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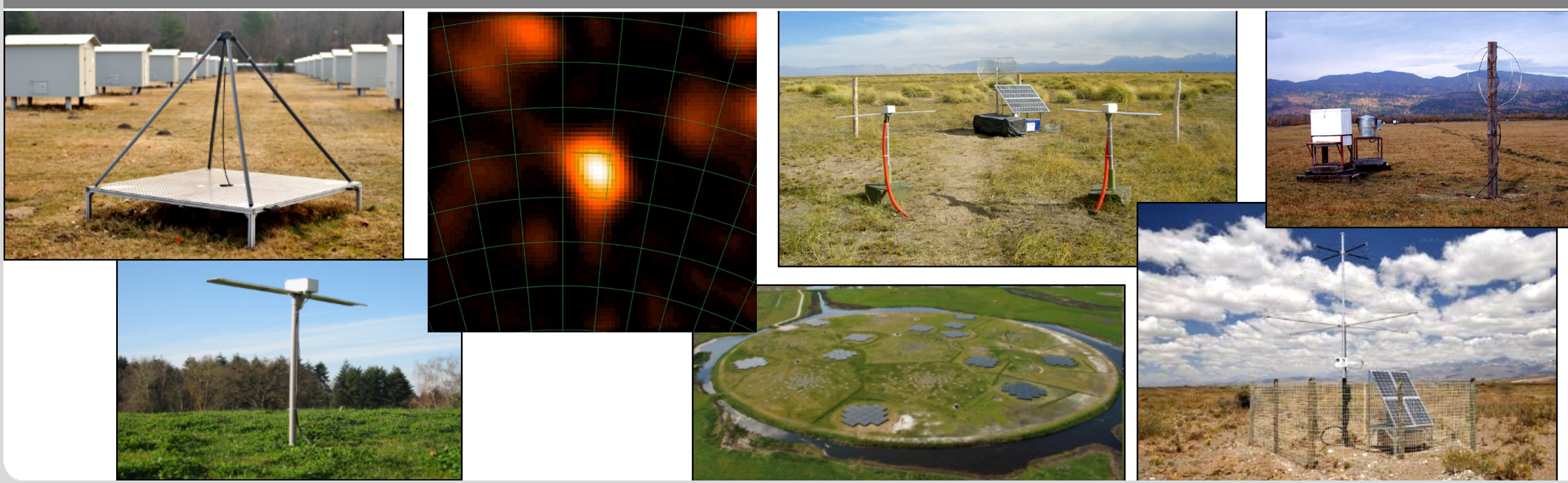
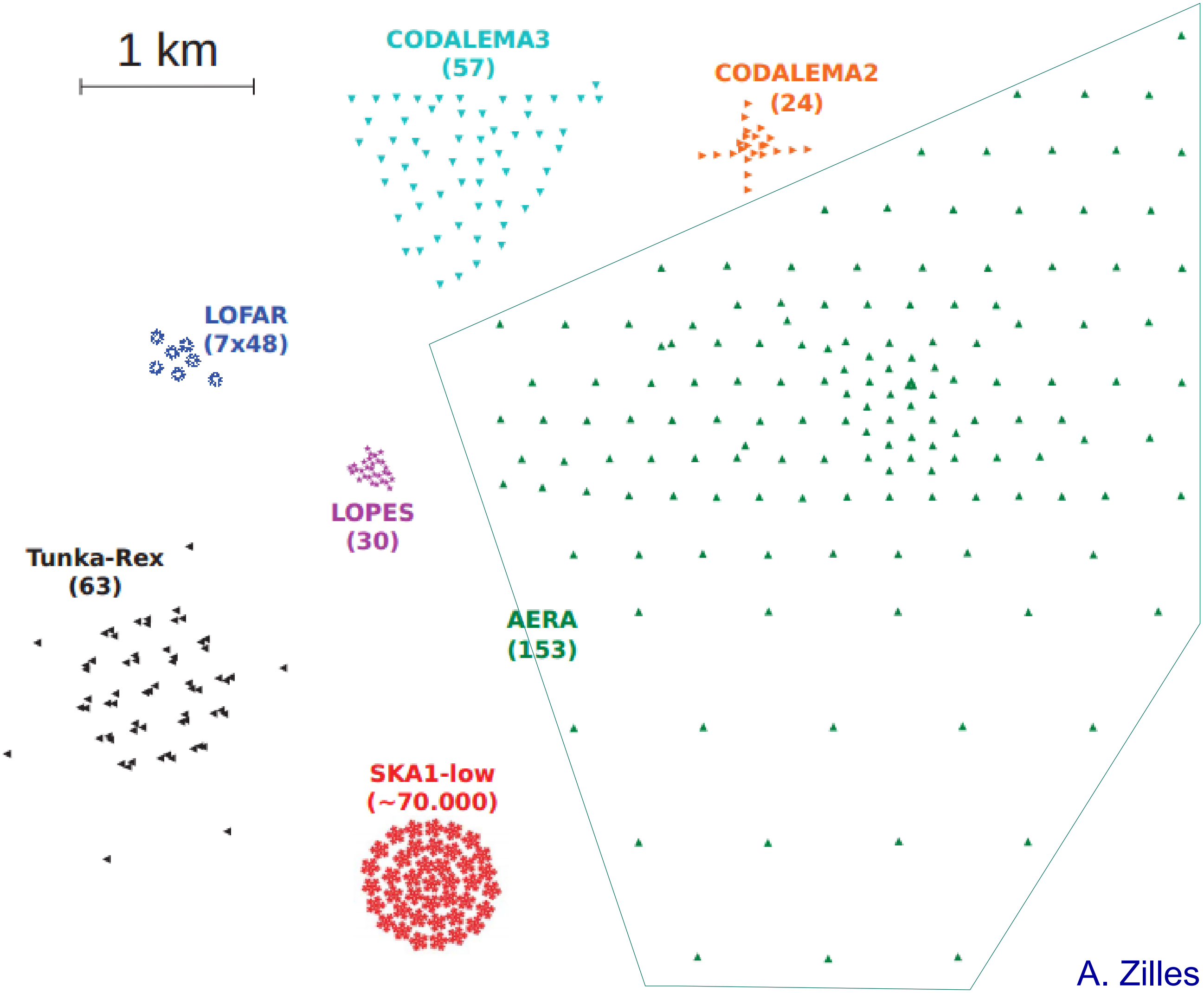
see also T. Huege,
Physics Reports 620 (2016) 1,
doi:10.1016/j.physrep.2016.02.001,
arXiv:1601.07426

Radio detection of extensive air showers

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



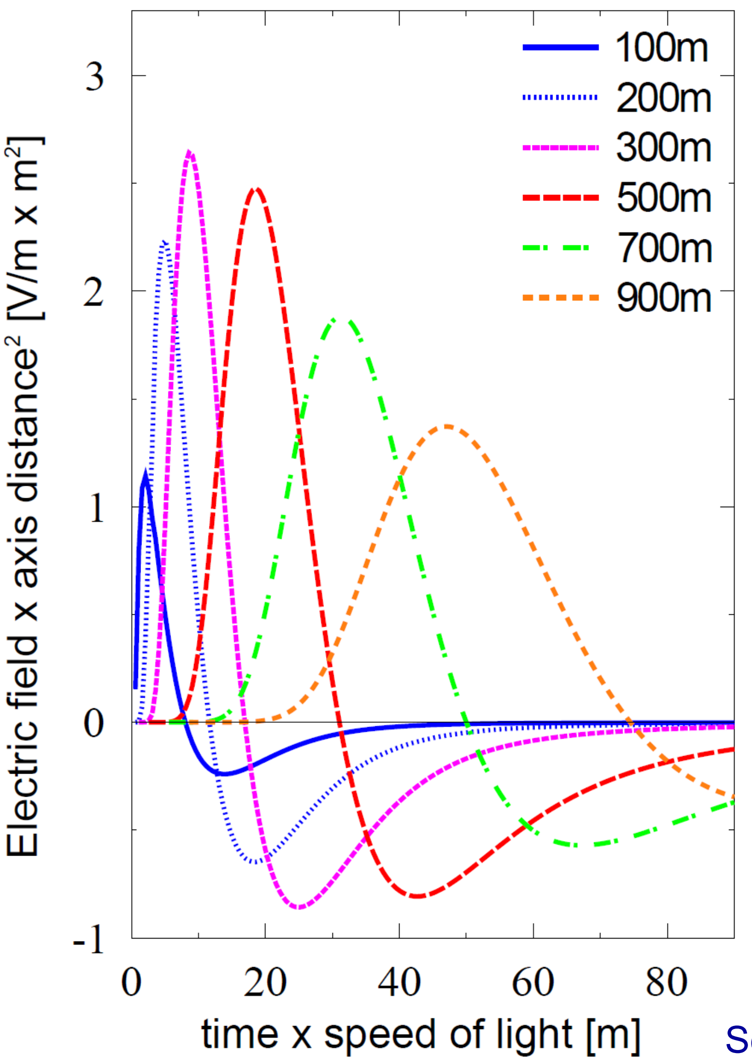
Comparison of ground experiments to scale

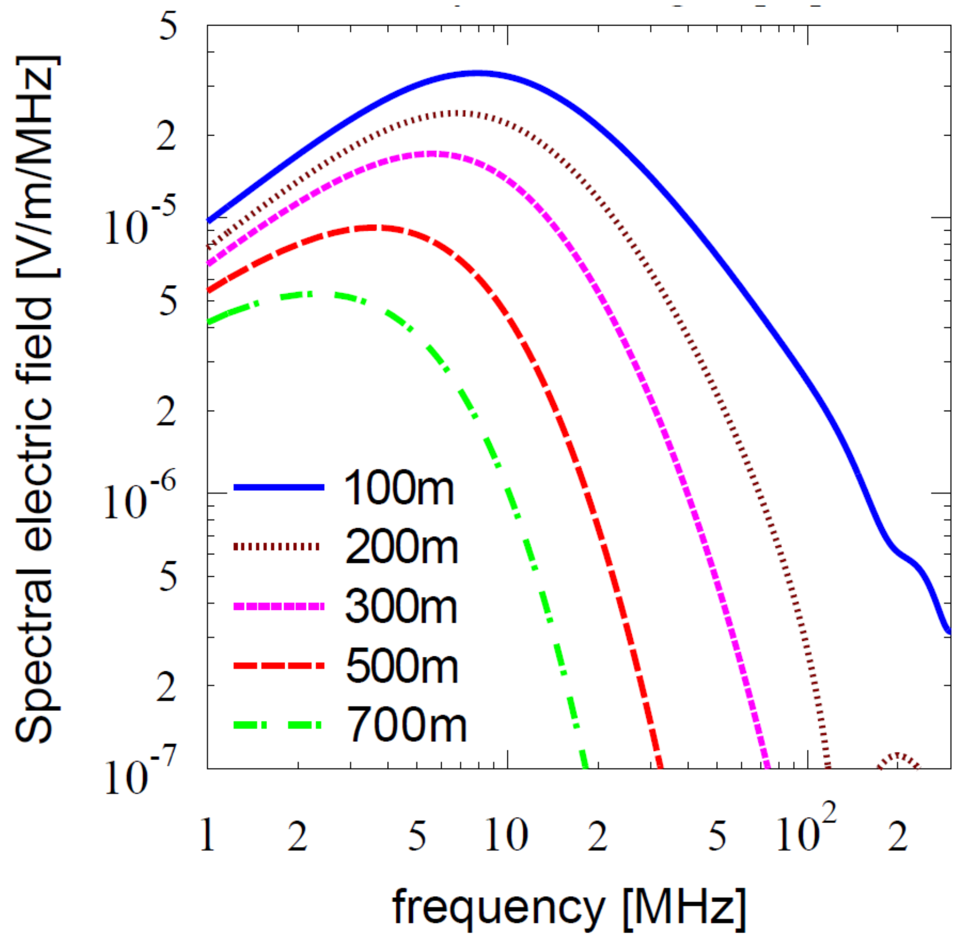


- from prototypes to large-scale experiments
- typical range 30-80 MHz, future higher
- sparse vs. dense arrays
- more to come: Auger Radio Upgrade, GRAND, IceTop Radio, …

The radio signal

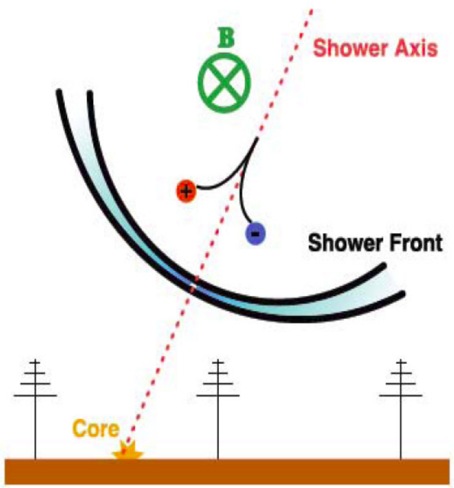
Broad-band pulses – mostly in MHz regime





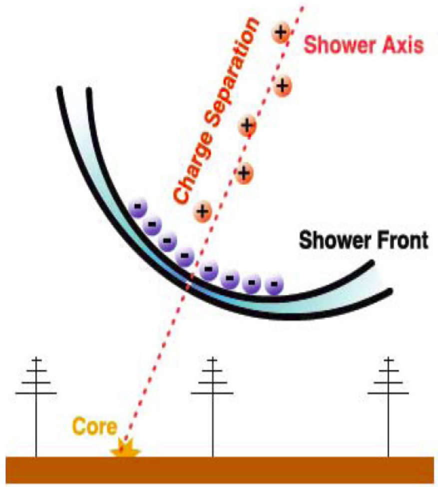
Scholten, Werner, Rusydi, Astropart. Phys. 29 (2008) 94–103.

