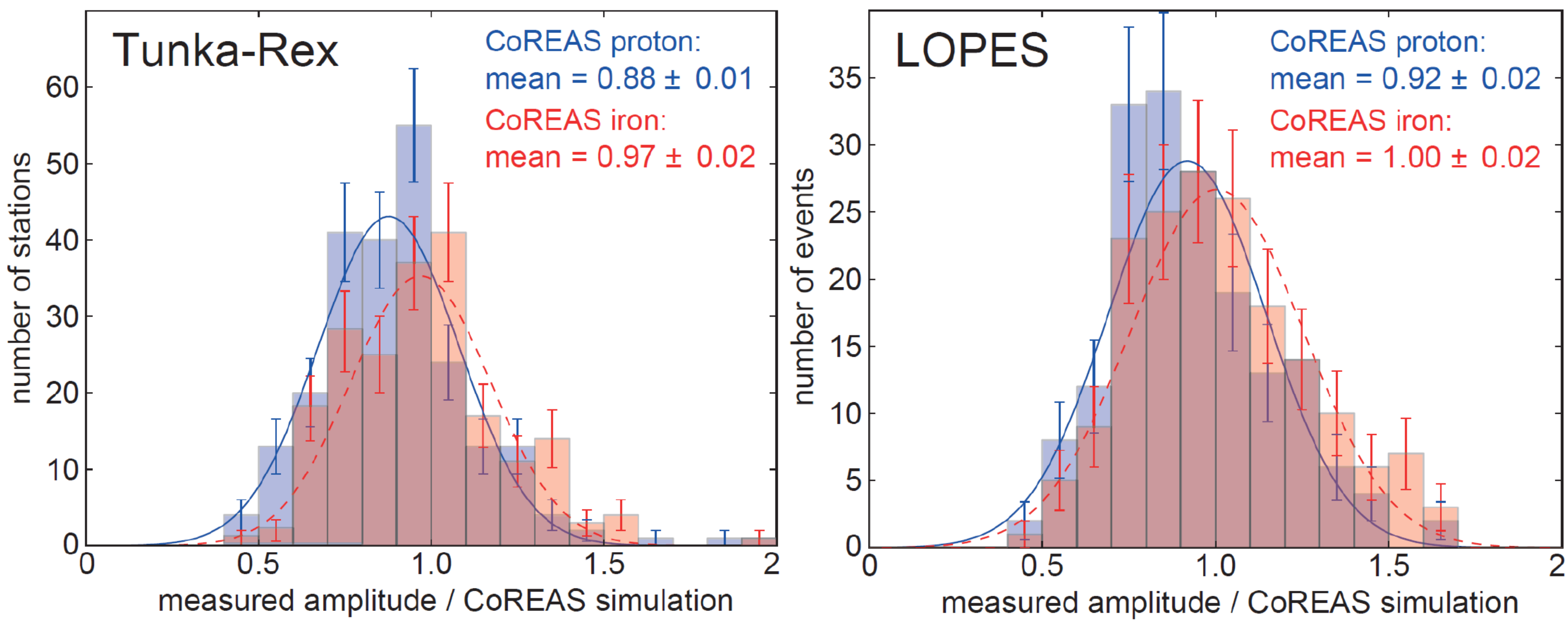


- absolute prediction of radiation energy agrees within 5.2% between two independent full Monte Carlo simulations, use for absolute calibration!

Gottowik, Glaser, Huege, Rautenberg, Astroparticle Physics 103(2018)87

(Cross-)calibration of the energy scale

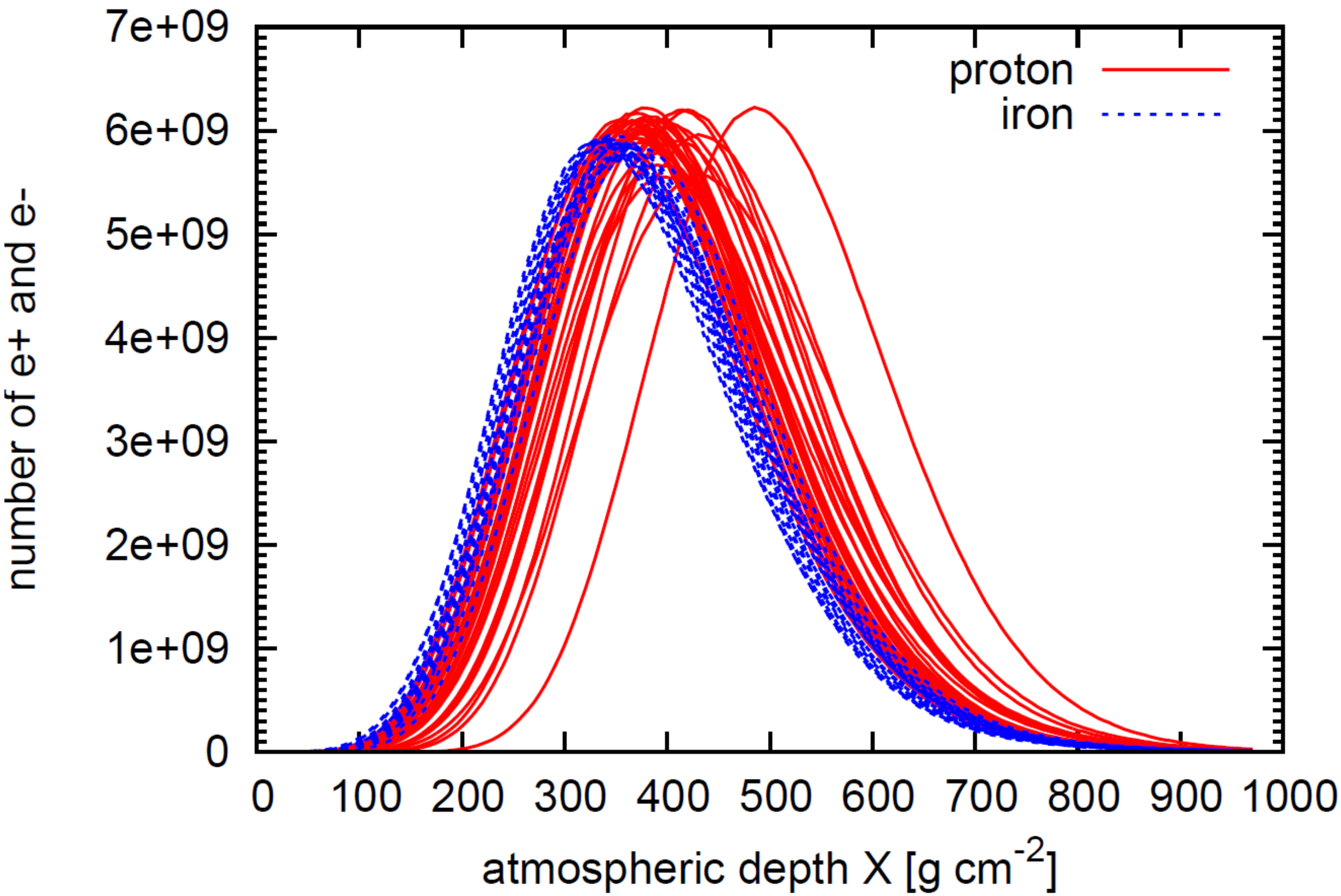
- many uncertainties in data interpretation are related to uncertainties of the absolute energy scale
- measuring radio emission allows calibrating the energy scale
  - among different experiments (e.g., Auger‘s radiation energy@10^{18} eV)
  - against first-principle calculations (within 10% seems feasible)



Tunka-Rex & LOPES Collaborations, ARENA 2016 and PLB

Mass sensitivity

The atmospheric depth - Xmax

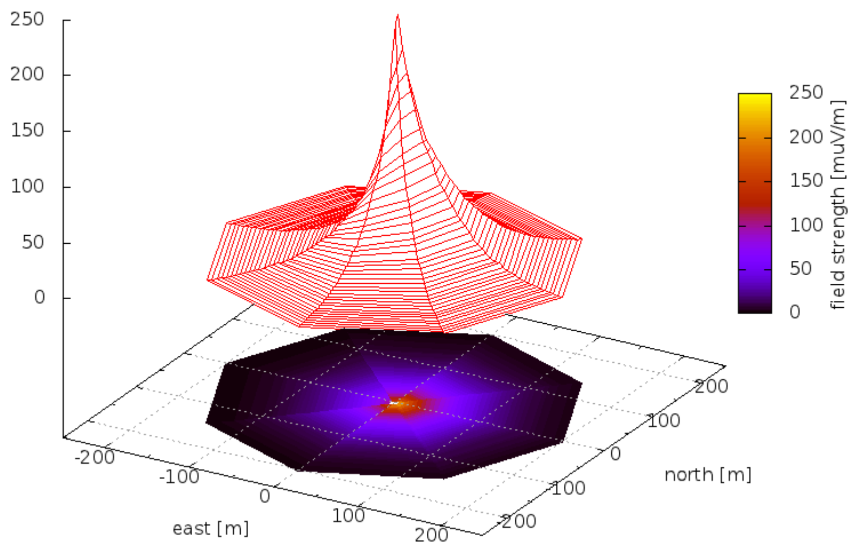


- mean of Xmax and fluctuations provide primary mass estimate

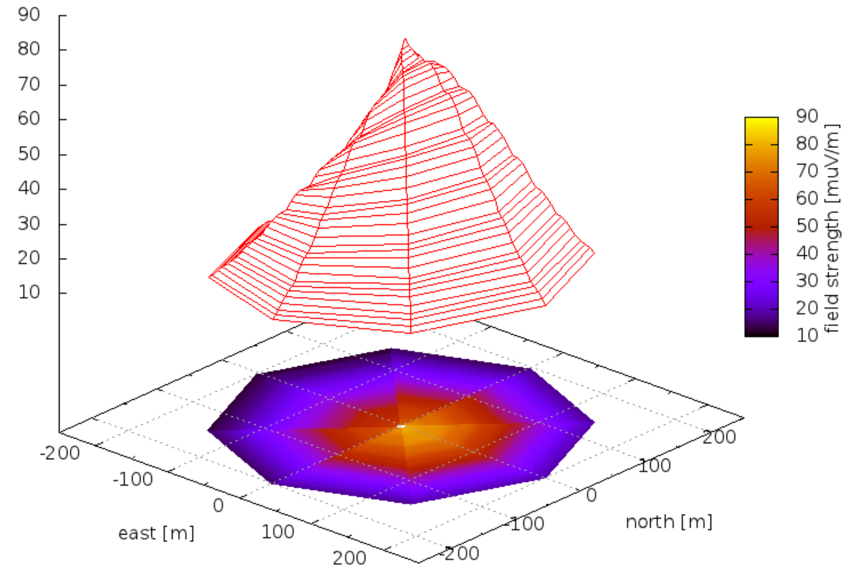
Lateral distribution as probe for composition

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

TH et al., ARENA2012

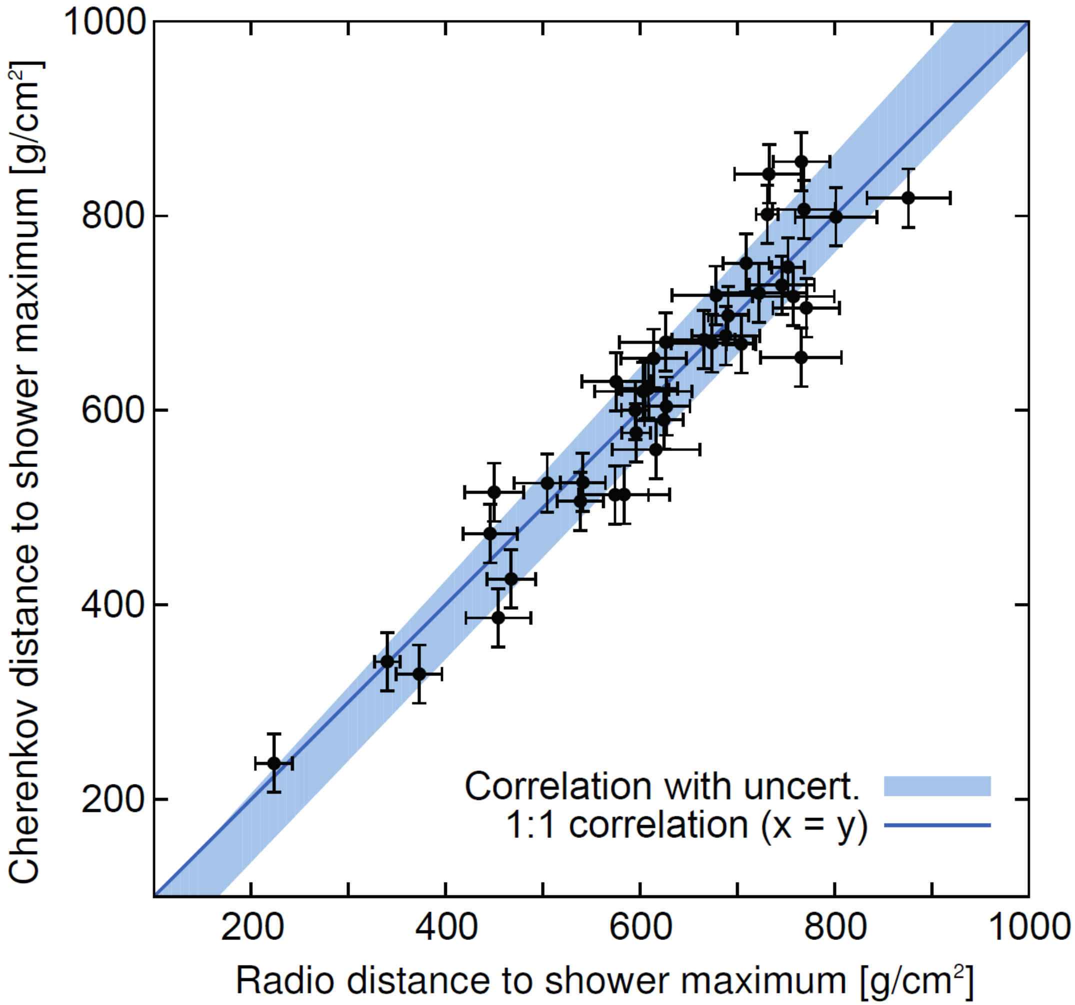


vertical proton shower
at LOPES frequencies
simulated with CoREAS



vertical iron shower
at LOPES frequencies
simulated with CoREAS

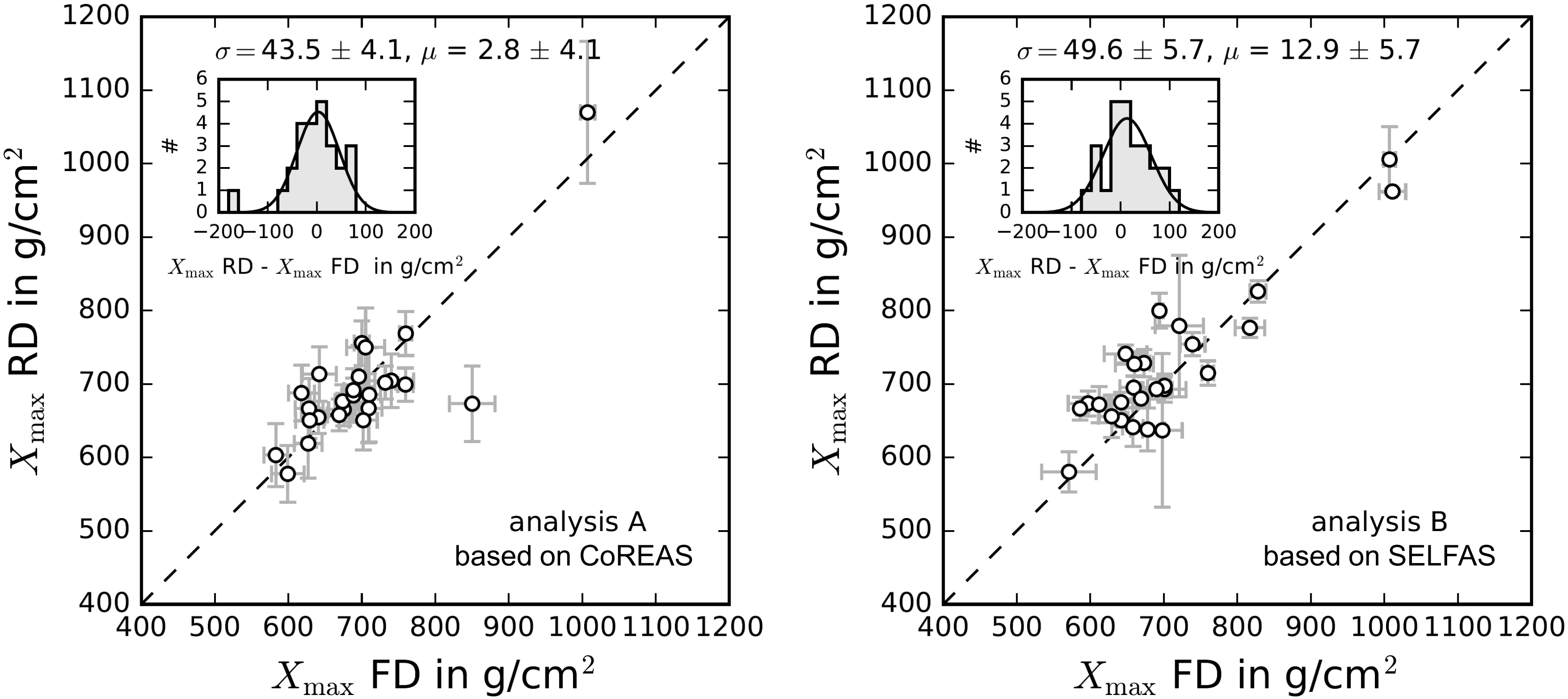
Experimental Xmax validation by Tunka-Rex



- 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.

