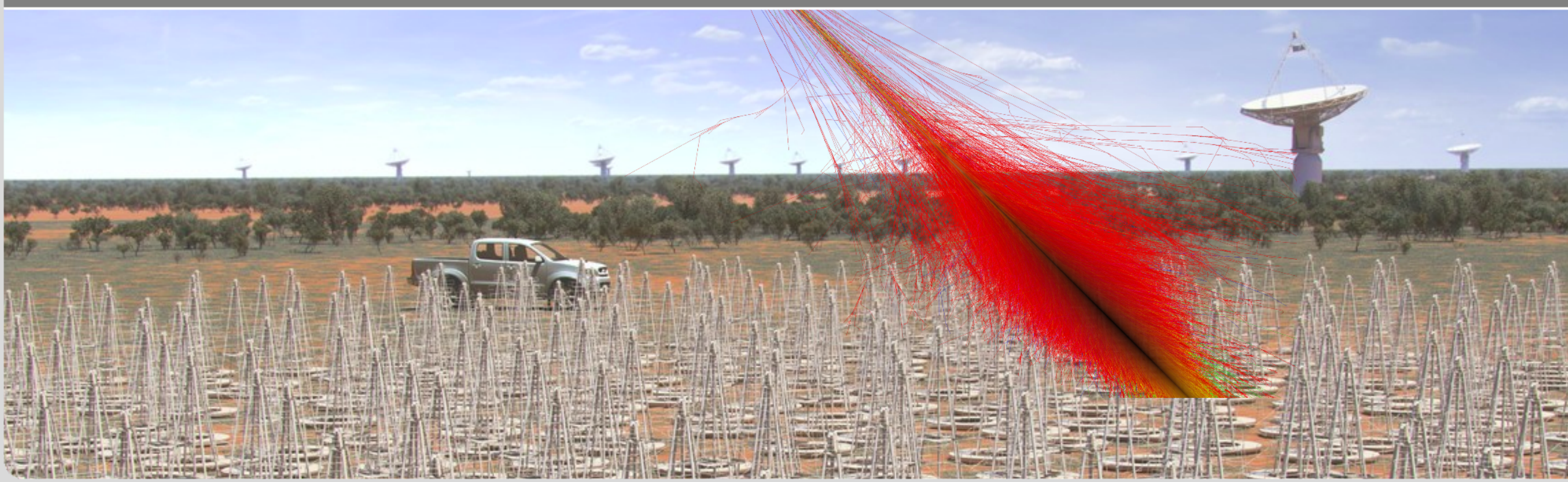
see also T. Huege et al., PoS(AASKA14)148, arXiv:1408.5288, PoS(ICRC2015)309, arXiv:1508.03465

Precision measurements of cosmic-ray air showers with SKA-low

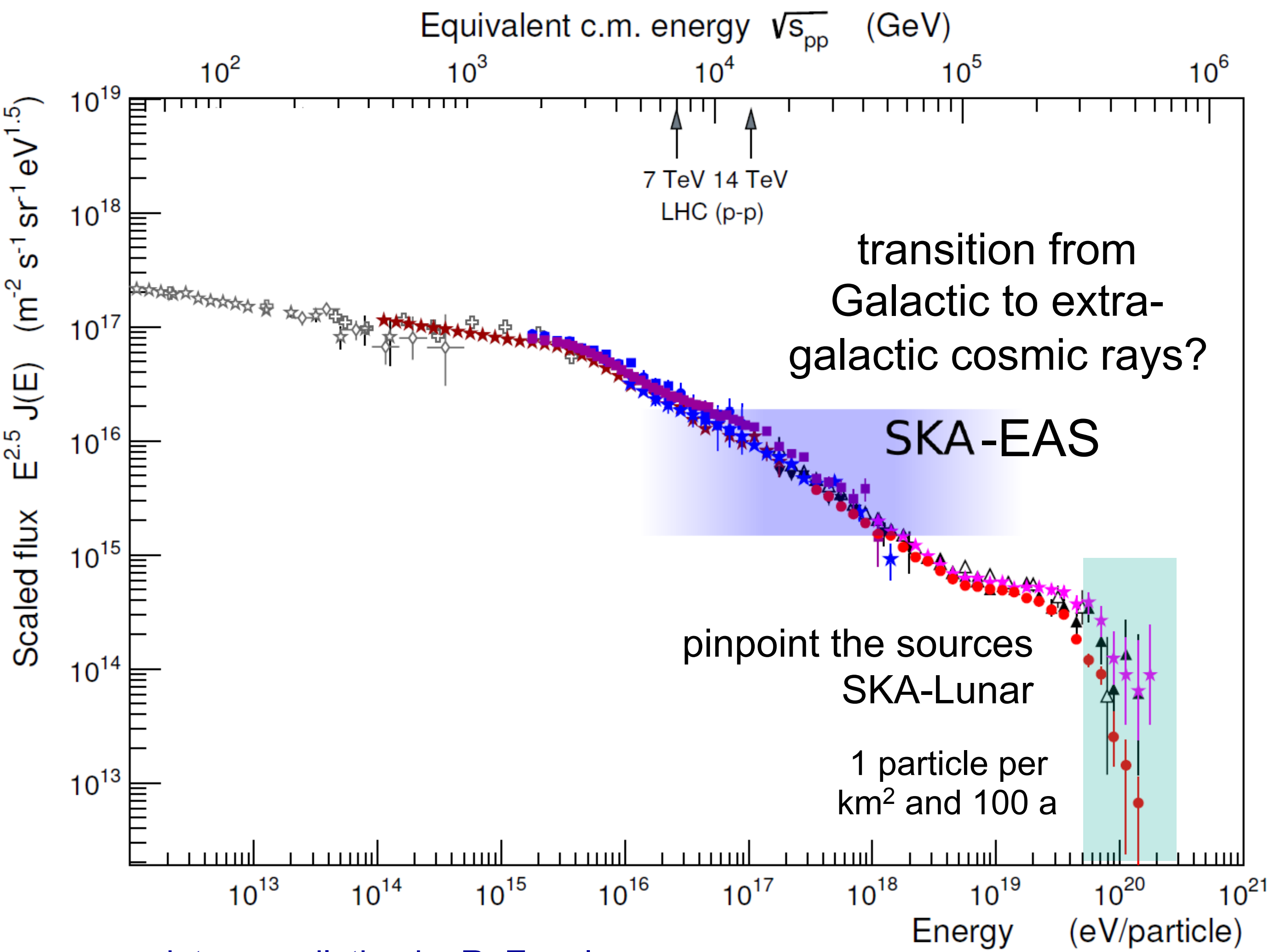
Tim Huege for the SKA High-Energy Cosmic Particles Focus Group