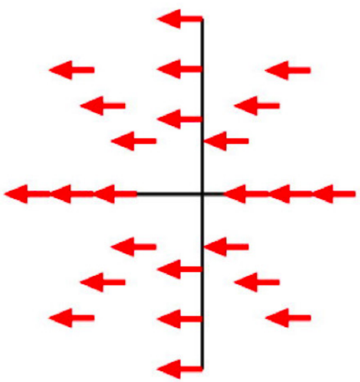
Macroscopic interpretation of radio emission



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

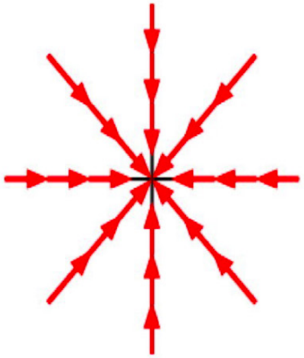
Kahn & Lerche (1967)





Askaryan (1962,1965)

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



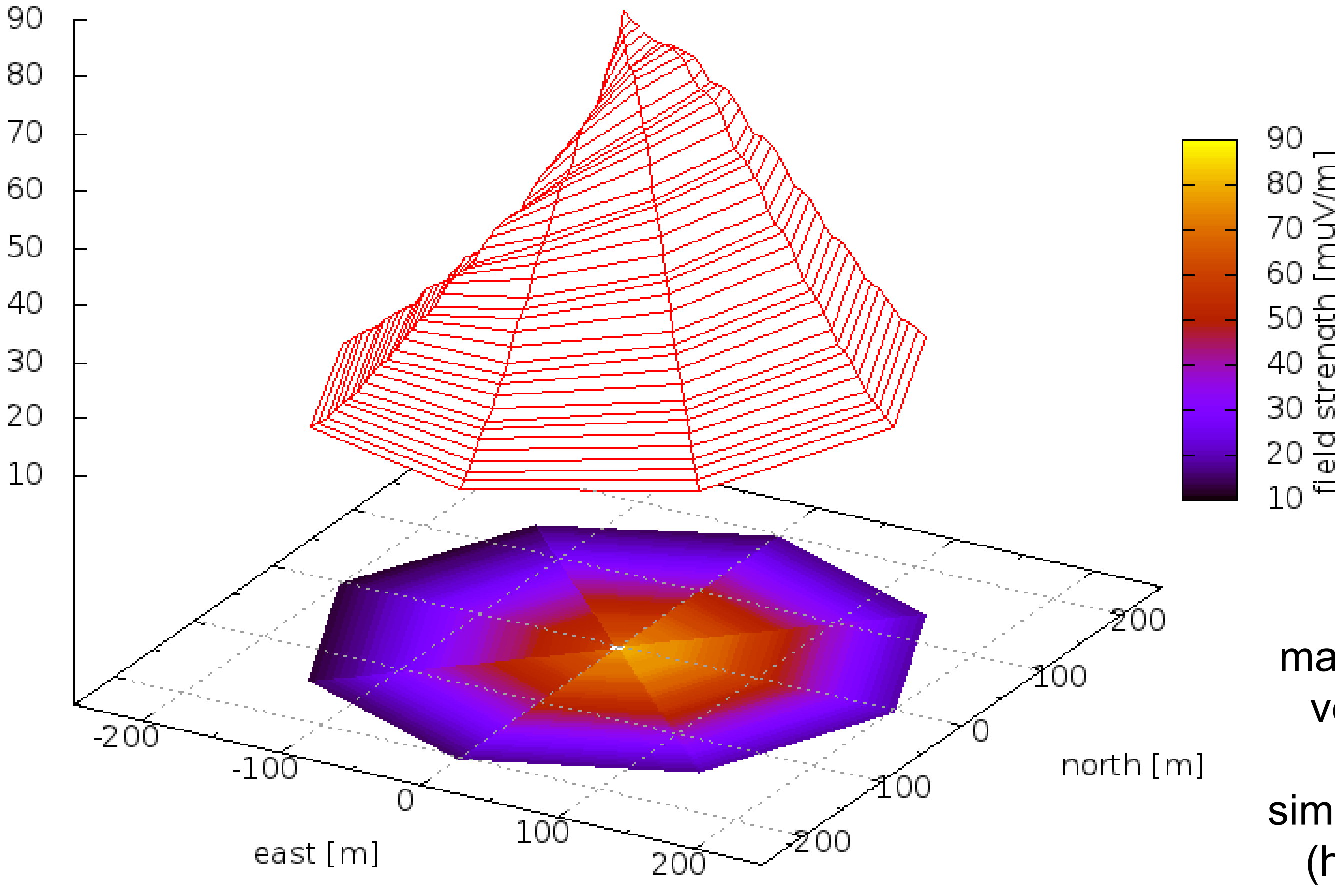
Pierre Auger Coll., Phys. Rev. D 89 (2014) 052002.

„***v*** x ***B***“

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

„***radial***“

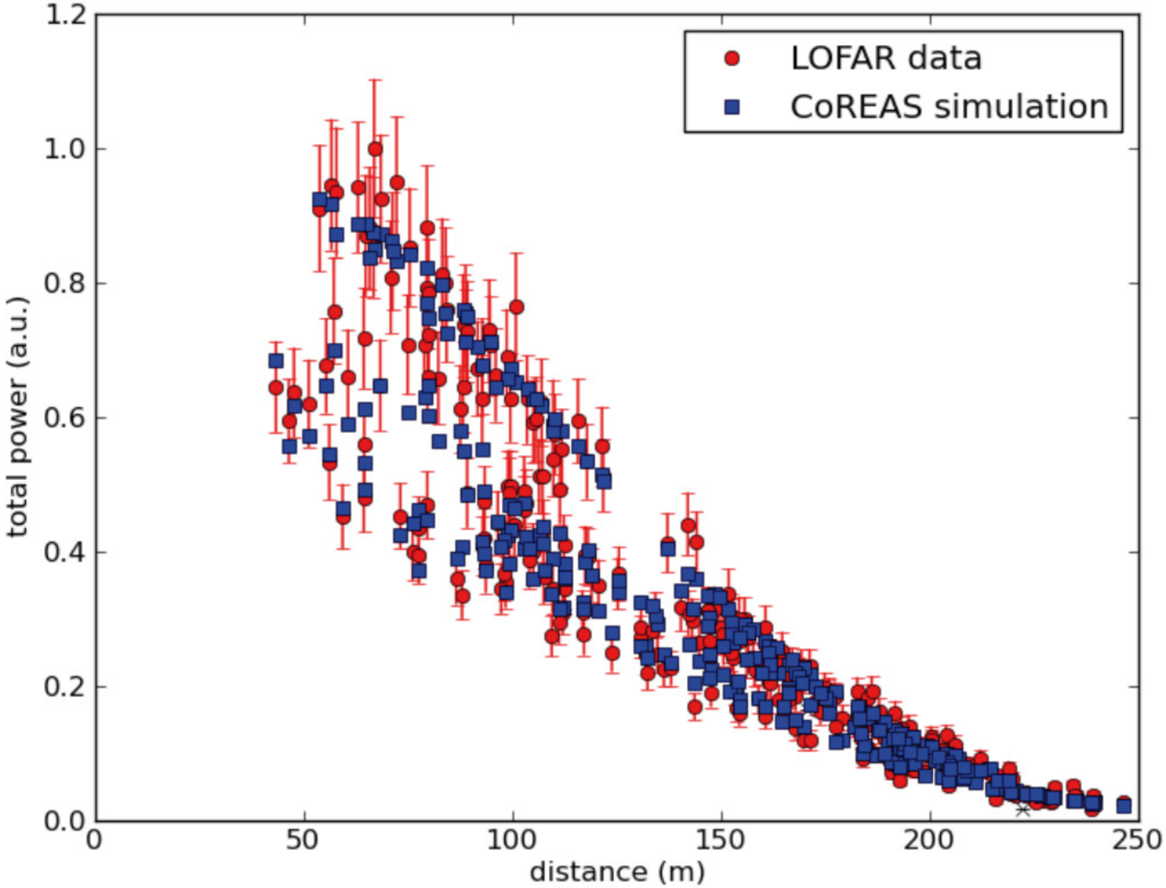
Complexity of radio-emission footprint



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

TH et al., ARENA2012

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.

Comparison of simulations with LOFAR data

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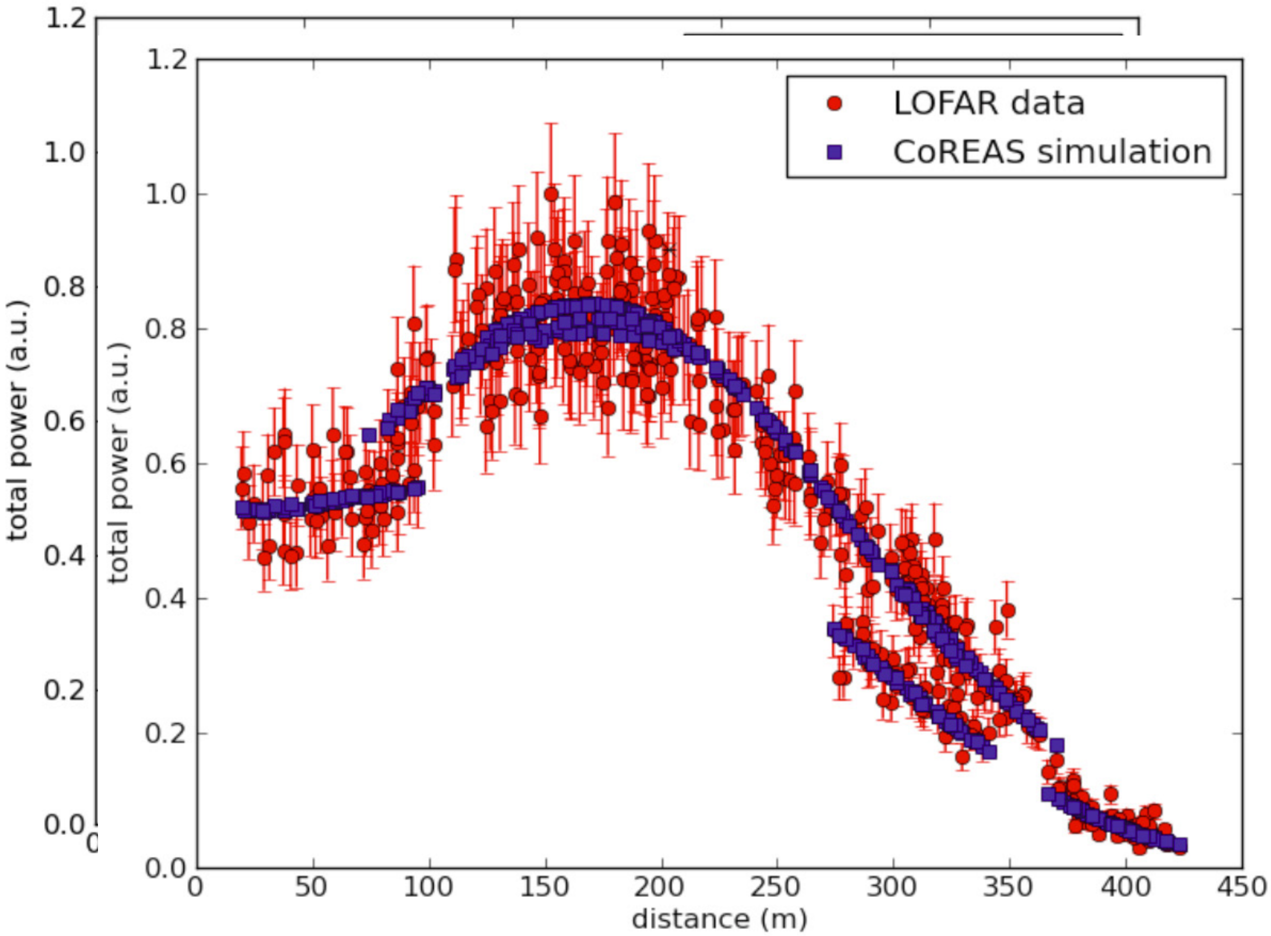