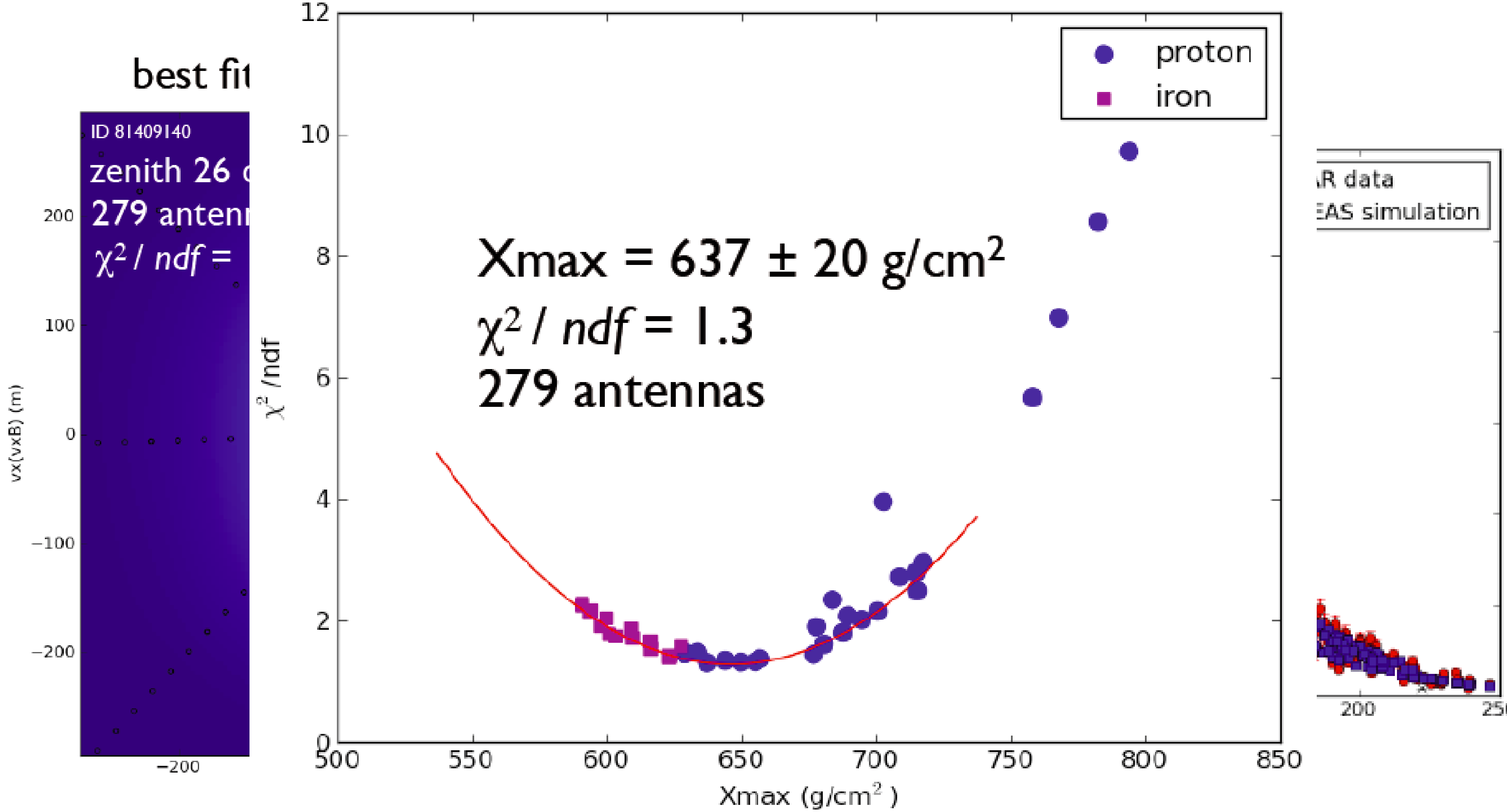
Experimental Xmax validation by Auger



- various reconstruction approaches being tested in AERA
- current combined FD-RD resolution ~45 g/cm^2, so RD alone <~40 g/cm^2
- still room for improvement (only uses amplitude information)

E. Holt for the Pierre Auger Collaboration, PoS(ICRC2017)492

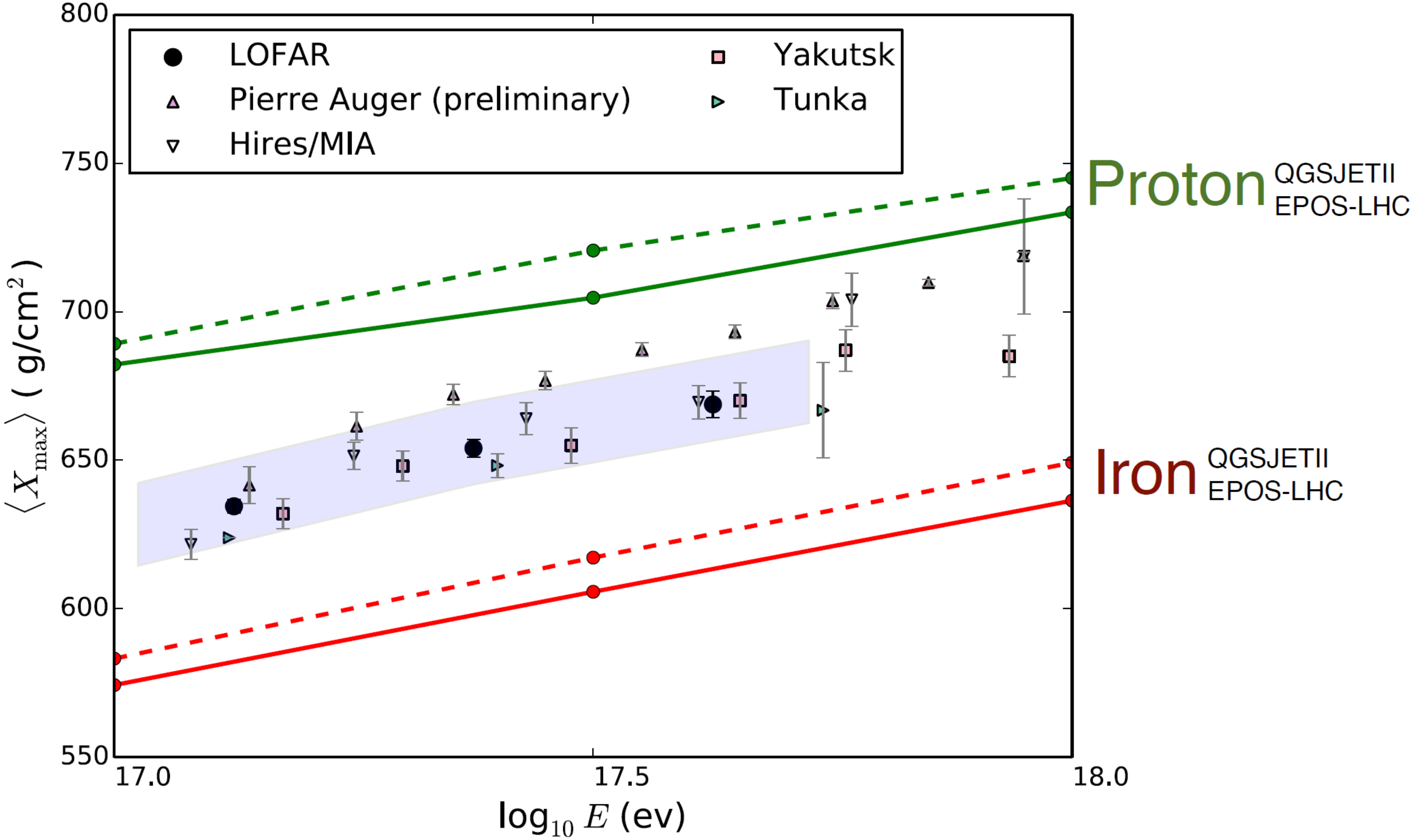
Fit of LOFAR particle and radio data



- data 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

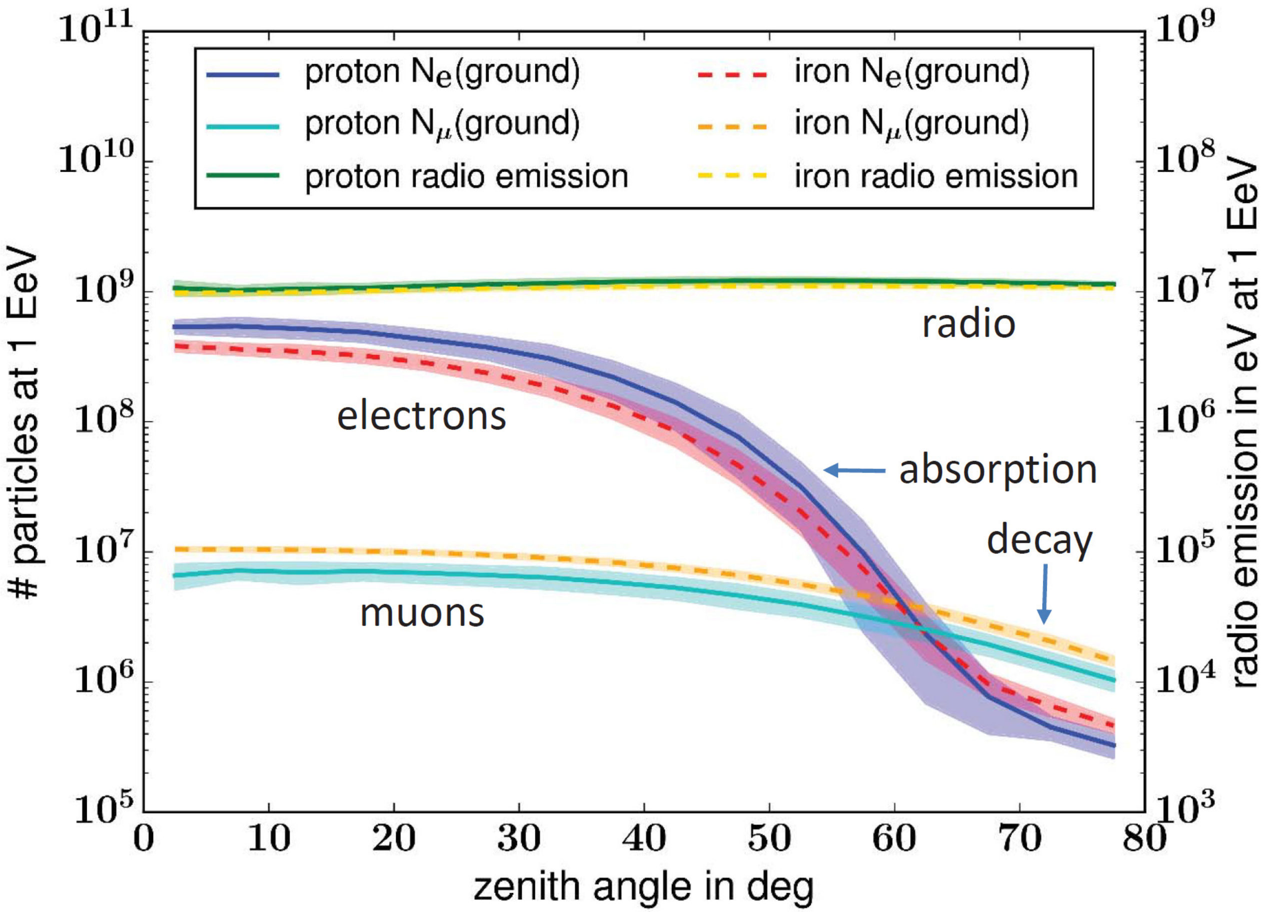
Lofar <Xmax> results



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

Complementarity of radio and muons

ground = Auger site 1452 m a.s.l.

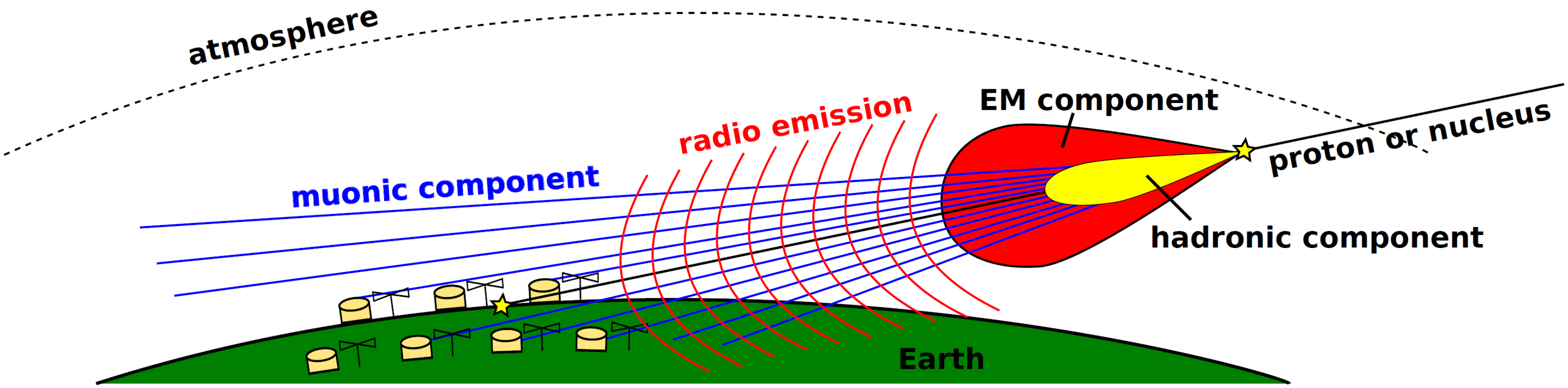


Increasing atmospheric depth to ground

- combination of muon and radio measurements promises to be very powerful, even for very inclined showers where EM cascade not measurable on ground