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- data can be reproduced by simulations
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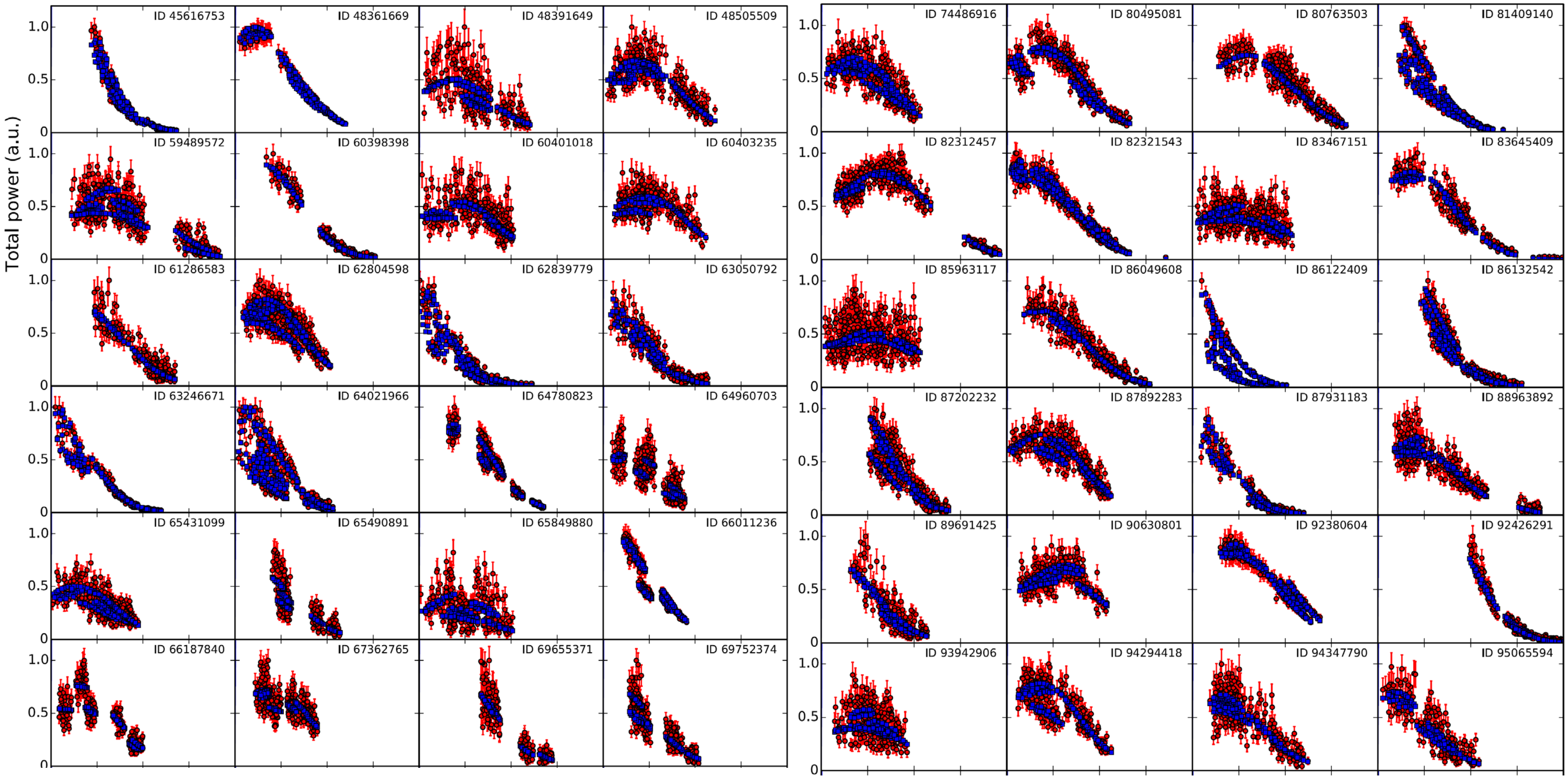
S. Buitink, A. Corstanje, J. E. Enriquez, et al., Phys. Rev. D 90 (2014) 082003.

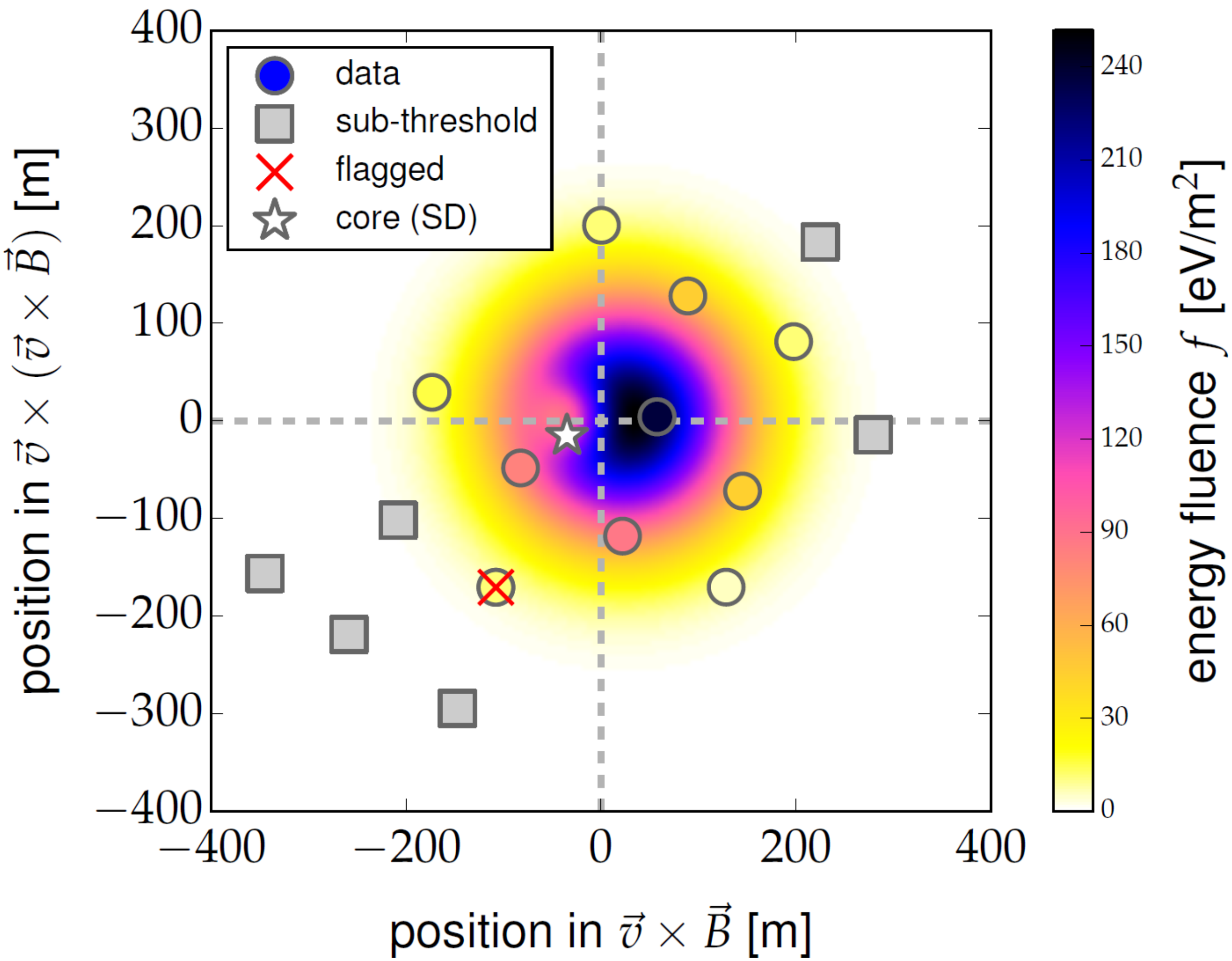
Many LOFAR events



- all LOFAR events are described very well

Energy reconstruction

AERA energy reconstruction – radiation energy

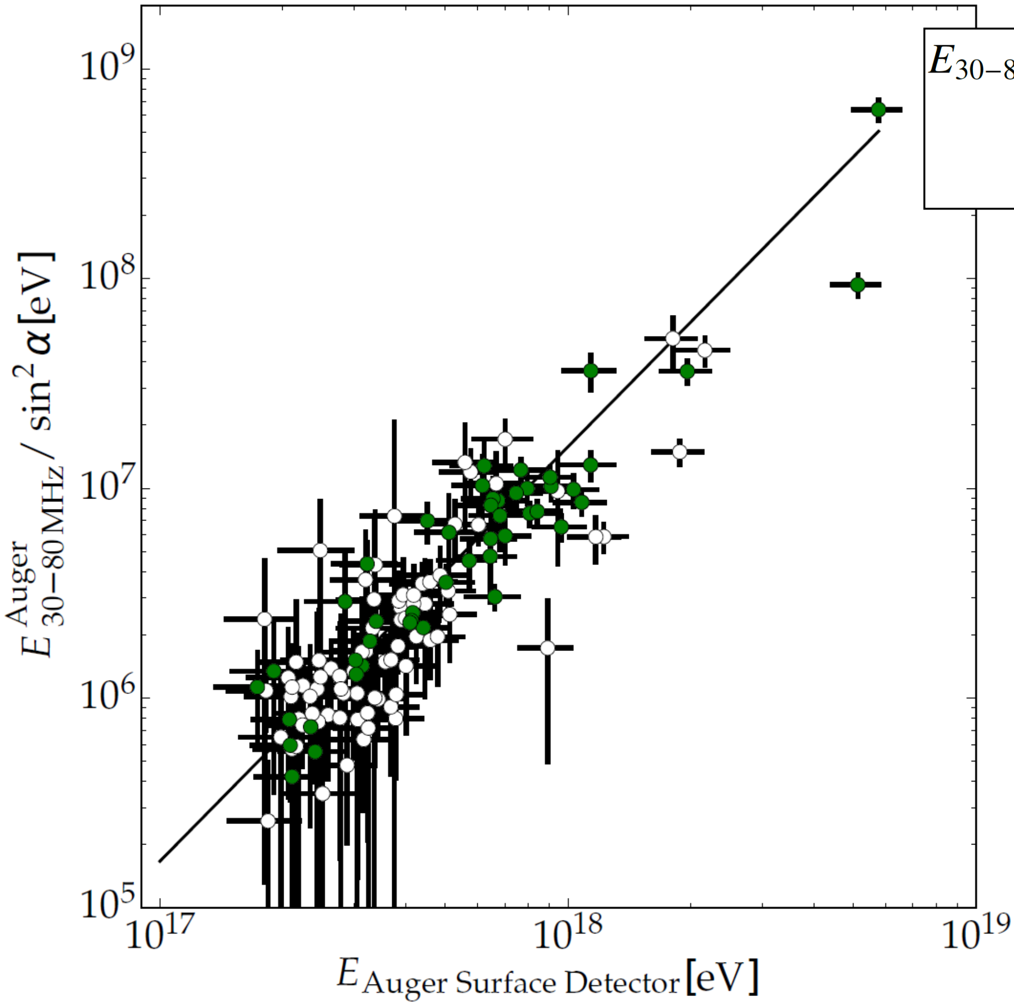


Piere Auger Coll., Phys Rev. D (2016), arXiv:1508.04267.