E. Holt et al.

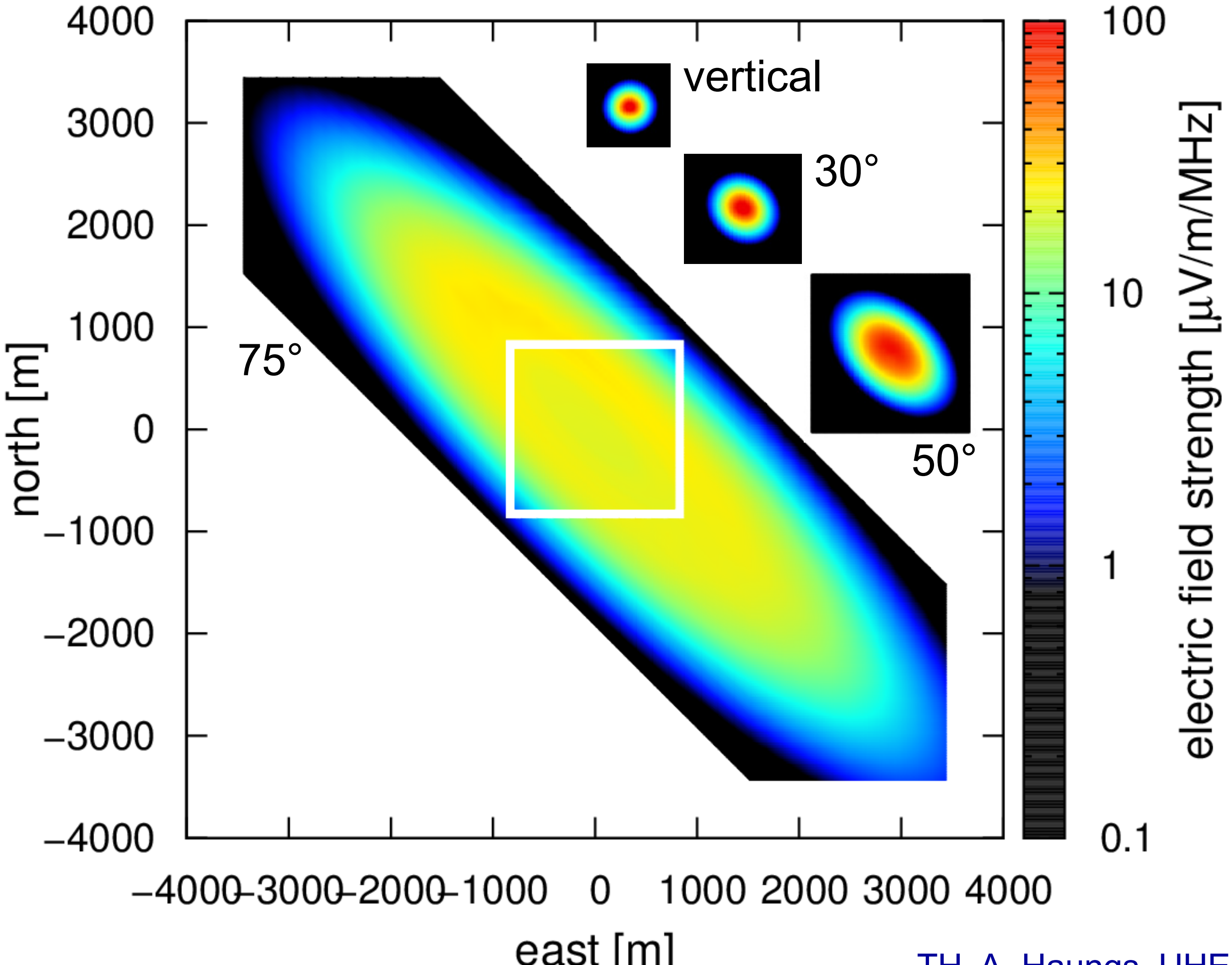
Radio measurements of inclined showers



- 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

Inclined air showers

Large-scale detection of inclined showers

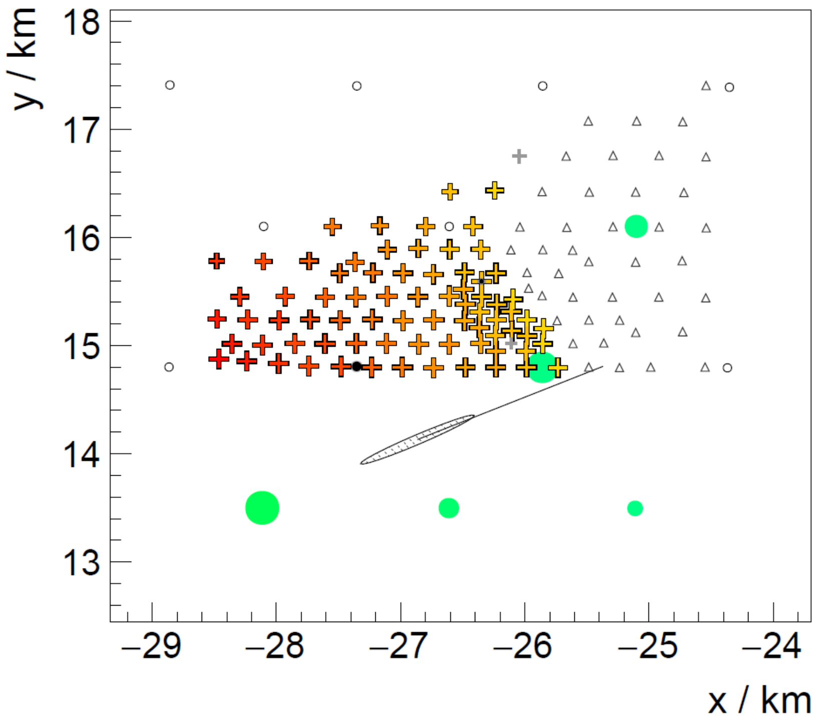


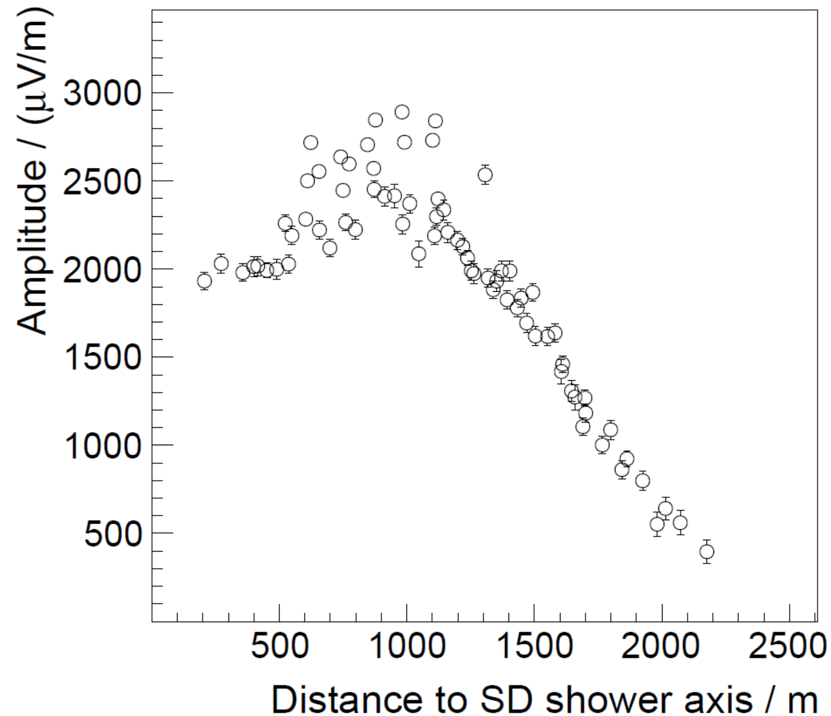
- large source distance leads to very large radio emission footprints in inclined air showers
- should be detectable with sparse arrays

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

AERA has measured >500 inclined showers

Karlsruhe Institute of Technology

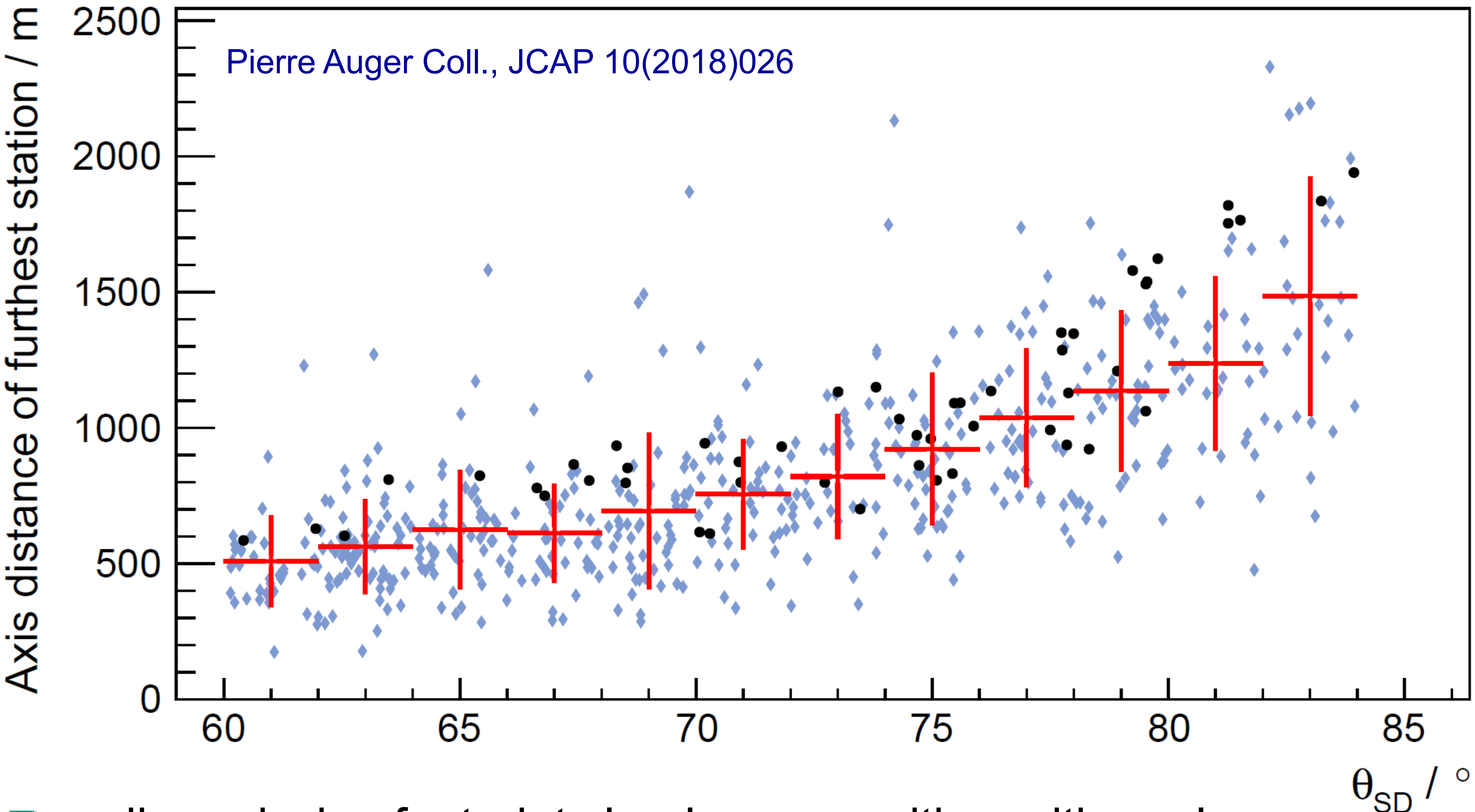




- air showers up to 88° zenith angle measured
- footprints with radii of more than 2 km in shower plane
- detection with 1.5 km antenna grid would be sufficient

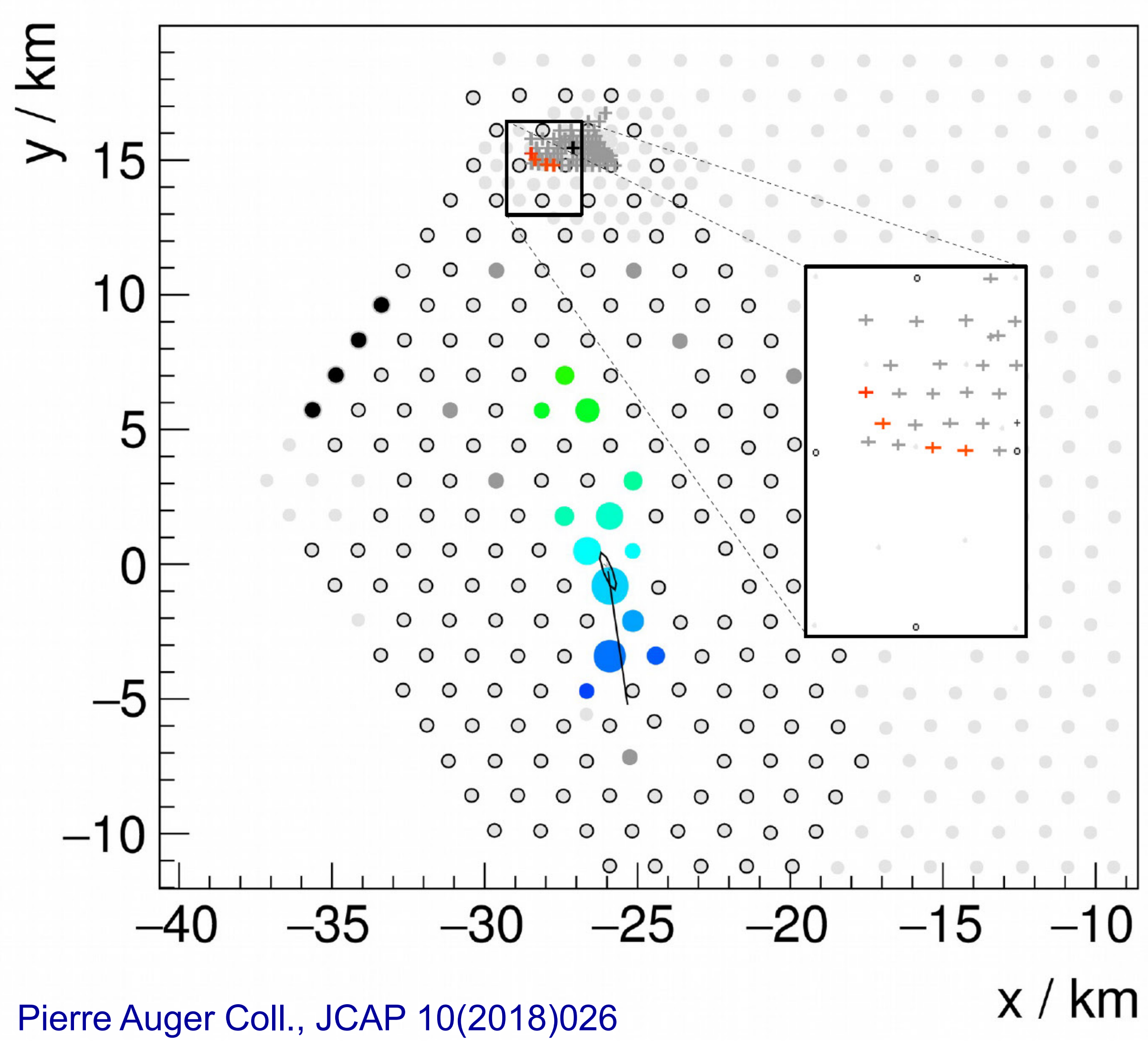
Pierre Auger Coll., JCAP 10(2018)026

Size of radio-emission footprint



- radio-emission footprint clearly grows with zenith angle
- as expected for beamed emission without atmospheric absorption

Radio-emission larger than particle footprint



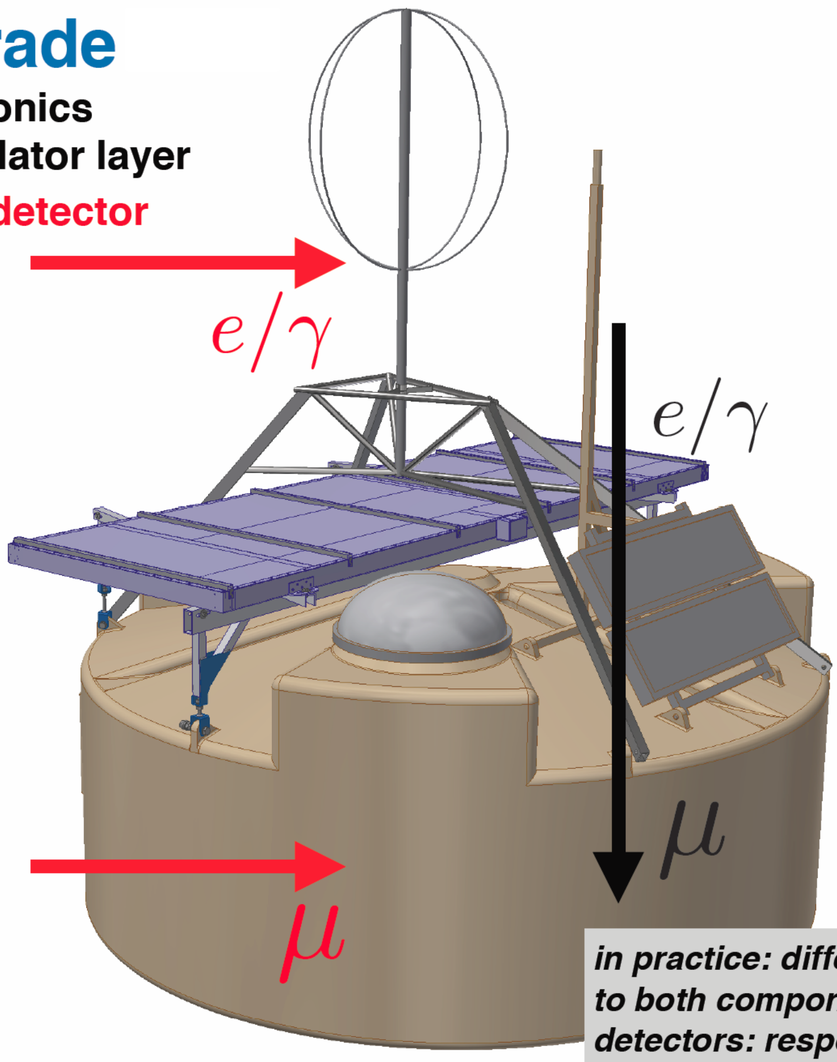
Pierre Auger Coll., JCAP 10(2018)026

- the radio-emission footprint can even be much larger than the particle footprint

Auger Radio Upgrade

upgrade

- **electronics**
- **scintillator layer**
- **radio detector**



in practice: different response to both components in both detectors: response matrix

- complement each Auger surface detector tank with a radio antenna
  - radio array on 3000 km^2 with a 1.5 km spacing
- fully funded, setup 2020/21
- complementary to scintillator upgrade
- extend upgraded measurement to larger zenith angles
  - increase sky coverage
  - cross-check systematics