- 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

Karlsruhe Institute of Technology

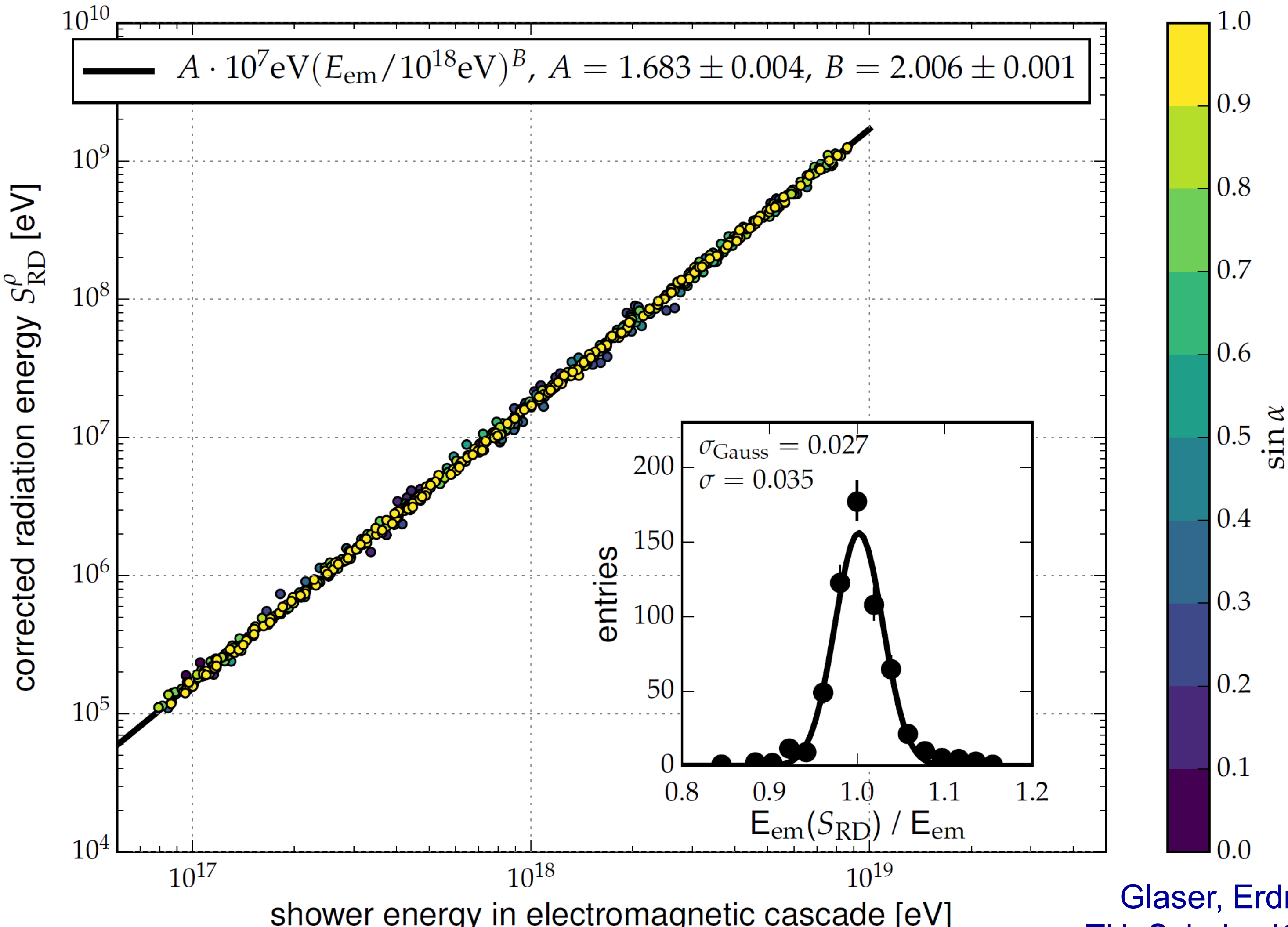


Piere Auger Coll., Phys Rev. Lett. (2016), arXiv:1605.02564.

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

- 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 electromagnetic energy



- very good correlation with electromagnetic energy, less than 5% intrinsic scatter
- can be predicted from first principles: absolute energy scale

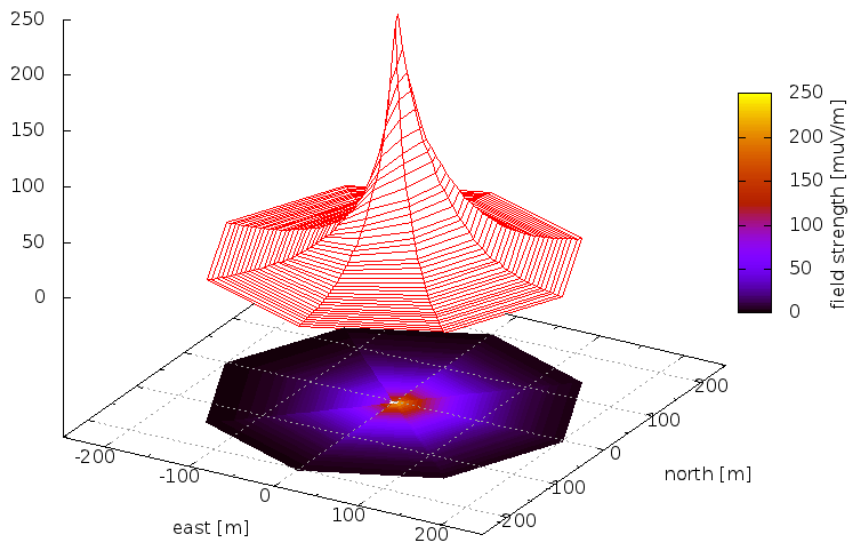
Glaser, Erdmann, Hörandel, TH, Schulz, JCAP 09 (2016) 024

Xmax reconstruction

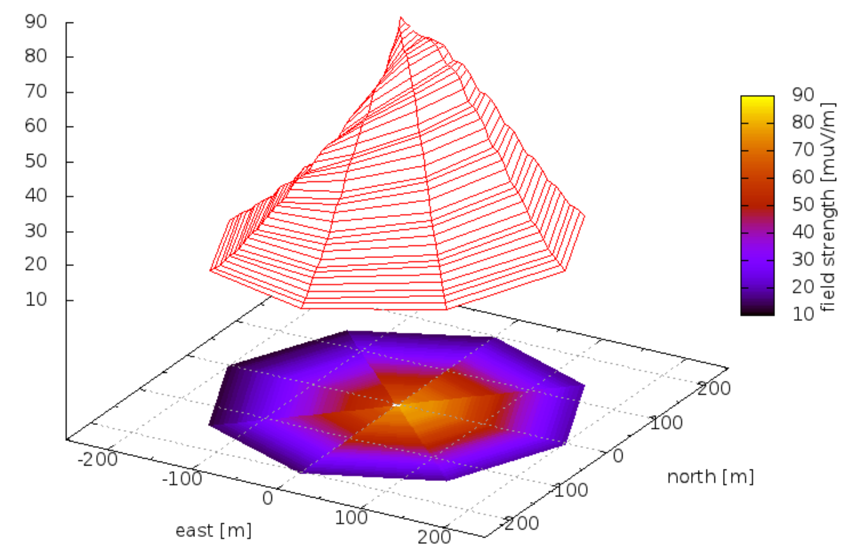
Lateral distribution as probe for composition

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

TH et al., ARENA2012

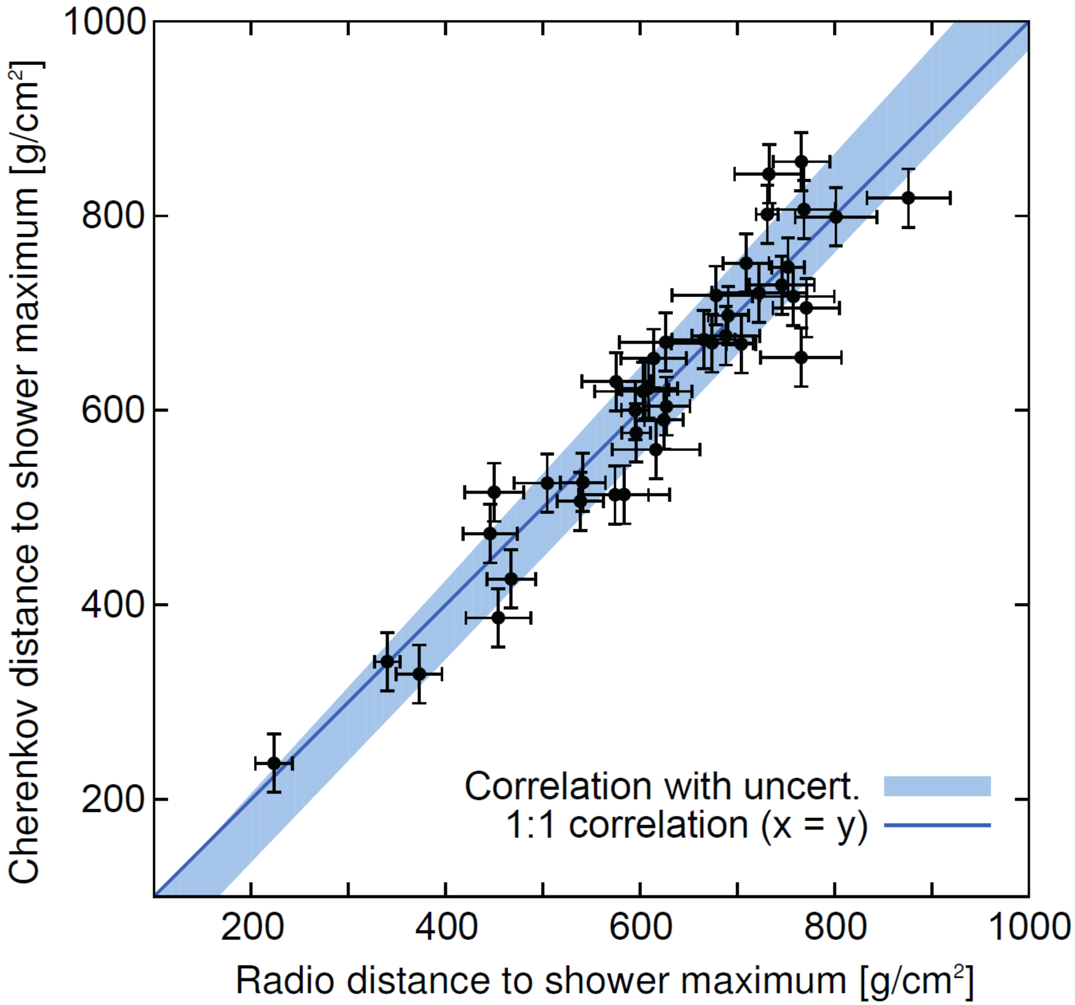


vertical proton shower
at 40-80 MHz
simulated with CoREAS



vertical iron shower
at 40-80 MHz
simulated with CoREAS

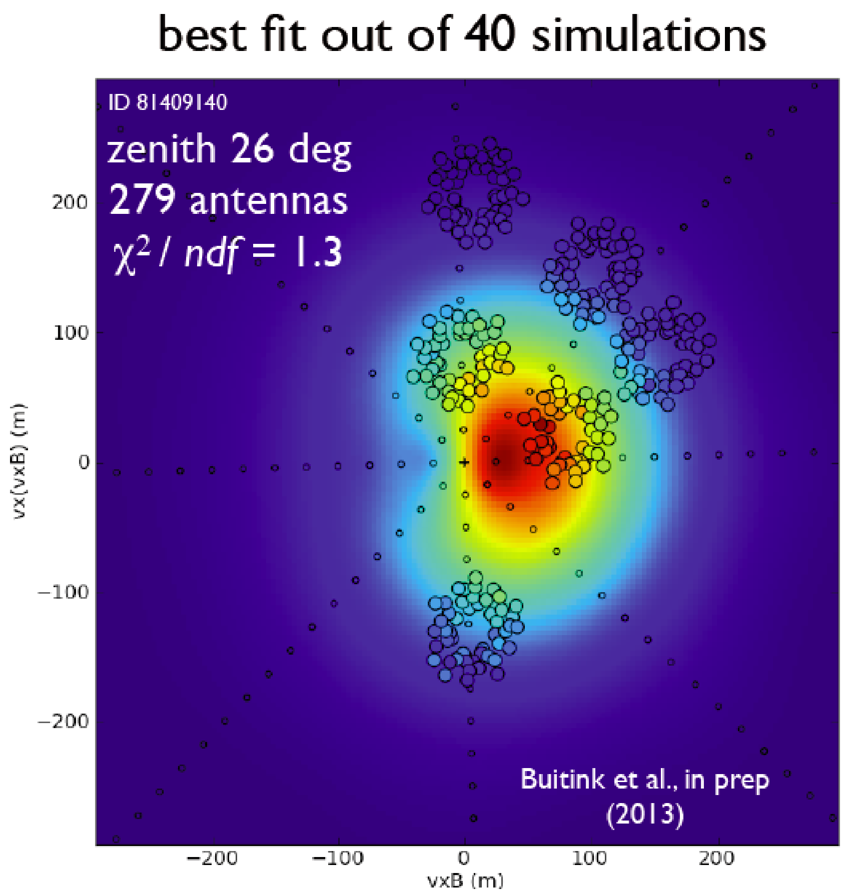
Experimental Xmax validation by Tunka-Rex