Performance summary

Strengths and limitations of radio detection

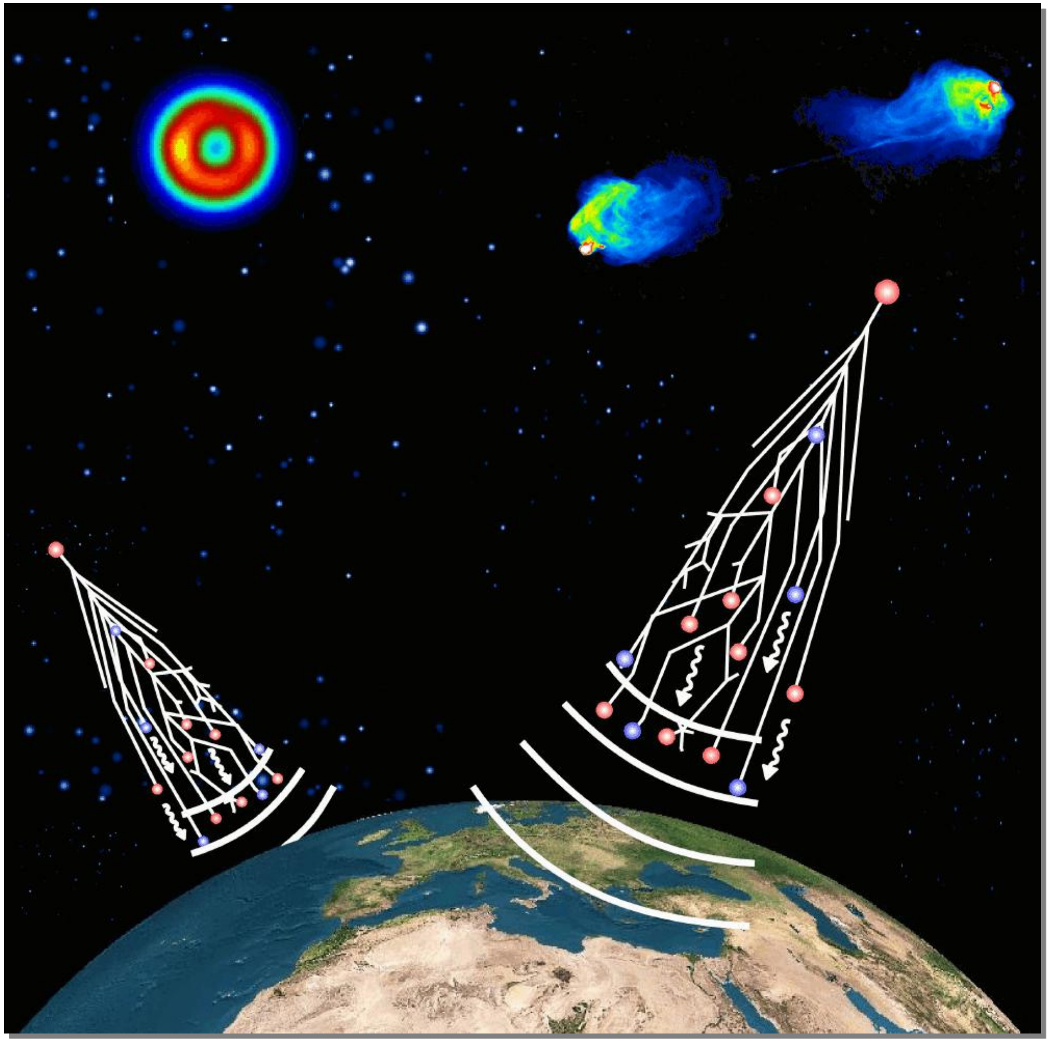
radio signal can be predicted from first principles	emission well-understood, can be used to set energy scale
measures pure electromagnetic shower component	direct comparison to FD, little influence of hadronic interactions
no absorption in the atmosphere, calorimetric energy measurement	σ_E < 15%, possibly below 10%, cross-calibration between detectors
near 100% duty cycle	>95%
high angular resolution	σ < 0.5°
particle mass sensitivity	σ_{Xmax} < 20 g/cm^2 dense (< 40 sparse)
simple (cheap) detectors	$1000/detector (+infrastructure)
required detector spacing	<300 m (θ<60°) >1 km (θ>65°)
direction-dependent threshold	cut heavily or rely on simulations
radio-backgrounds	E > 10^{17} eV, exploit external triggers

Summary

- radio detection has matured from pioneering prototypes to large-scale measurements in the recent decade
- we have reached competitive resolution in radio event reconstruction
  - arrival direction
  - particle energy
  - depth of shower maximum
- Monte Carlo simulations have played a key role in this success

Contents

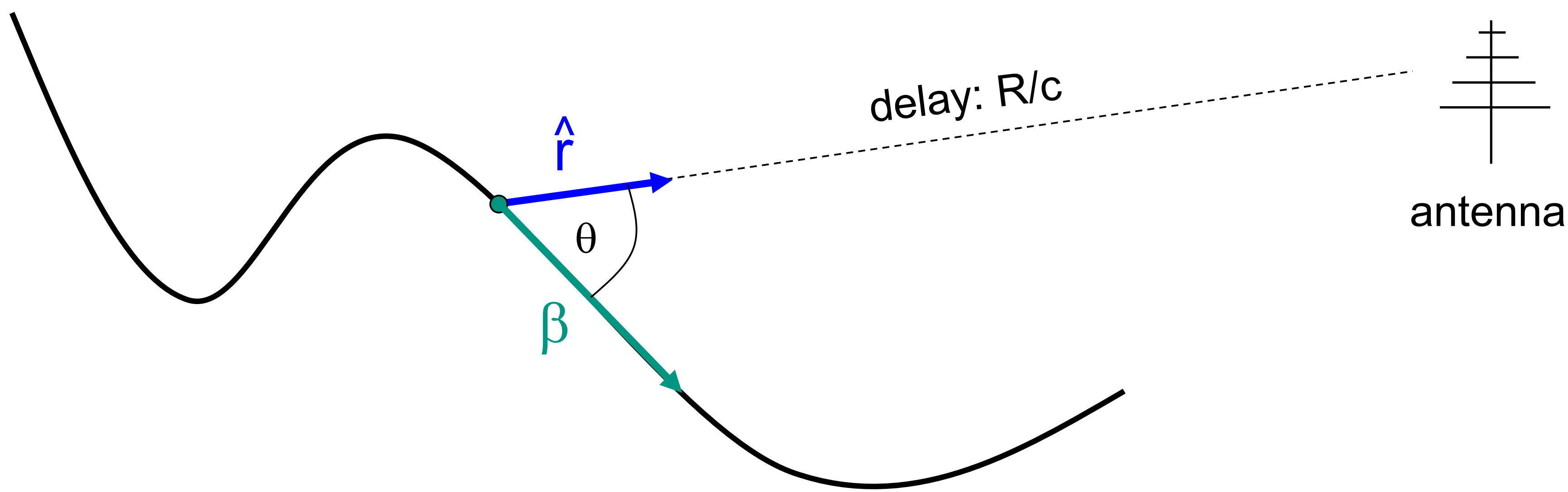
- why radio detection?
- from prototypes to maturity in 15 years
- simulating radio emission – CoREAS



What is CoREAS?

- a C++ plugin to CORSIKA using the COAST interface
  - fully integrated in the build system
- calculation of radio emission from EAS using the „endpoint formalism“

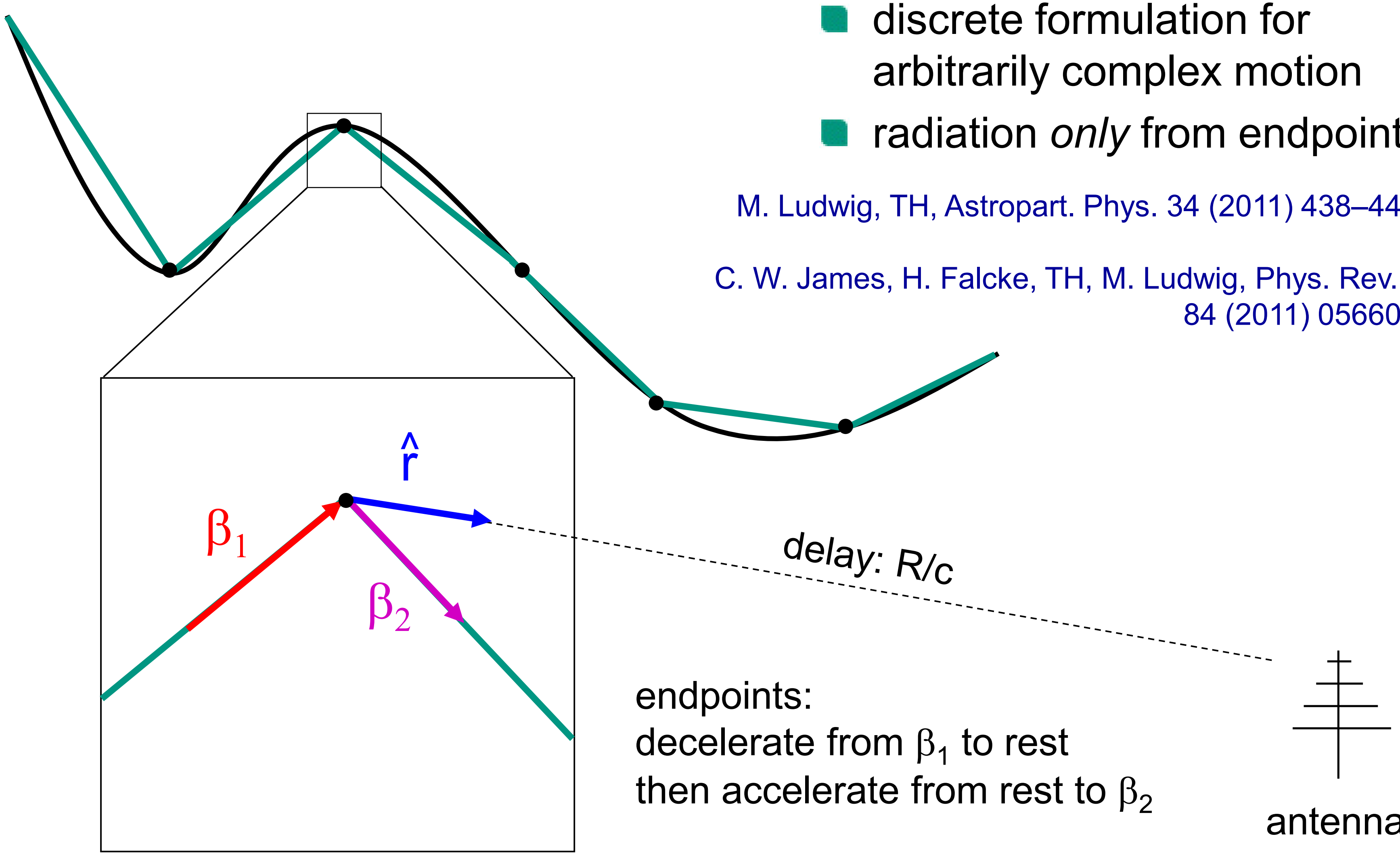
Charged particle motion: Liénard-Wiechert fields



$$\vec{E}(\vec{x},t) = q\left[\frac{\hat{r}-n\vec{\beta}}{\gamma^2(1-n\vec{\beta}\cdot\hat{r})^3R^2}\right]_{\mathrm{ret}} + \frac{q}{c}\left[\frac{\hat{r}\times[(\hat{r}-n\vec{\beta})\times\dot{\vec{\beta}}]}{(1-n\vec{\beta}\cdot\hat{r})^3R}\right]_{\mathrm{ret}}$$

- continuous formulation
- difficult to apply in Monte Carlo codes

Discretization of particle motion: endpoints



- 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

Radiation from a single endpoint

Karlsruhe Institute of Technology

- time domain formulation

$$\vec{E}_{\pm}(\vec{x},t) = \pm\frac{1}{\Delta t}\frac{q}{c}\left(\frac{\hat{r}\times[\hat{r}\times\vec{\beta}^*]}{(1-n\vec{\beta}^*\cdot\hat{r})R}\right)$$

- frequency domain formulation

$$\vec{E}_{\pm}(\vec{x},\nu) \;=\; \pm\frac{q}{c}\,\frac{e^{ikR(t_0')}}{R(t_0')}\,\frac{e^{2\pi i\nu t_0'}}{1-n\vec{\beta}^*\cdot\hat{r}}\,\hat{r}\times[\hat{r}\times\vec{\beta}^*]$$

- for deceleration from β* to rest (stopping point)

+ for acceleration from rest to β* (starting point)

What is CoREAS?

- a C++ plugin to CORSIKA using the COAST interface
  - fully integrated in the build system
- calculation of radio emission from EAS using the „endpoint formalism"
  - downgoing showers in curved and flat geometries fully supported
  - upgoing and skimming geometries untested
- ASCII output of electric field traces per antenna
  - soon: HDF5 converter for processed data and better simulation handling
- full MPI parallelization up to thousands of cores
- gdastool: simulate with realistic atmosphere at given time and location, including effects of atmospheric humidity

Technical information: CoREAS manual

KIT Karlsruhe Institute of Technology

CoREAS 1.3 User's Manual

Tim Huege[*]

December 19, 2017

1 What's new in CoREAS V1.3?

This version allows the choice of a more realistic refractive index profile in the radio simulations. The enclosed GDAS-tool, described in more detail in the CORSIKA manual, queries the GDAS atmospheric database for a given location and time and downloads a corresponding density and humidity profile. The density profile is fitted to generate the 5-layer atmosphere fed to CORSIKA. At the same time, a consistent, tabulated refractivity profile is fed to CoREAS. This allows in particular the inclusion of humidity effects in the refractive index profile. Also, performance should once more have been (slightly) improved as now refractivity and integrated refractivity are tabulated directly and do not need to be calculated from the density.

This functionality was actually already included in CORSIKA v7.63, however since then some slight improvements to the CoREAS implementation and bug fixes to the GDAS-tool were made.

I would like to thank Tobias Winchen and Pragati Mitra for contributing this very valuable functionality to CoREAS.

2 What's new in CoREAS V1.2?

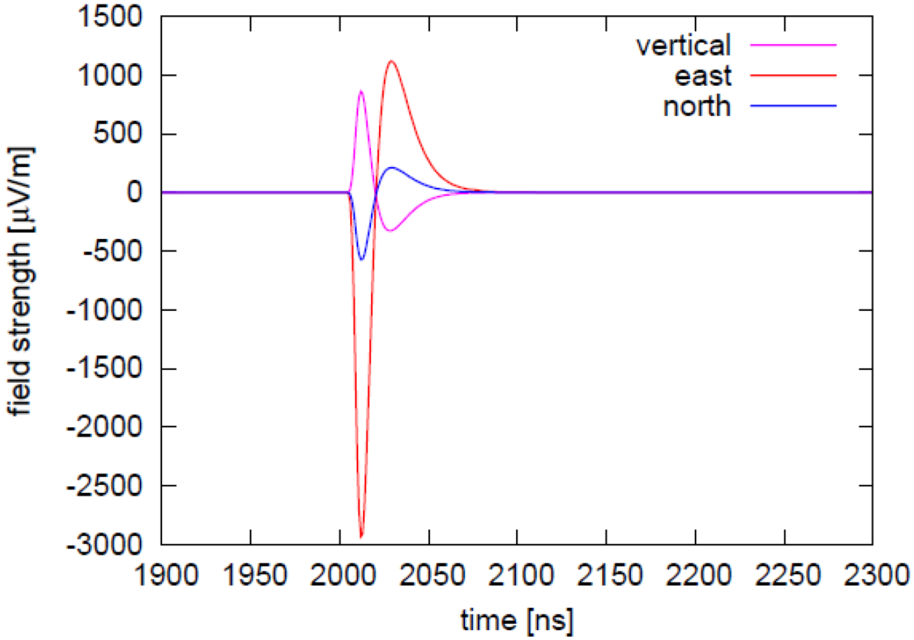
The physics of CoREAS is unchanged between version 1.1 and version 1.2. However, a bug was fixed that was present in all previous CoREAS releases. It affected simulations with zenith angles beyond 75 degrees zenith angle, for which a step-wise numerical integration of the refractive index along the line of sight should have been carried out – but was not. Up to 80 degrees zenith angle, the deviations caused by this bug were minor. Simulations with zenith angles beyond 80 degrees zenith angle were significantly affected, though, and should be redone with CoREAS V1.2 or later. Please note that the needed computation time increases significantly for inclined showers due to the stepwise integration. This might be improved in a future version. If job-times get too long to be handled, please have a look at the quick-start guide for the MPI-parallelized version of CoREAS.