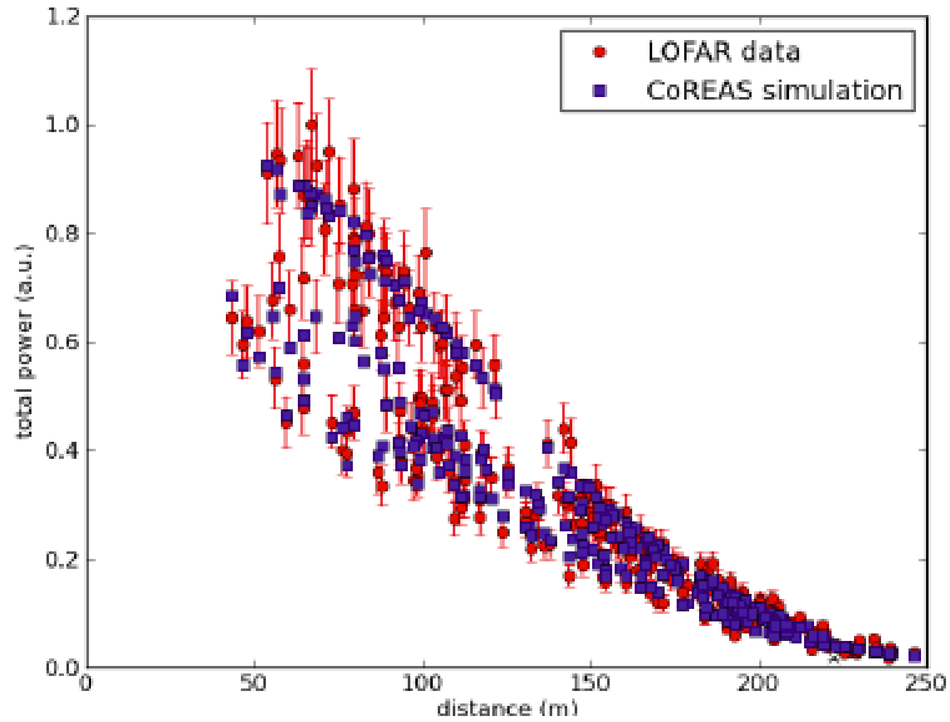


- slope of radio-LDF as Xmax estimator
- Xmax from optical Cherenkov detectors and radio antennas agrees very well
- combined Xmax resolution ~50 g/cm^2, Tunka alone ~28 g/cm^2

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

Fit of LOFAR particle and radio data

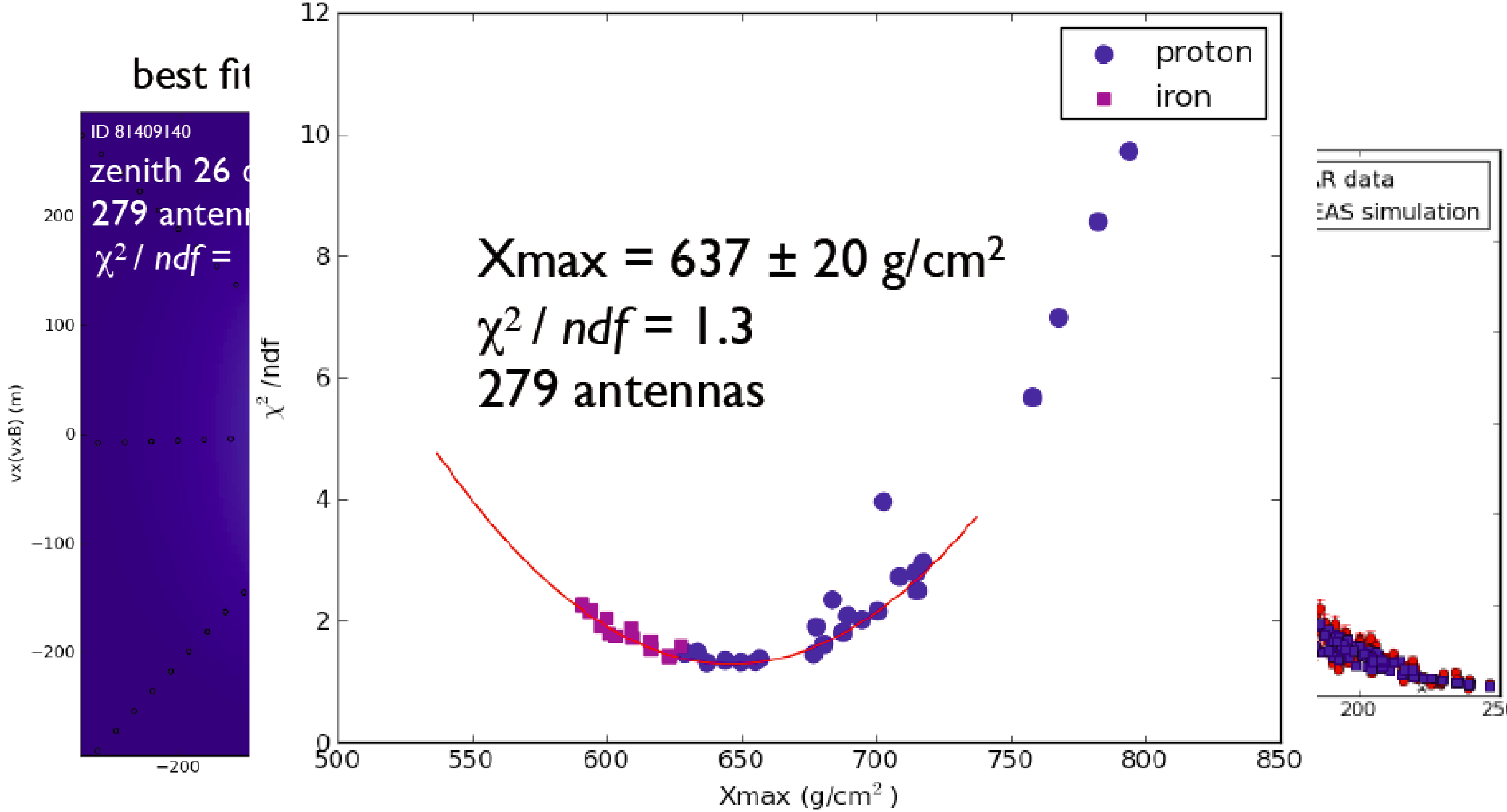




- data fit to CoREAS simulations gives Xmax to ~17 g/cm^2

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

Fit of LOFAR particle and radio data

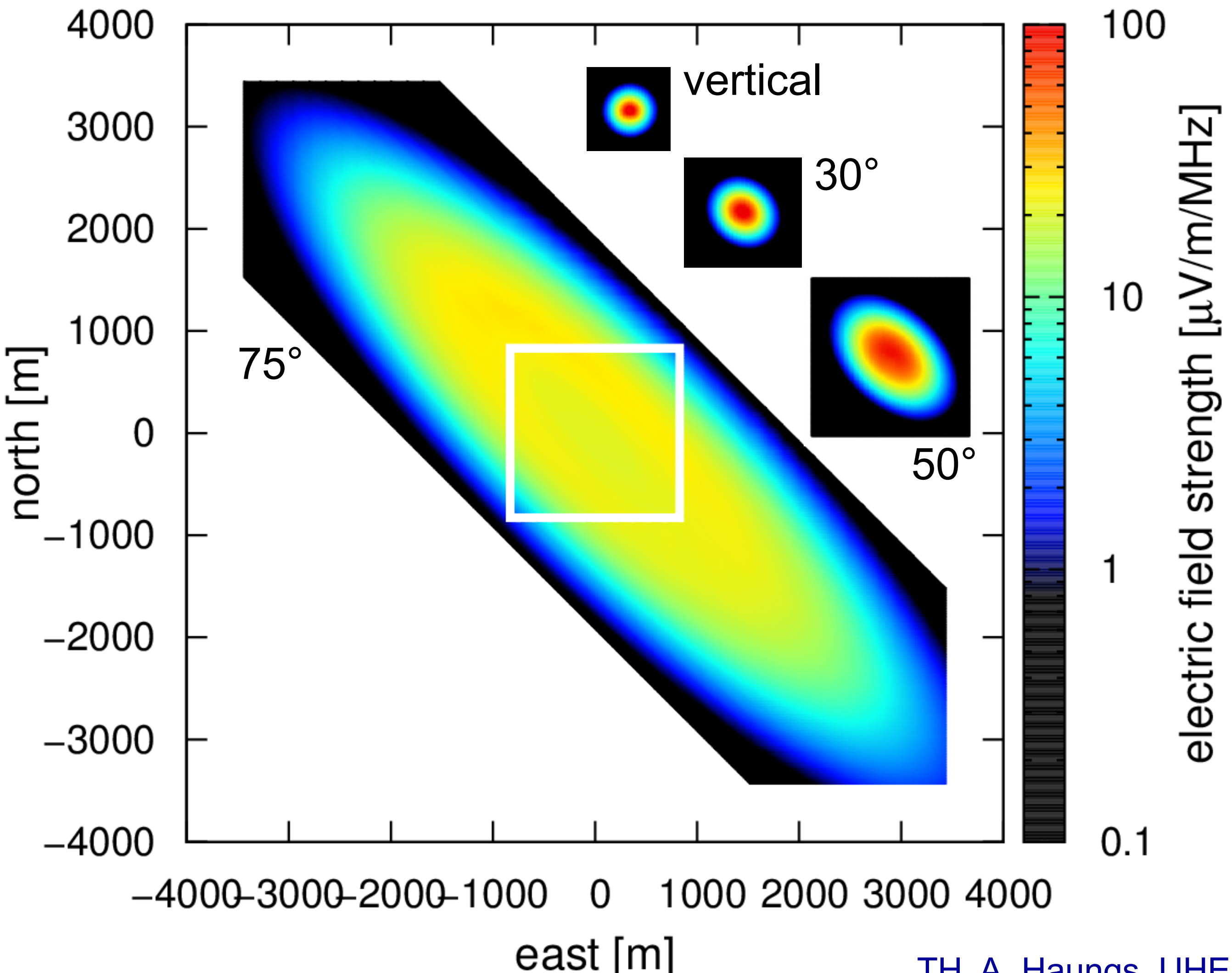


- data fit to CoREAS simulations gives Xmax to ~17 g/cm^2

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

Horizontal air showers

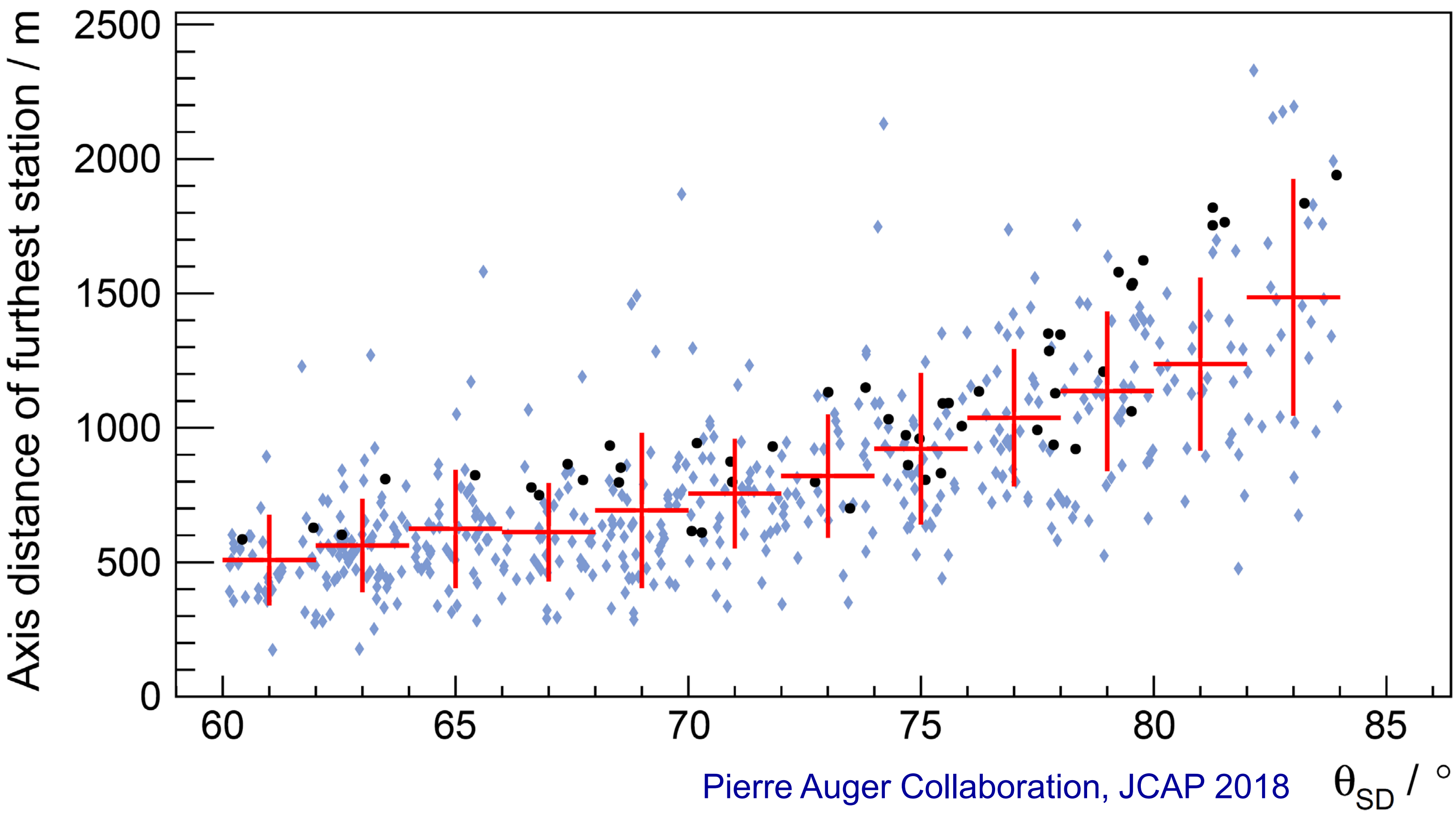
Required detector spacing – inclined showers



- 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



- hundreds of inclined air showers measured by AERA
- size of footprint grows with zenith angle, up to 2 km in shower plane

Summary and conclusions

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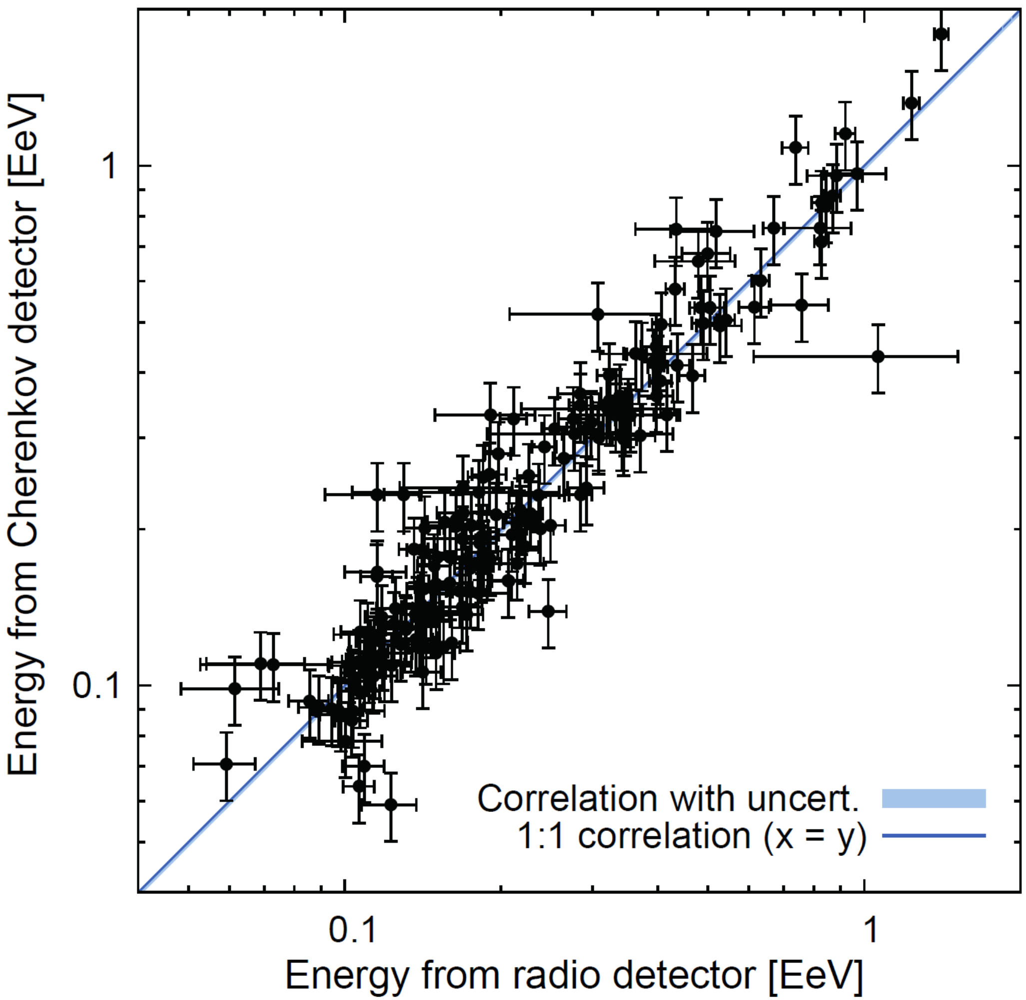
- radio detection of CRs has boomed and matured in the last decade
- we have clearly established
  - detailed understanding of radio emission physics (within 10%)
  - determination of arrival direction (well below 0.5°)
  - determination of air shower energy (~10%)
  - radio signal sensitivity to Xmax (<20 g/cm^2 for dense arrays)
- potential for application
  - independent calibration of energy scale from first principle calculations
  - air shower physics via measurement of purely electromagnetic cascade
  - mass sensitivity via Xmax or em/muon measurements

Backup

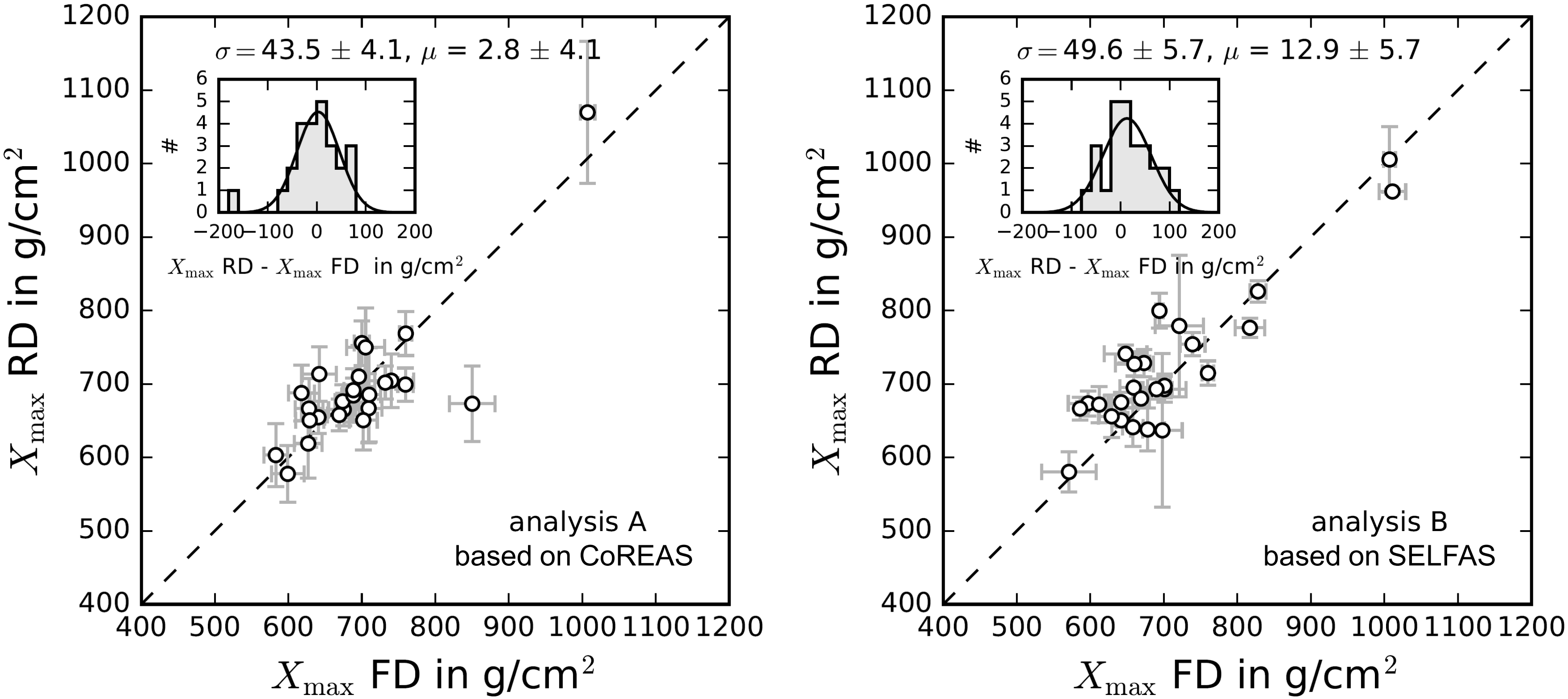
Tunka-Rex energy reconstruction



- 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.

Experimental Xmax validation by Auger

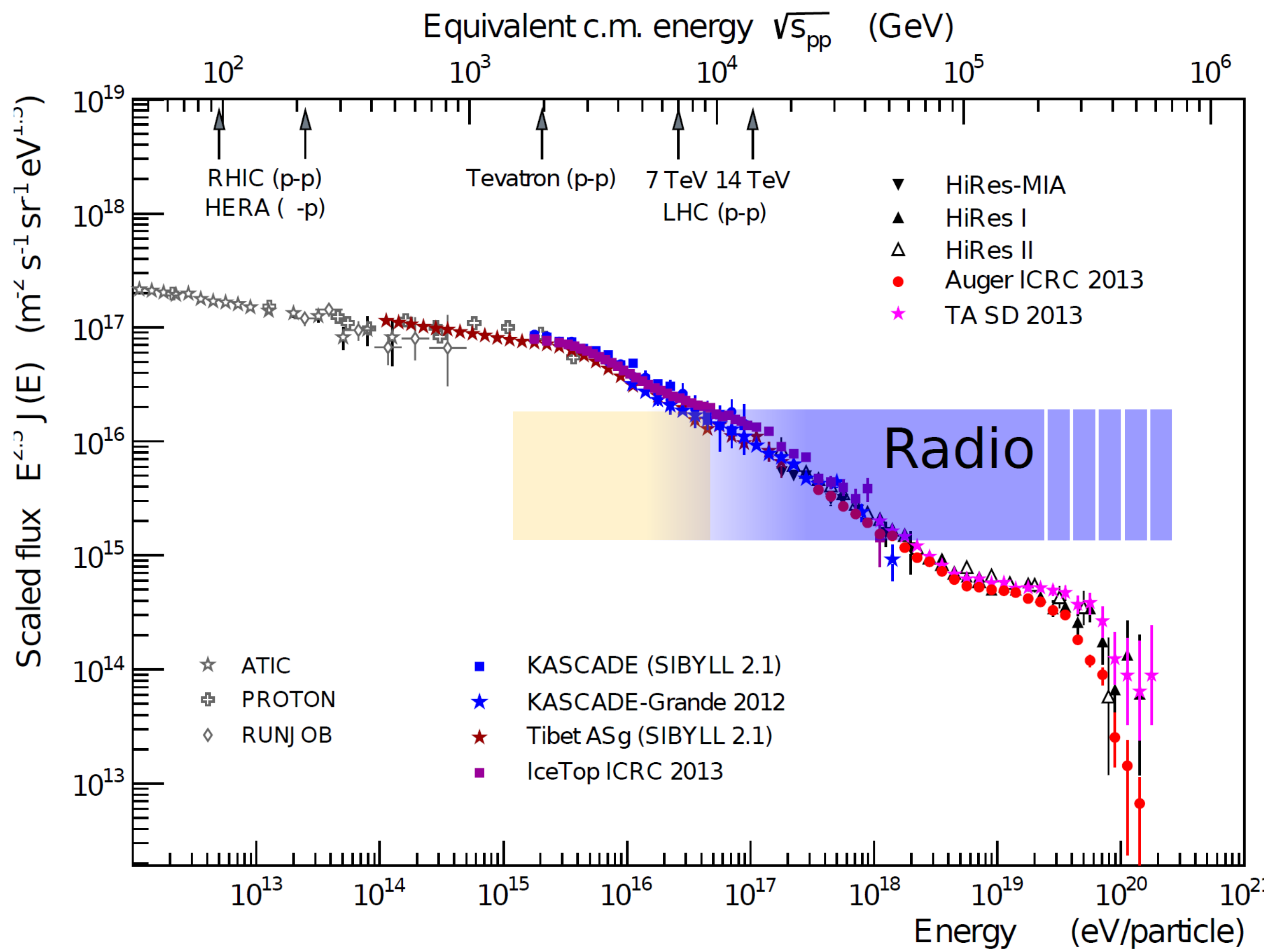


- various reconstruction approaches being tested in AERA
- current combined FD-RD resolution ~45 g/cm^2, so RD alone <~40 g/cm^2
- still room for improvement (only uses amplitude information)