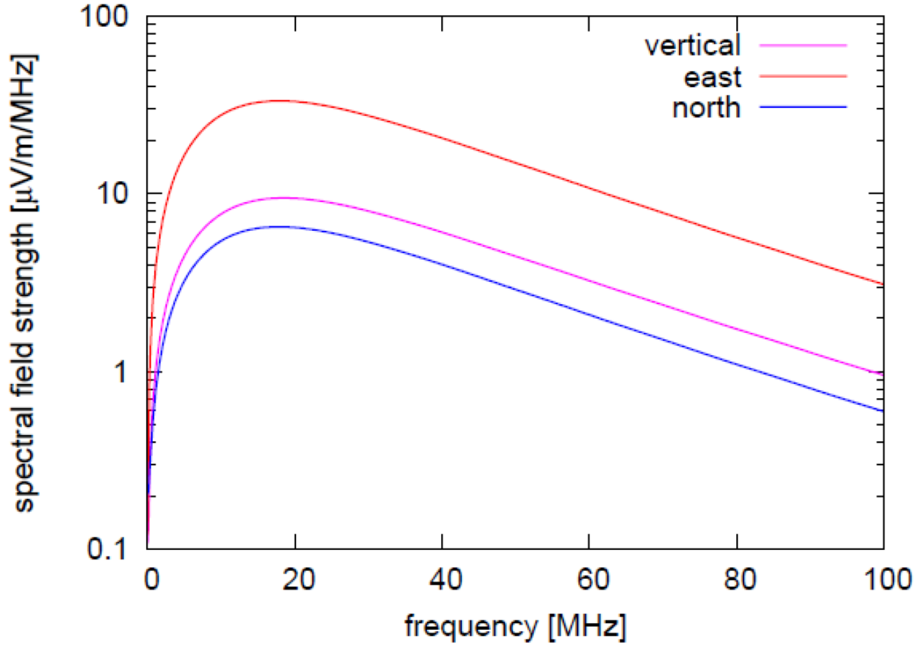
The performance of CoREAS V1.2 has been significantly optimized with respect to earlier versions. This has been achieved by tabulating the atmosphere rather than calling CORSIKA-internal functions that rely on calculations of

[*]email: tim.huege@kit.edu

- manual available with
  - installation instructions
  - definition of coordinate systems, unit conventions, …
  - definition of input and output data formats
  - example input files, example gnuplot script

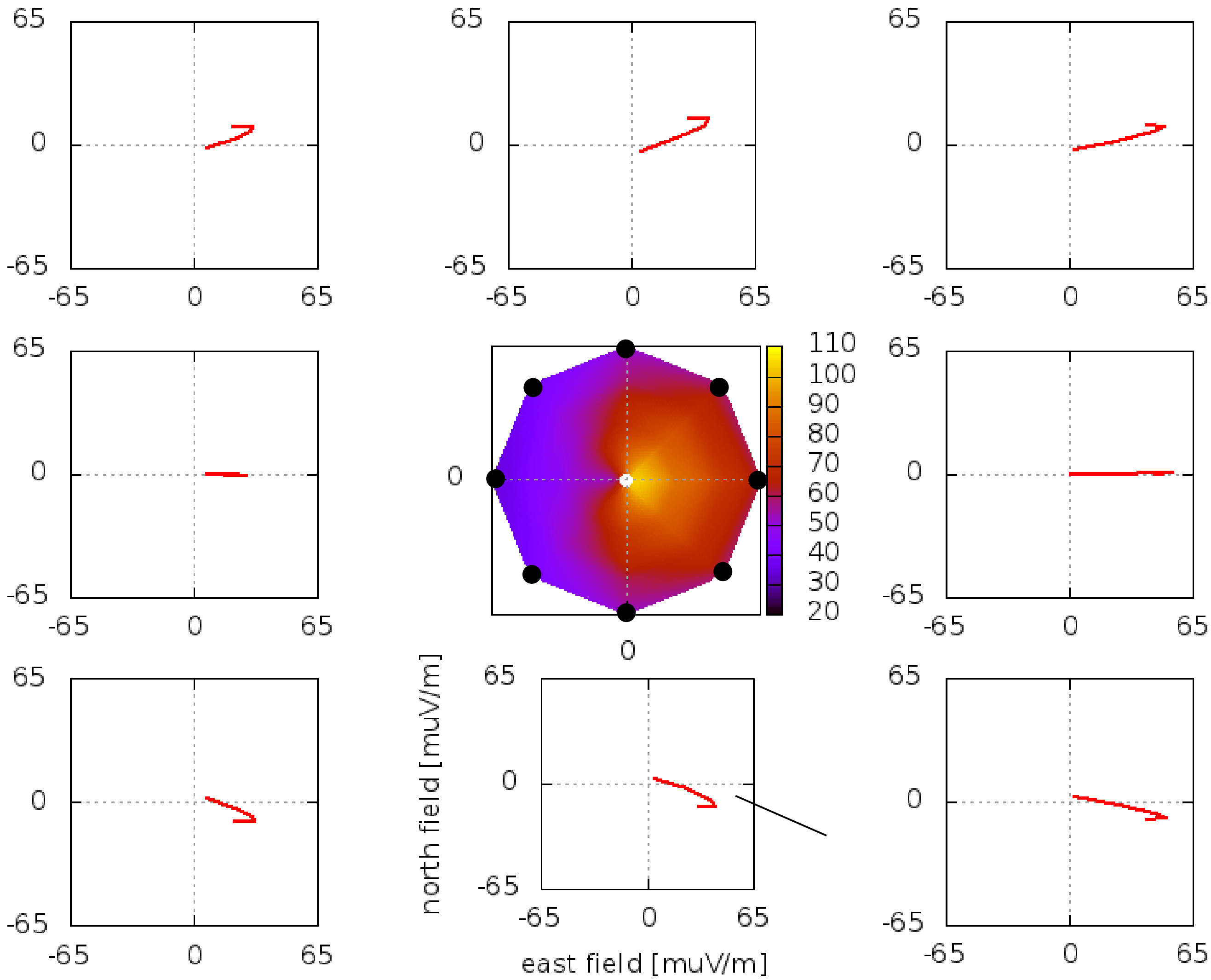
COREAS output: raw e-field traces per antenna





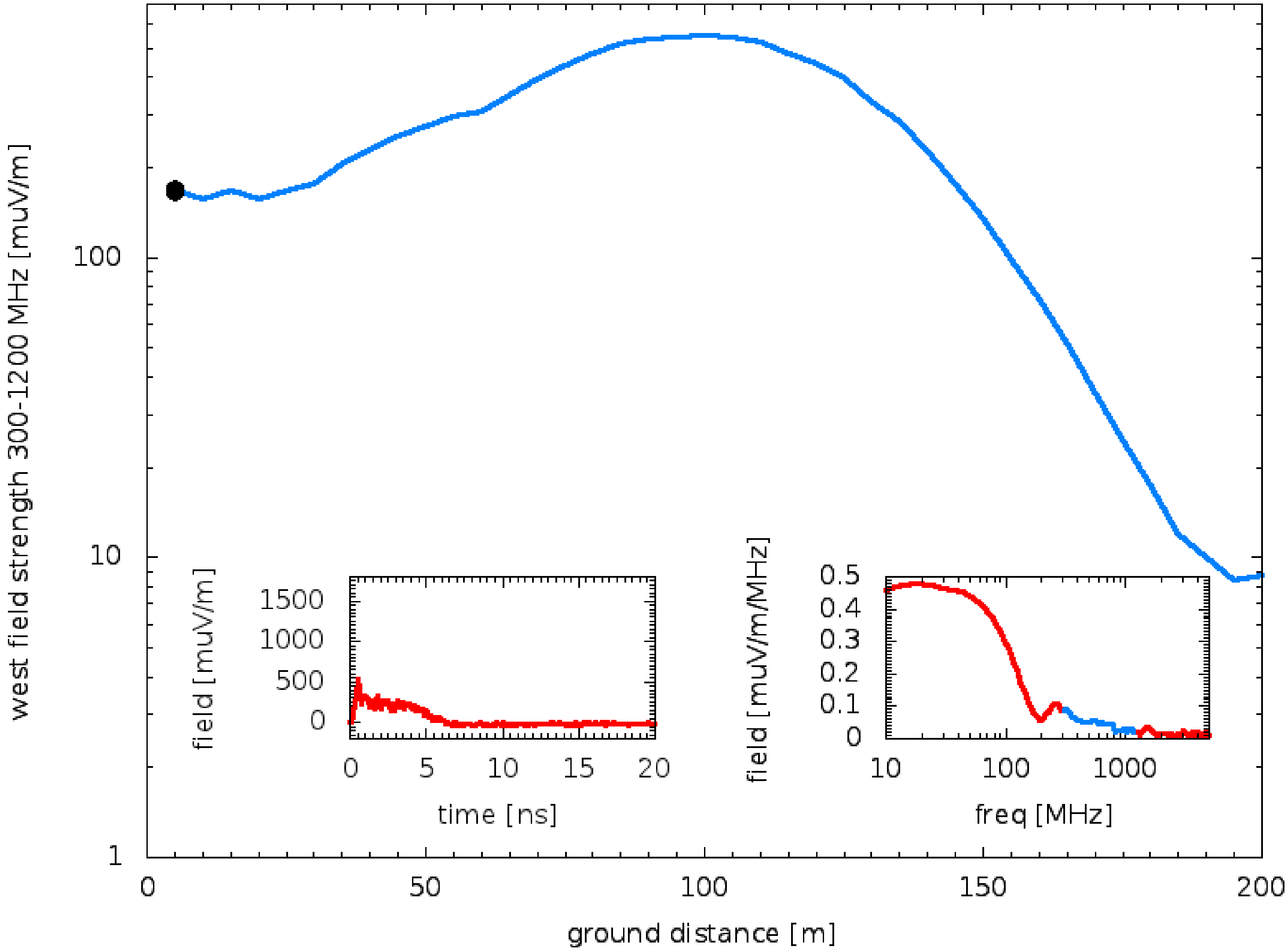
- use external programme to do fast Fourier transforms for spectra
- can then be bandpass-filtered and transformed to v x B / v x v x B plane
  - HDF5 converter includes functionality for this

Complexity of signal polarization



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

Pulse shape and spectrum as f(lateral distance)

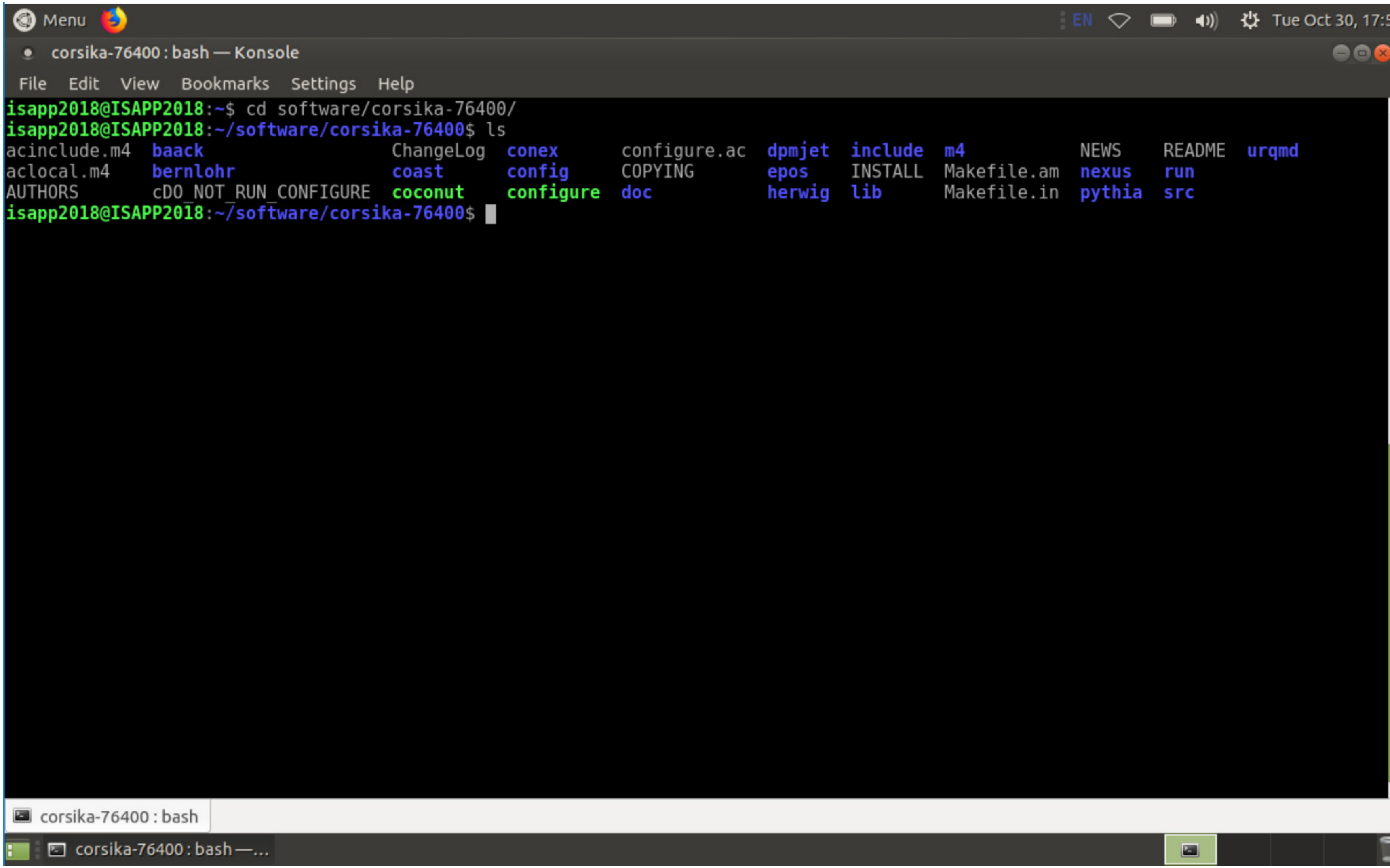


- near the Cherenkov angle, spectra can reach up to GHz frequen-cies
- Cherenkov ring at 300 – 1200 MHz

Plans for radio in next-generation CORSIKA

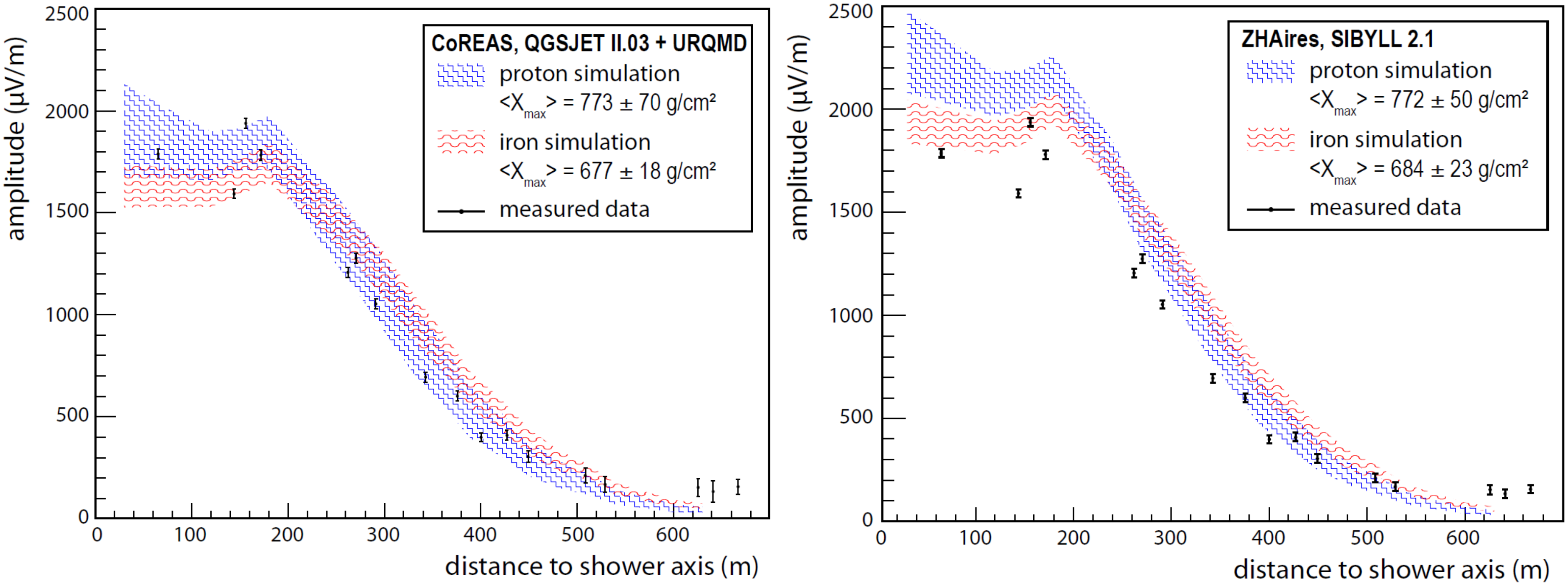
- fully integrate radio from the start
- shake off limitations imposed by current CORSIKA
  - support dense media (e.g. ice)
  - support transition from air to dense media
  - support complex propagation effects (refraction, …)
- exploit modern computing infrastructure
  - full CPU parallelization
  - investigate GPU parallelization
- possibly combine cascade equations and radio-emission calculations
- and more … your ideas!?

Short practical demonstration …



Backup slides

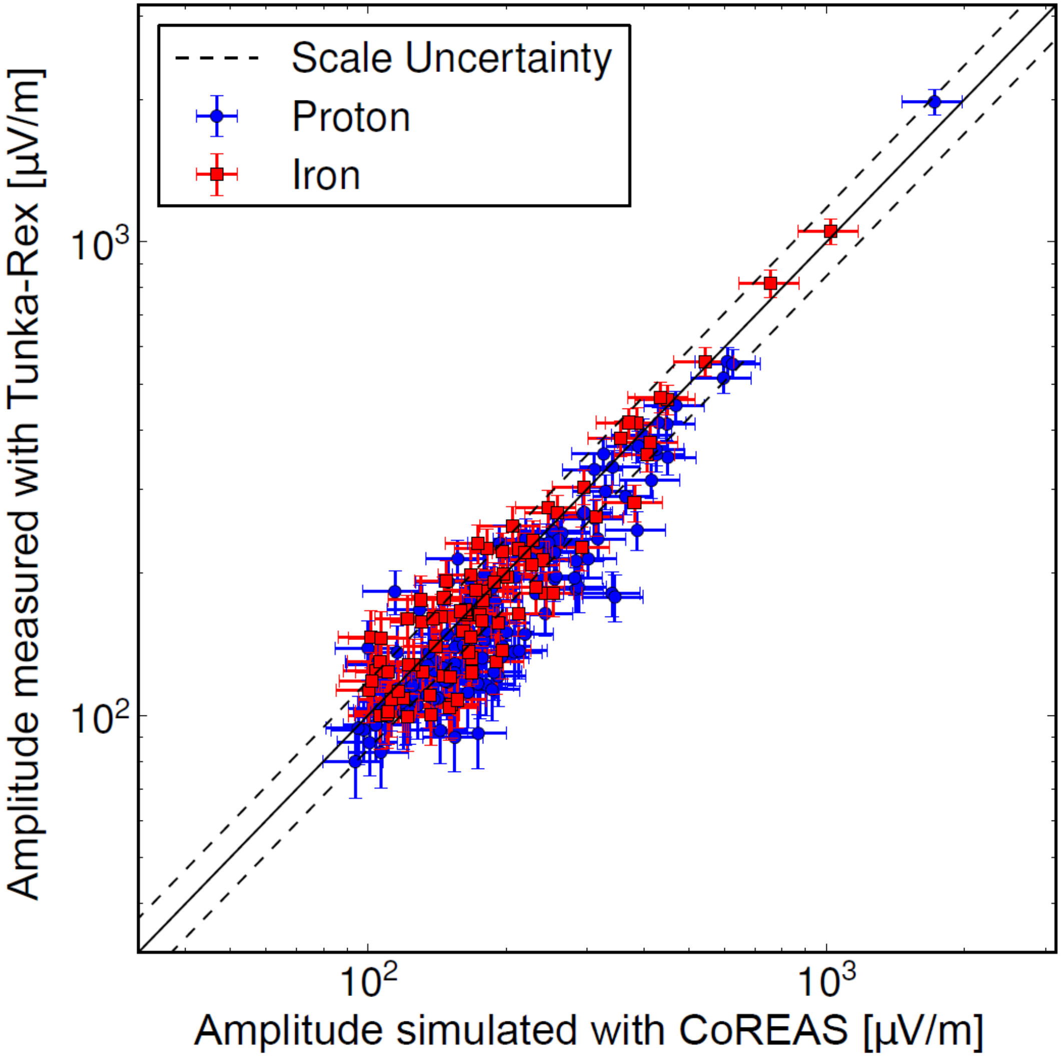
Comparison of simulations with AERA data



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

Pierre Auger Collaboration, ICRC2013, id #899

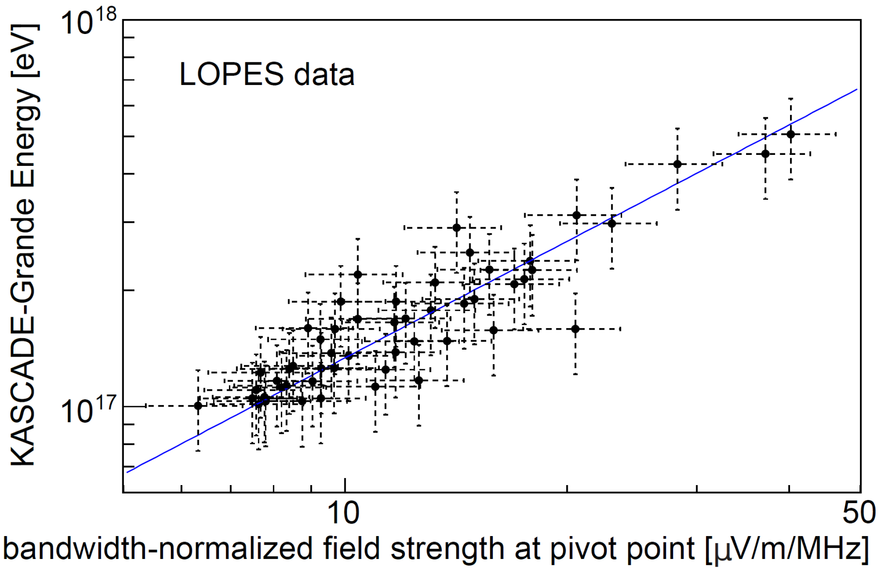
Comparison of simulations with Tunka-Rex data

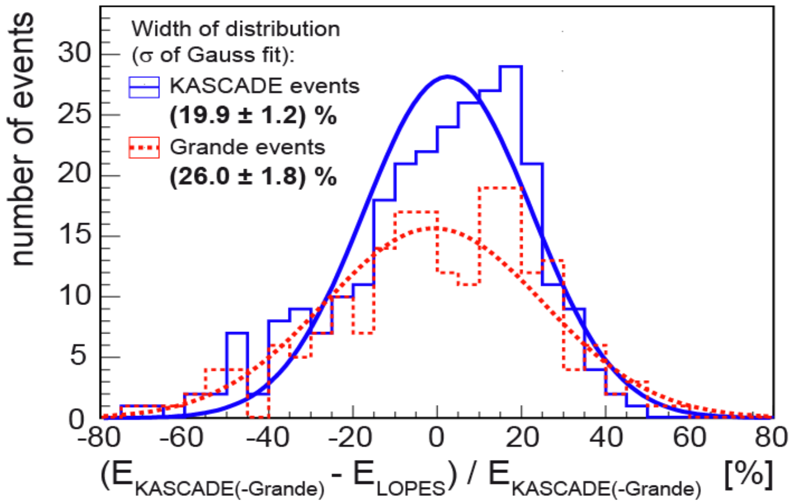


- very good agreement between CoREAS simulations and Tunka-Rex data

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

LOPES energy reconstruction





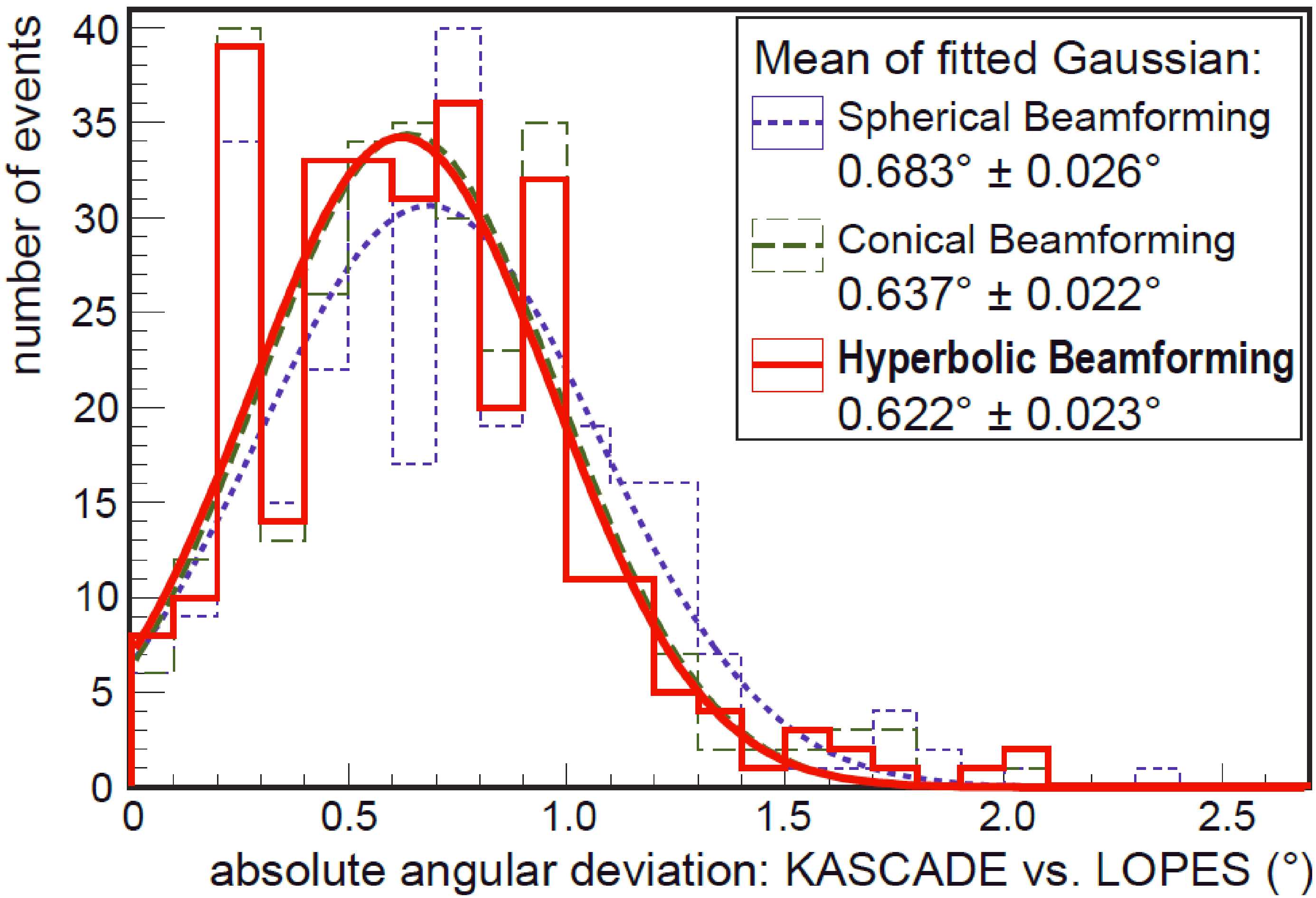
- linear correlation with 20-25% combined LOPES-KASCADE-Grande energy resolution
  - radio probably better, limited by KASCADE-Grande energy uncertainty of ~20%
  - simulations: ~8% intrinsic

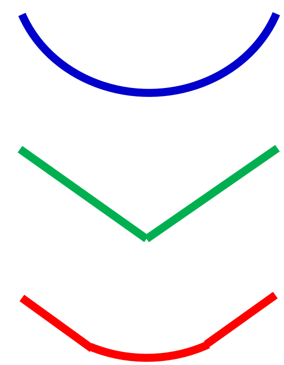
LOPES Coll., Phys. Rev. D 90 (2014) 062001.

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

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

Accuracy of direction reconstruction



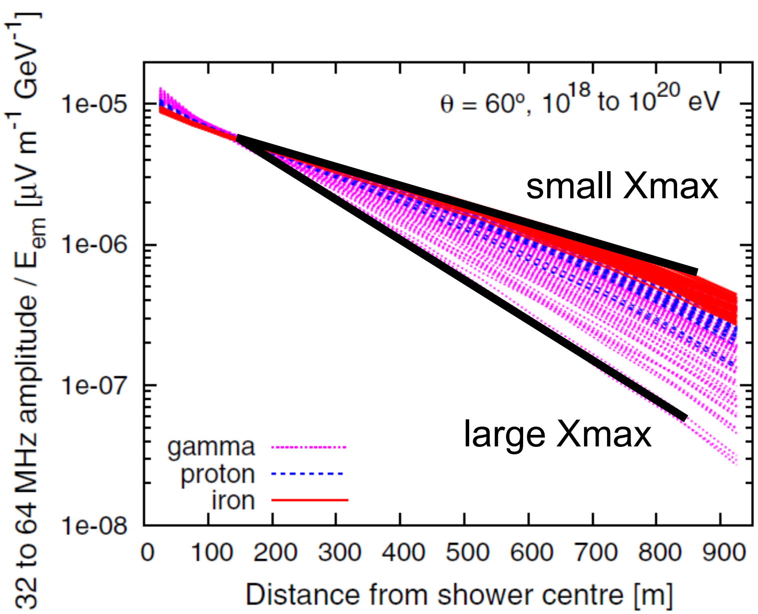


- bigger arrays should do even better

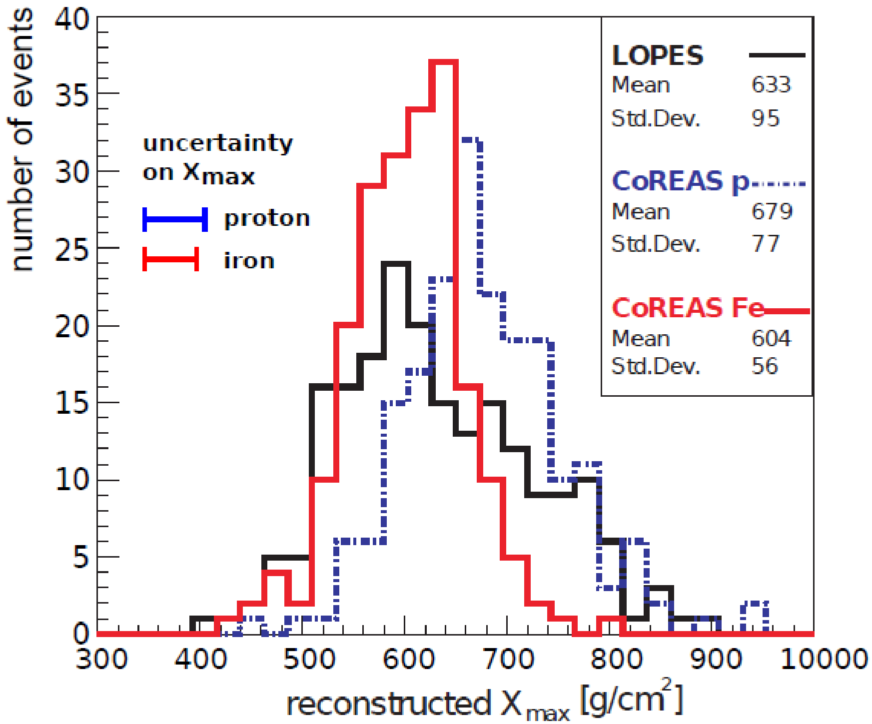
Tim Huege <tim.huege@kit.edu>

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 σ_{Xmax} ~ 50 g/cm²)