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

To understand the sources of cosmic rays …

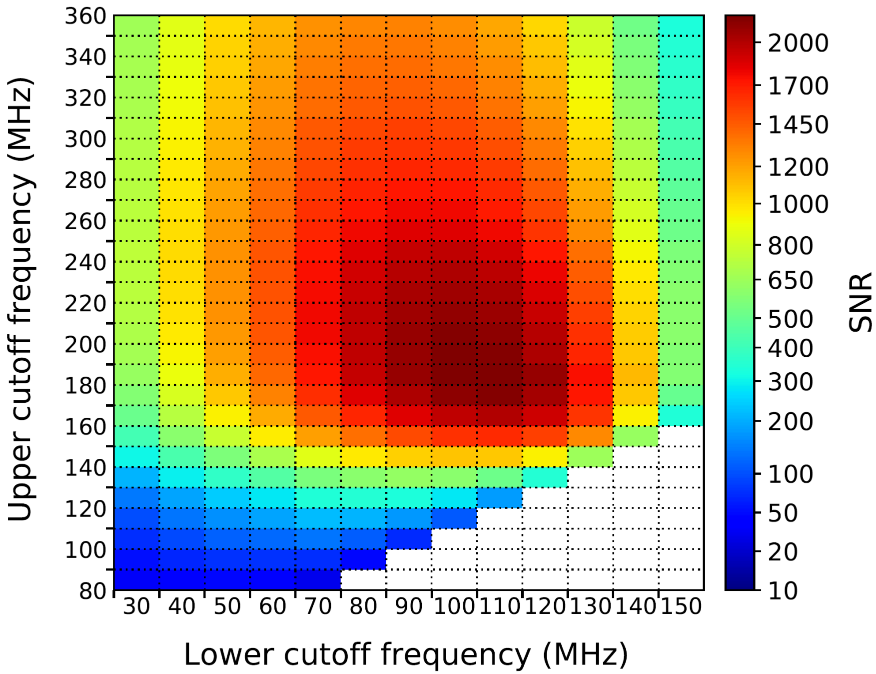
- we need to know their
  - arrival direction
  - energy
  - and mass
- we need large statistics
  - large effective areas and high duty cycles

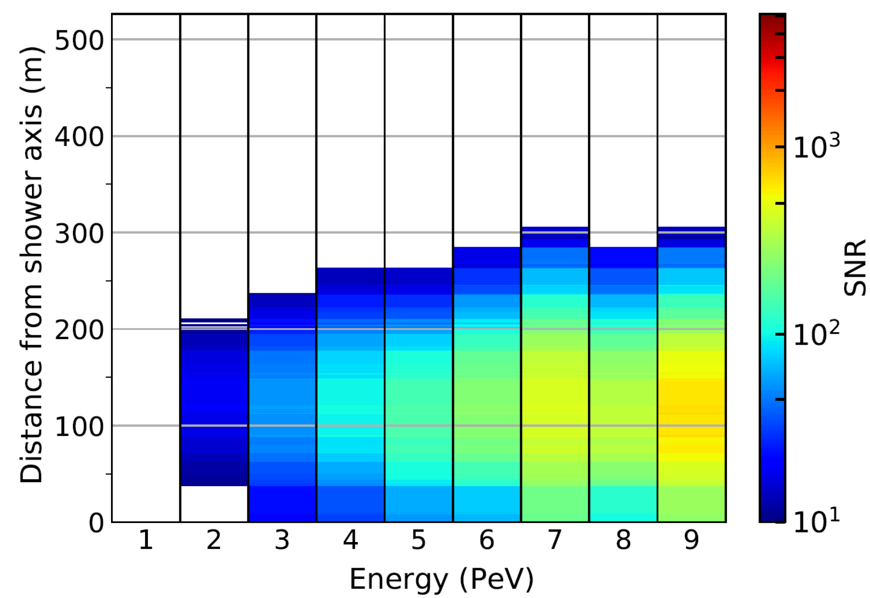


adapted from R. Engel

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)





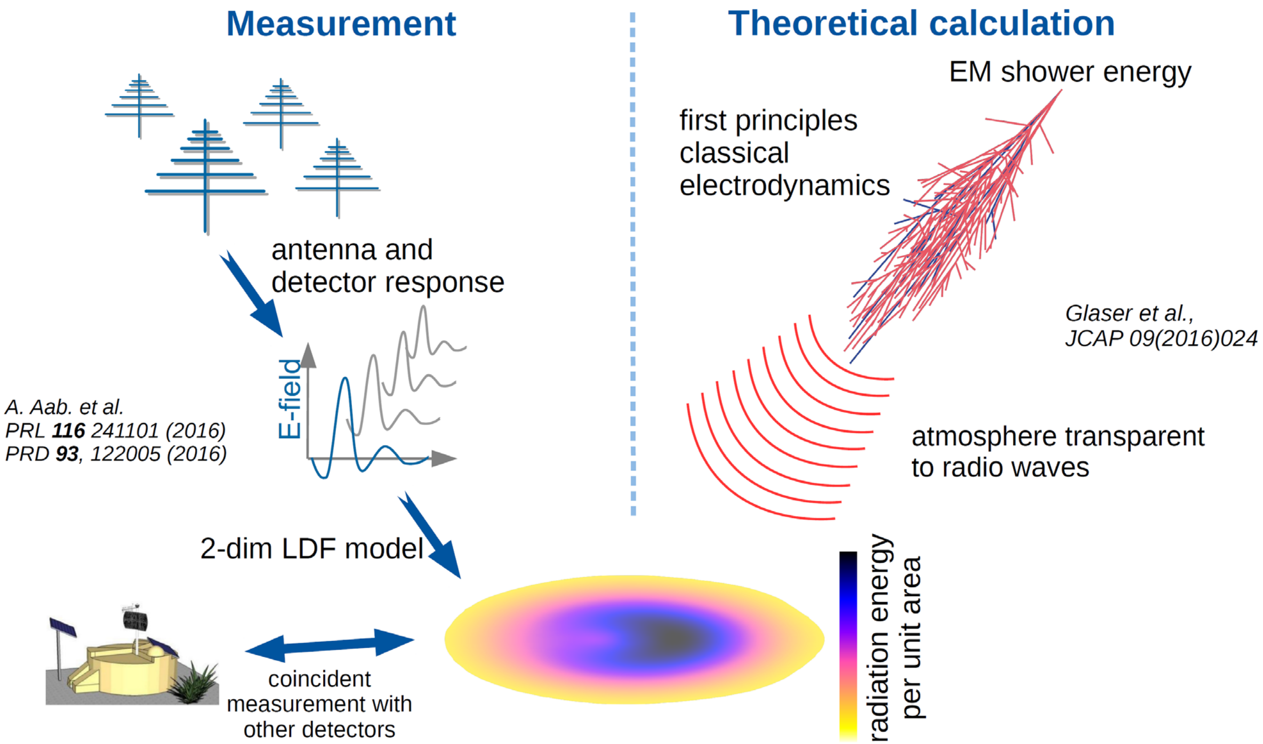
(d) proton, $\theta = 61°, \phi = 0° (\alpha = 79°)$

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

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!



Comparison of CoREAS and ZHAireS

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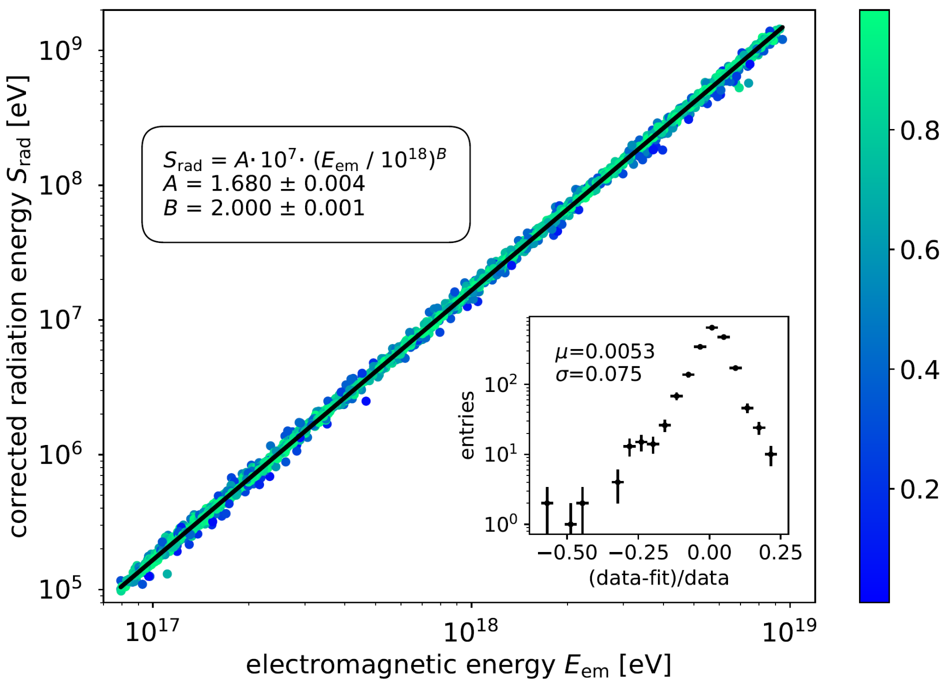
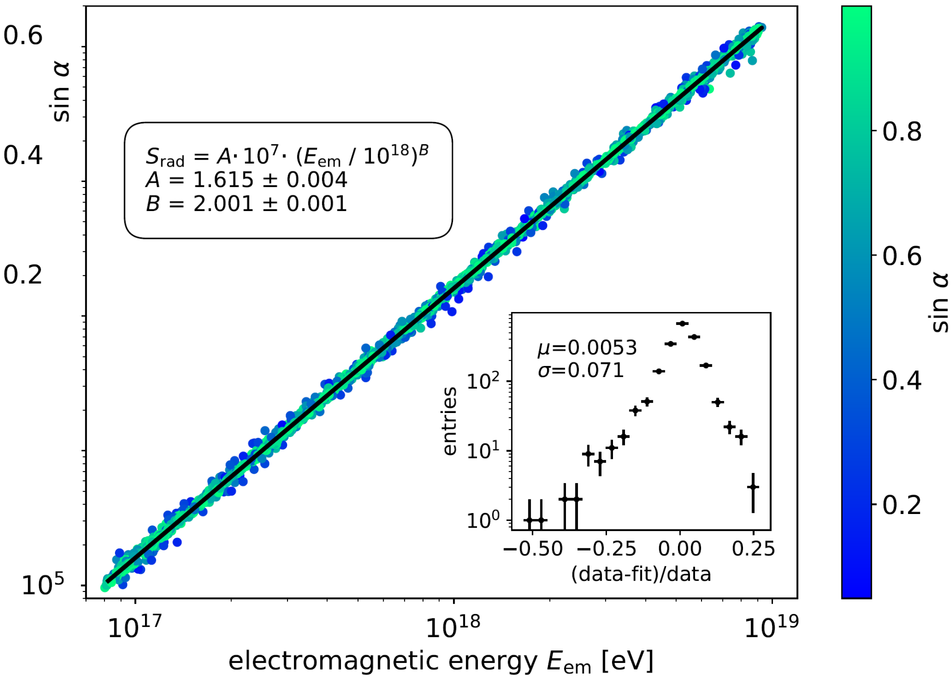
CoREAS, **16.8 MeV** radiation
@ 10^{18} eV electromagnetic energy