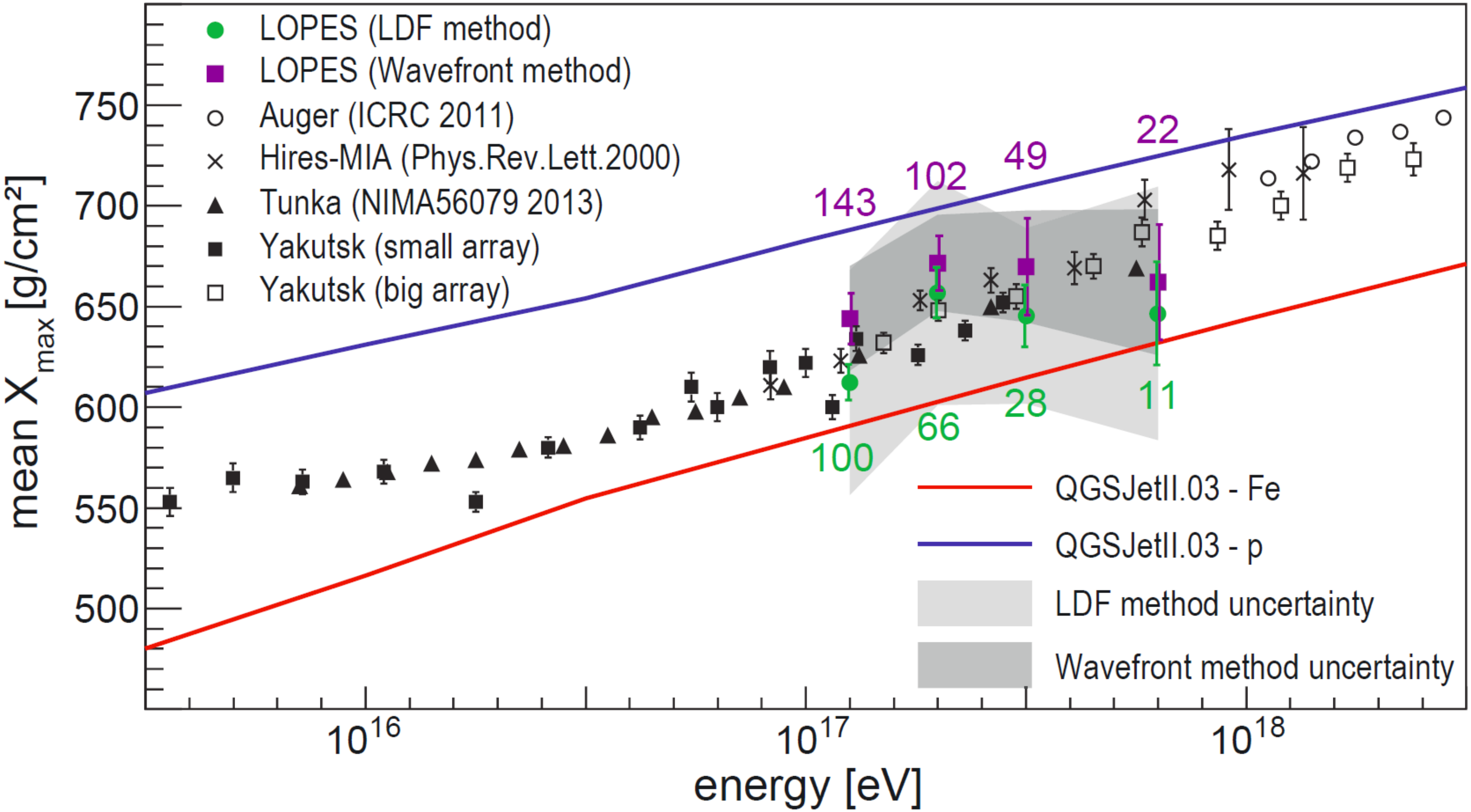


TH, Ulrich, Engel (Astrop. Phys. 2008)



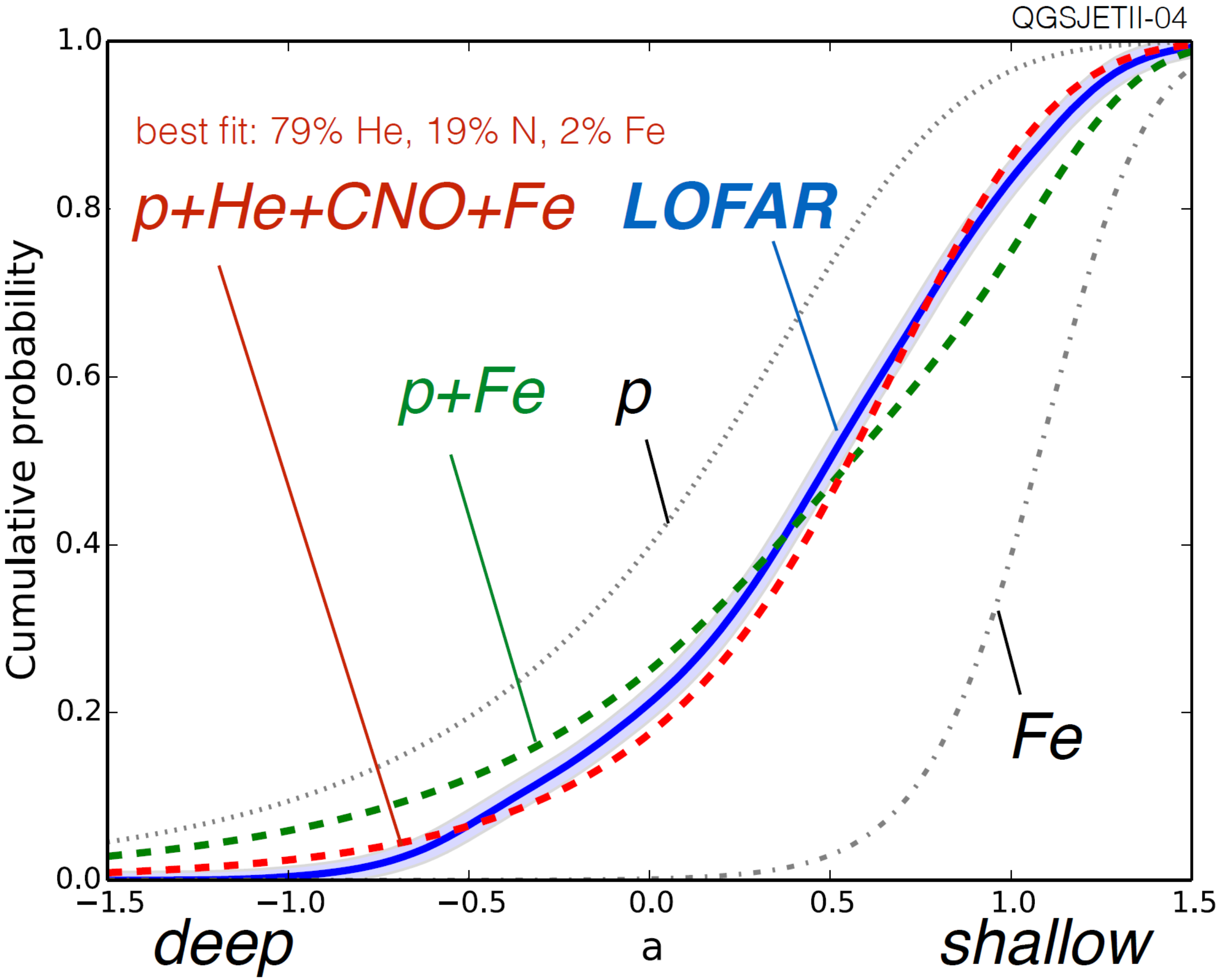
LOPES Coll., Phys. Rev. D 90 (2014) 062001.

Xmax reconstructed from LOPES data



LOPES Coll., J. Phys.: Conf. Ser. 632 (2015) 012102.

LOFAR unbinned analysis



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

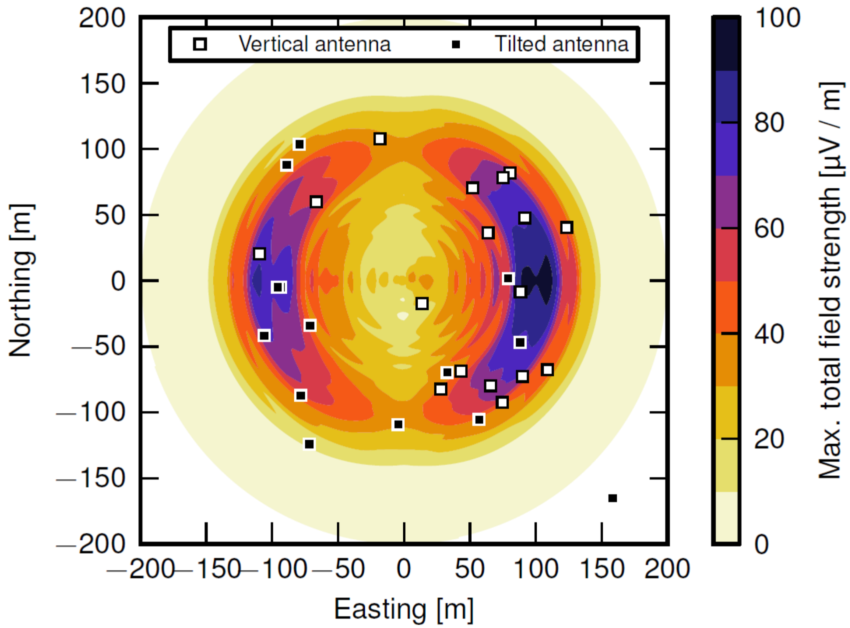
- compare measured distribution of

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

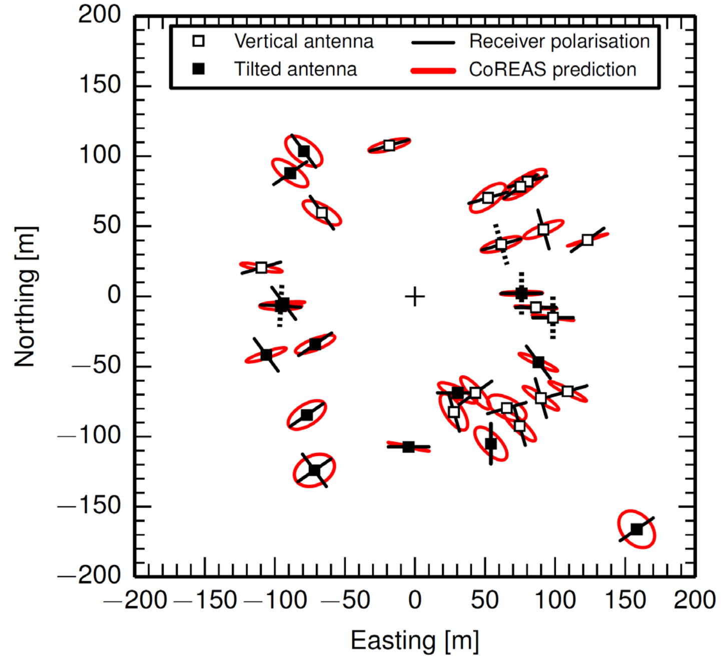
  with simulated distributions
- result shows large fraction of light primaries at 10^{17}-$10^{17.5}$ eV

CoREAS sims & CROME results

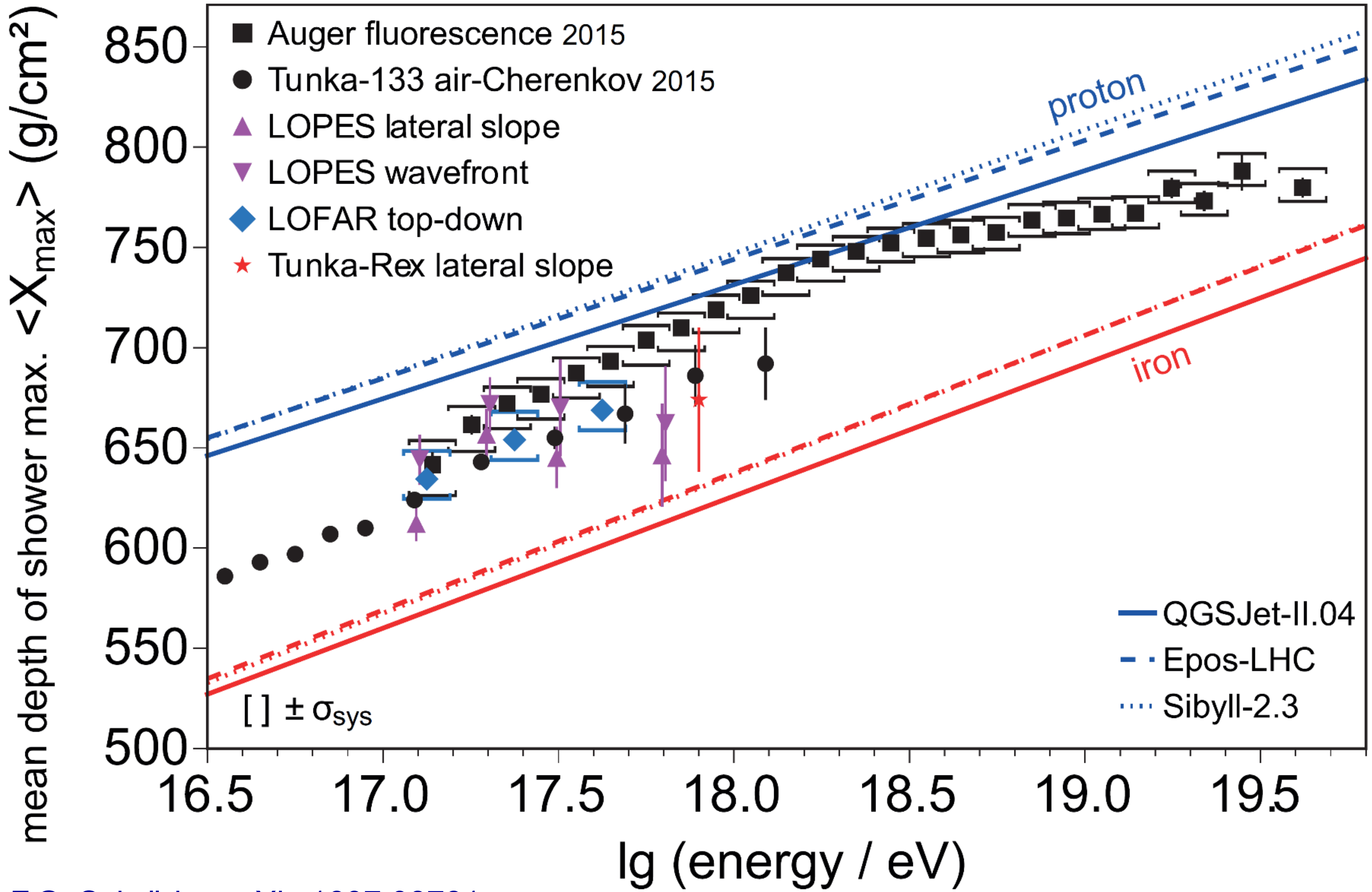
- GHz emission in agreement with predictions by CoREAS



CROME Coll., PRL 113 (2014) 221101



Xmax measurements with radio detectors



F.G. Schröder, arXiv:1607.08781

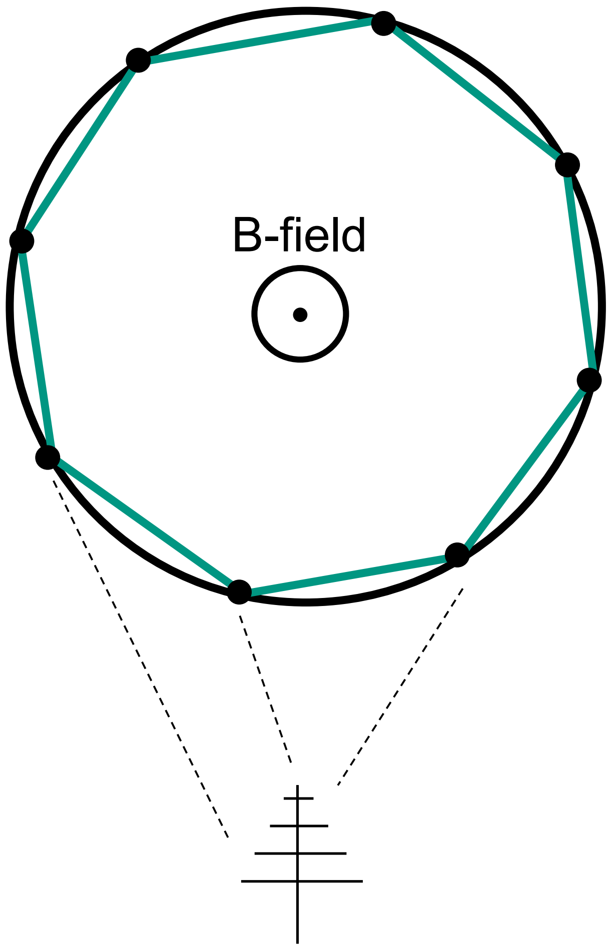
How expensive are individual detectors?