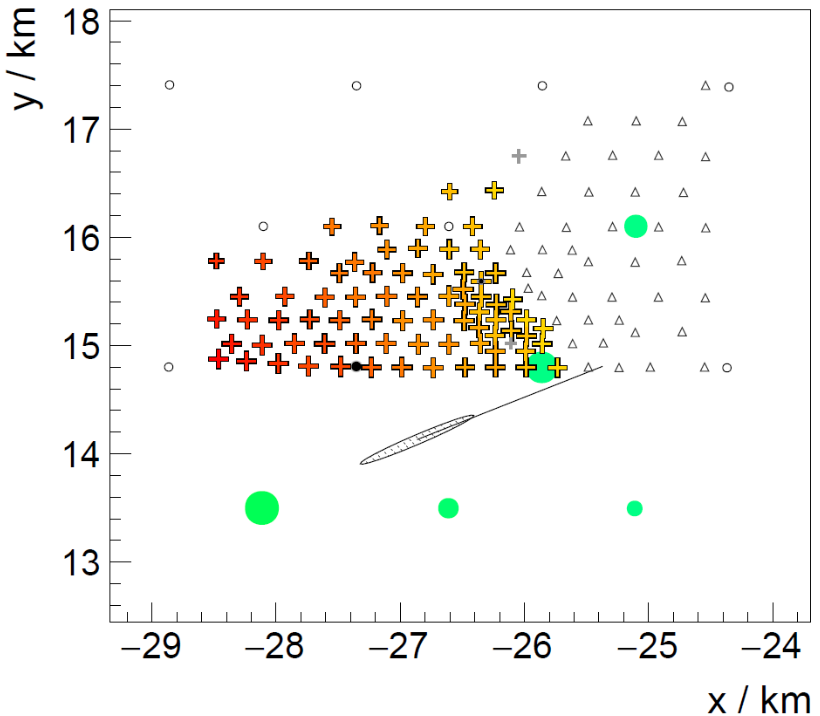


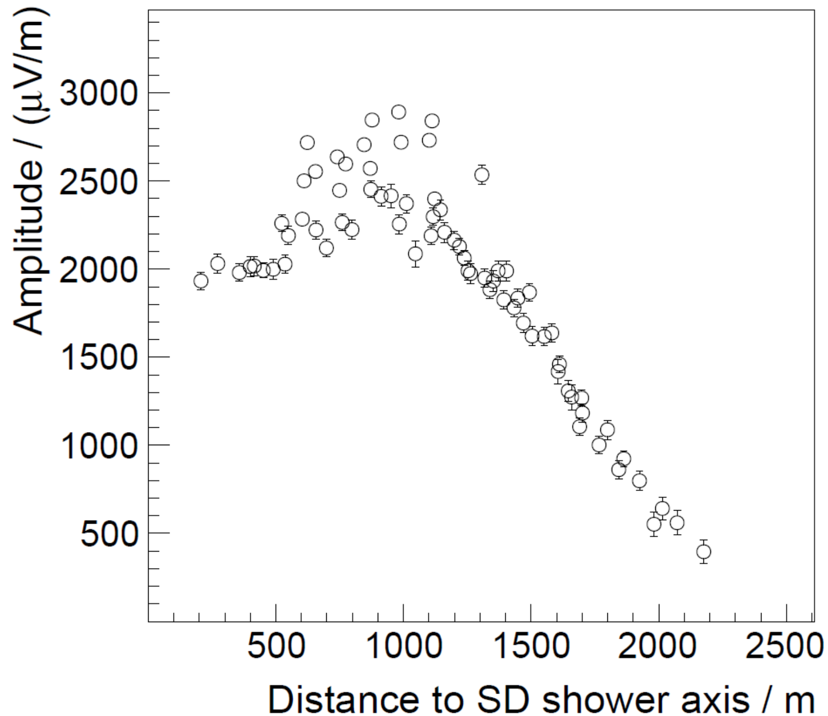
ZHAireS, **16.15 MeV** radiation
@ 10^{18} eV electromagnetic energy

- 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

AERA has measured >500 inclined showers

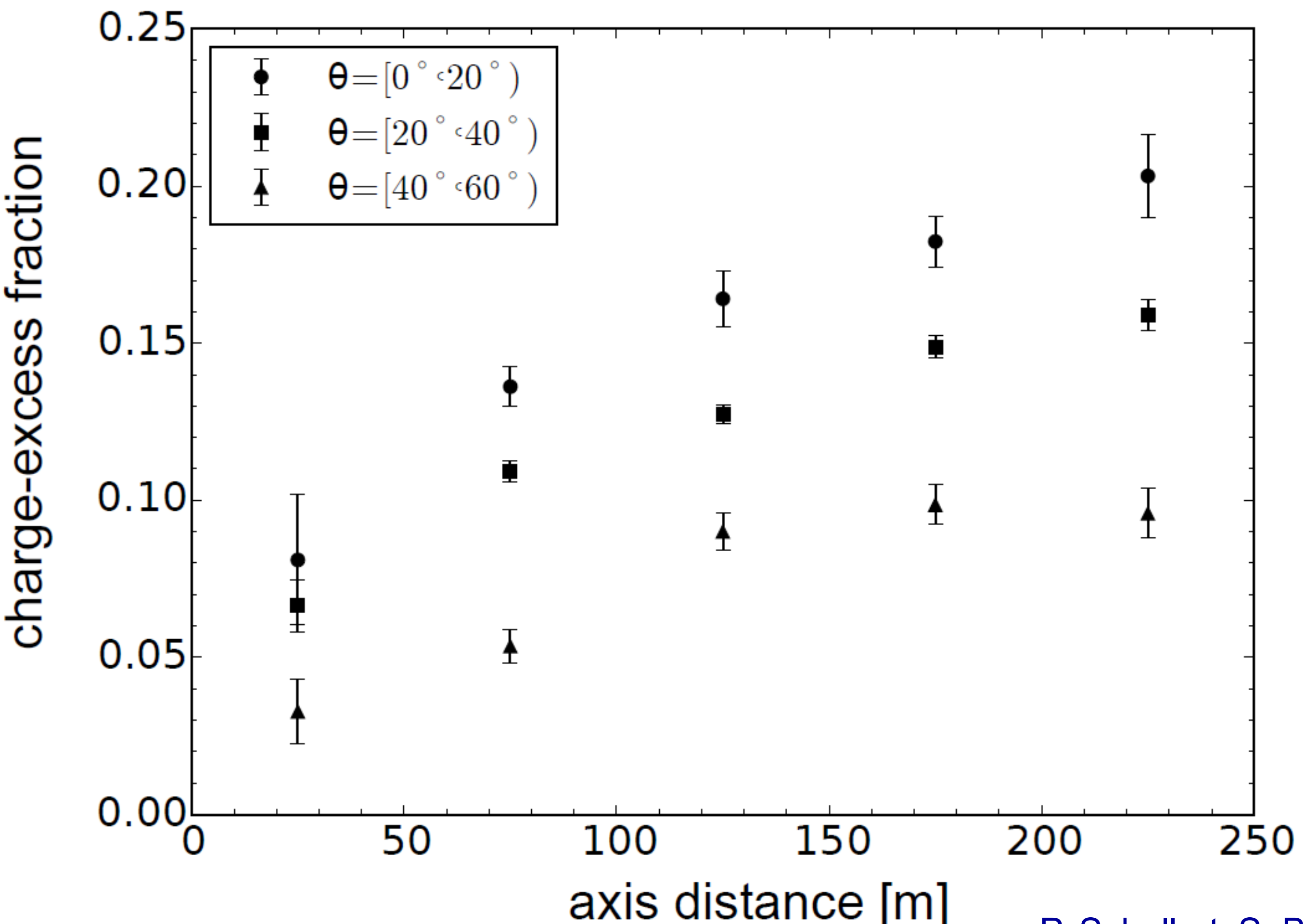




- air showers up to 88° zenith angle measured
- footprints with radii of more than 2 km in shower plane
- detection with 1.5 km antenna grid would be sufficient

Pierre Auger Coll., JCAP 10(2018)026

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.

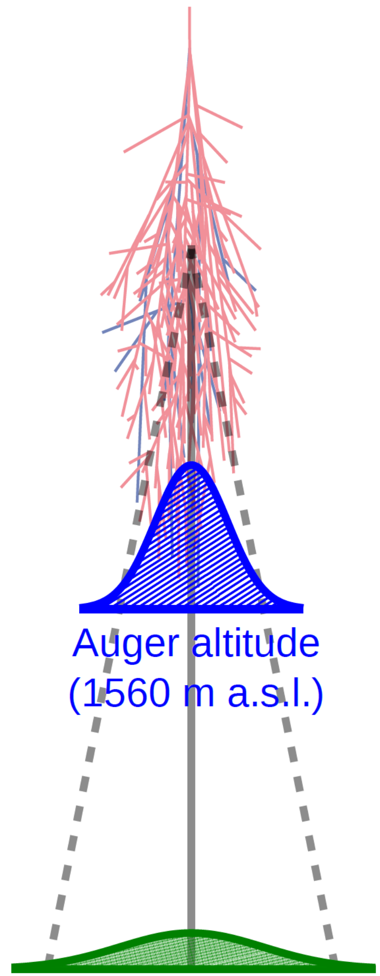
Radiation energy and energy-scale calibration

Radiation Energy

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

Amplitude at optimal lateral distance

$$A$$

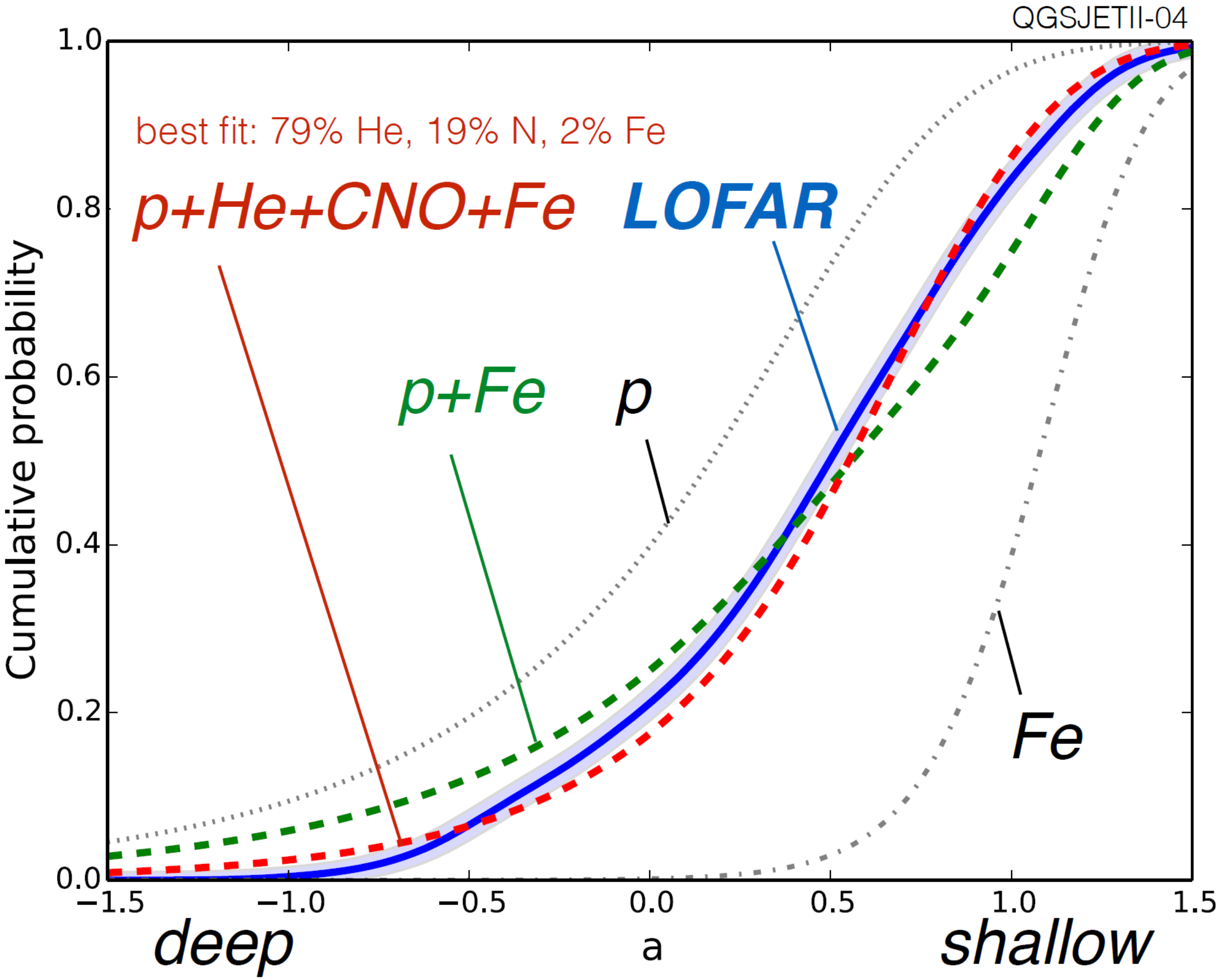


The Radiation Energy reflects the calorimetric energy of the air shower. It is independent of observation altitude.

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.

LOFAR unbinned analysis



- 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

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