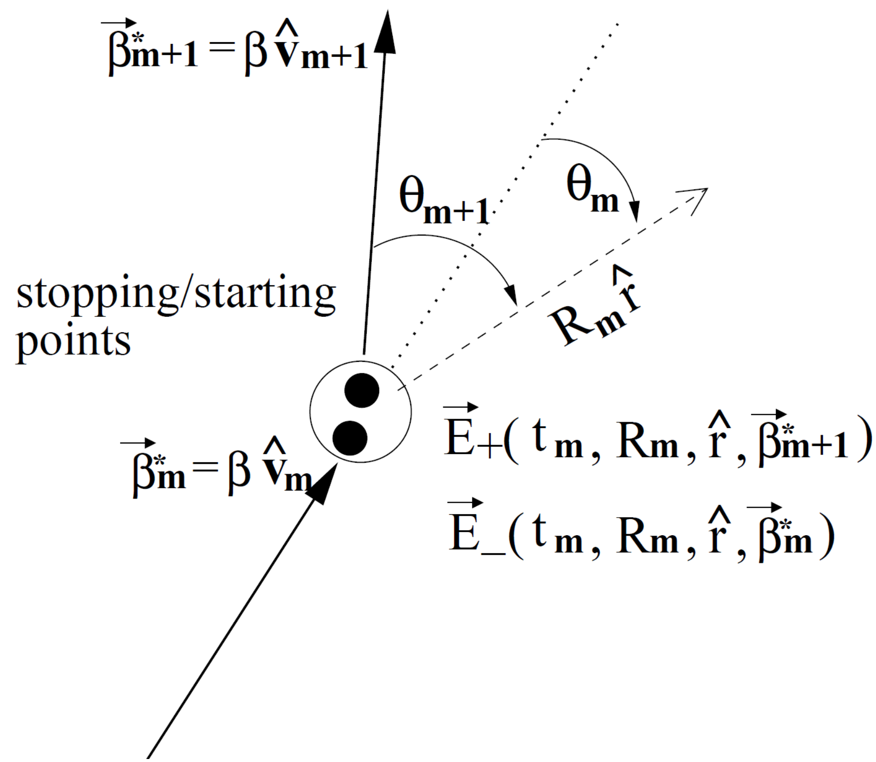
- antenna can be cheap, SALLA antenna plus low-noise amplifier costs <500 US$
- digital electronics more expensive, but profit from Moore‘s law
- most expensive part is „infrastructure“ (power supply, communications, …)
- sub-1000$ for antenna plus digital electronics certainly seem feasible

Tim Huege <tim.huege@kit.edu>

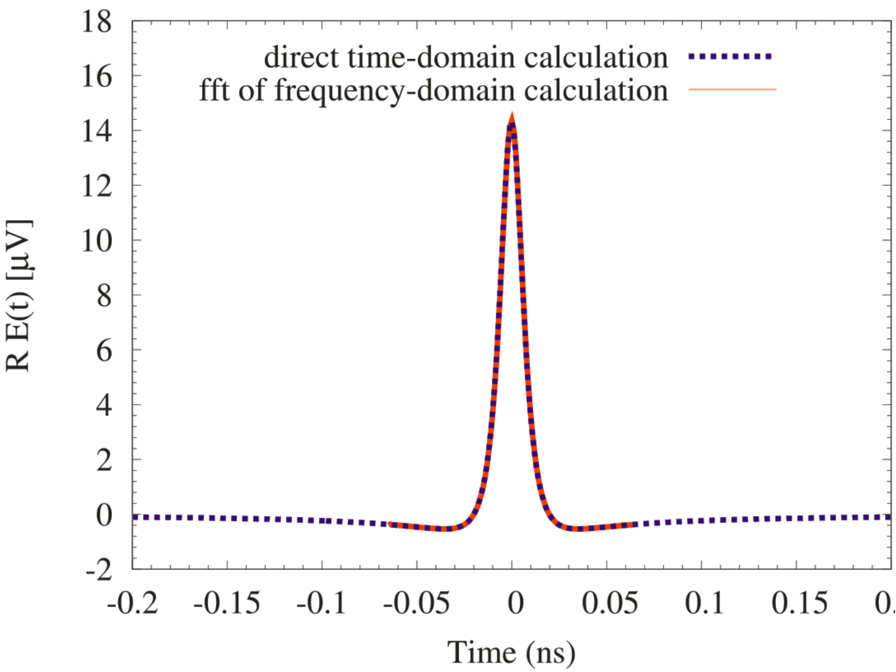
Reproducing Synchrotron Radiation

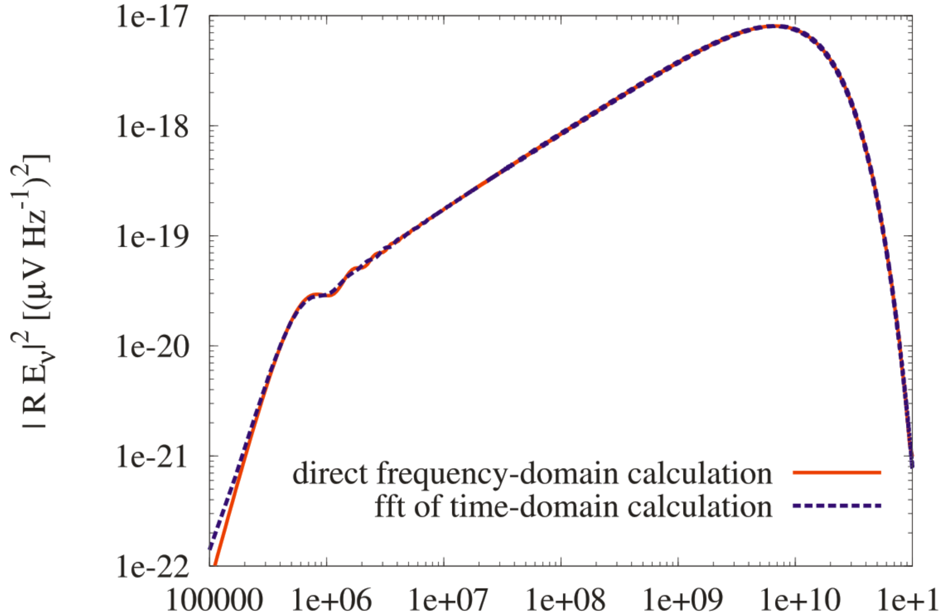
- discretize circular motion
  - fineness dictated by Δt, ν_{max}
- pairs of stopping and starting points





Reproducing Synchrotron Radiation

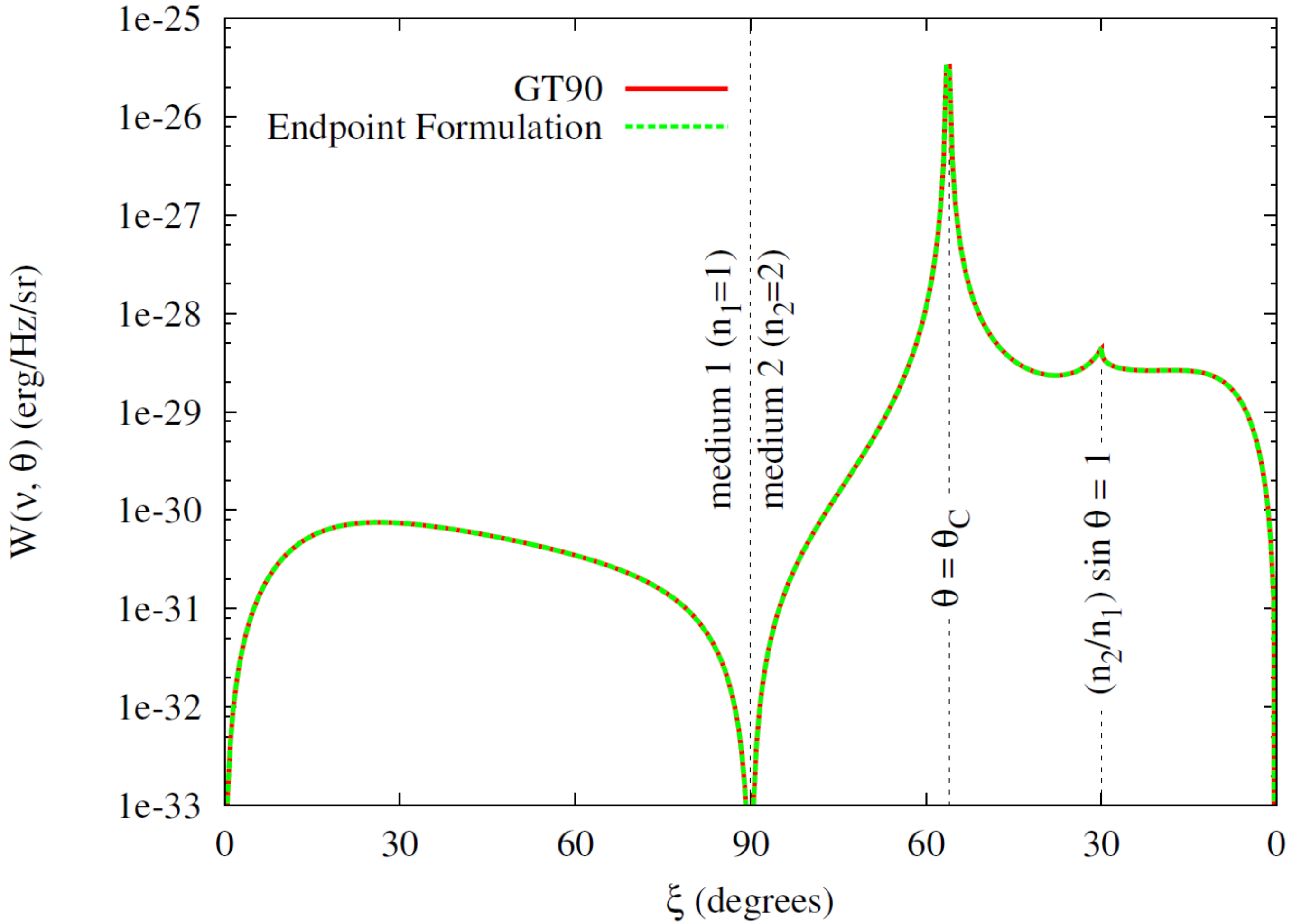




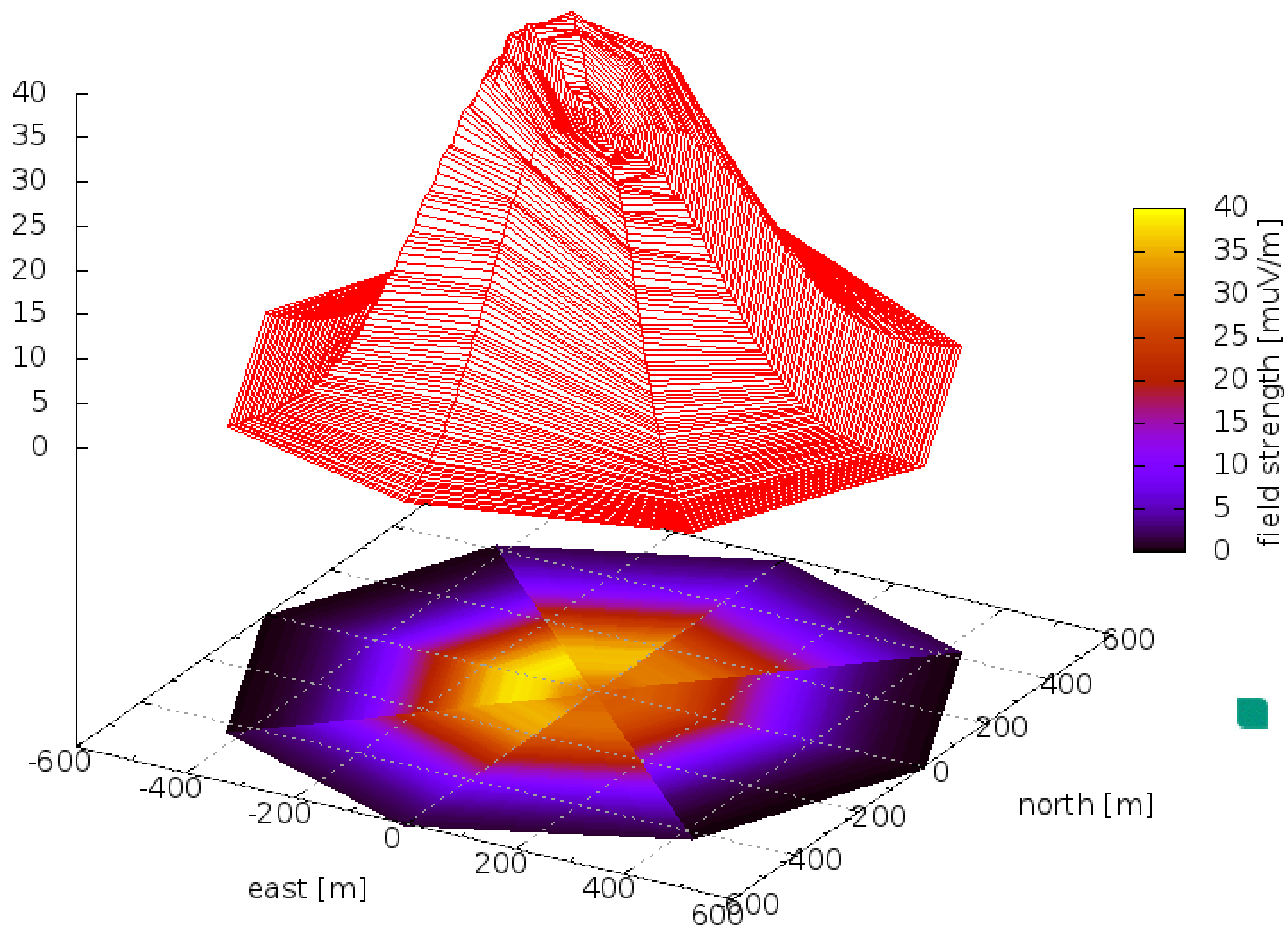
- direct calculations in time-domain and frequency-domain
- agreement with FFT of the other domain
- localized signal: time-domain is better for this problem

Reproducing Transition Radiation

- beautifully reproduced, for details please see arXiv:1007.4146

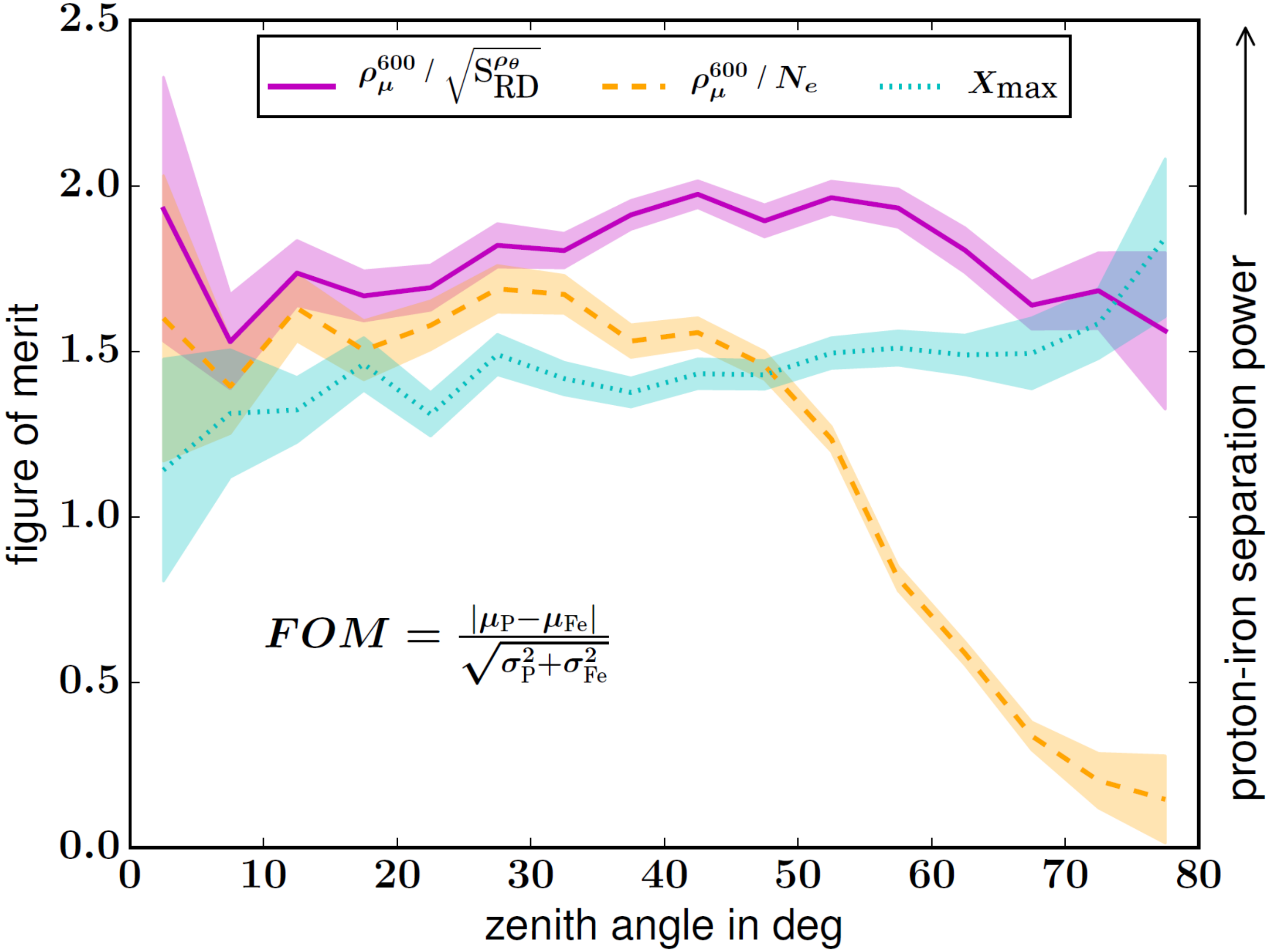


45 degree proton shower at LOPES



- 960 antenna locations,
  Δr = 5 m,
  Δφ = 45°

Composition sensitivity with radio



Tim Huege <tim.huege@kit.edu>