Cosmic Rays and their Radio Detection

High-energy cosmic rays

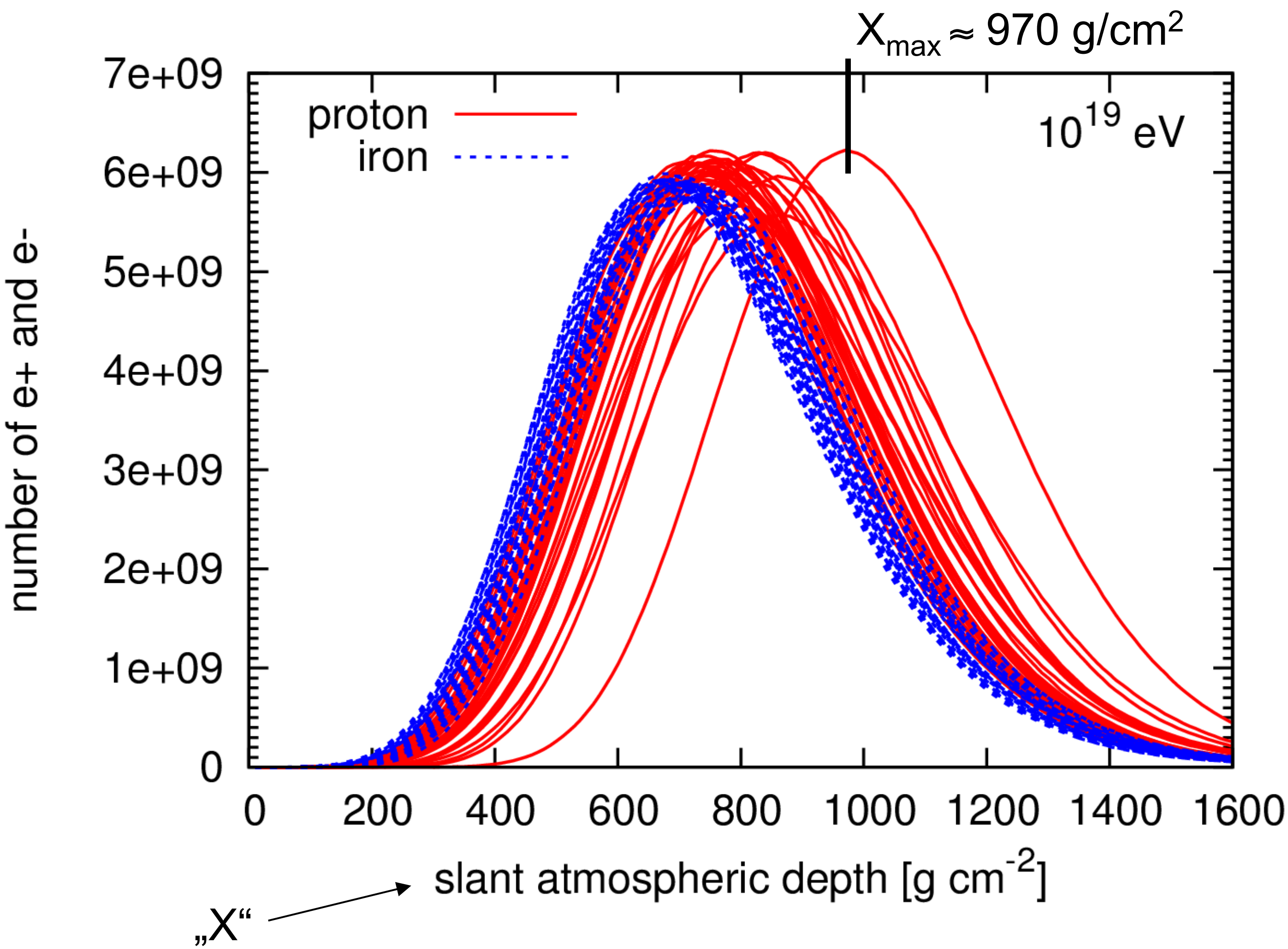
- studied for 100 years
- sources not understood
  - AGN?
  - GRBs?
  - …?
- tremendous efforts, large experiments
  - need high quality data for energy and mass
  - low fluxes



data compilation by R. Engel

Mass sensitivity: depth of particle shower

Karlsruhe Institute of Technology

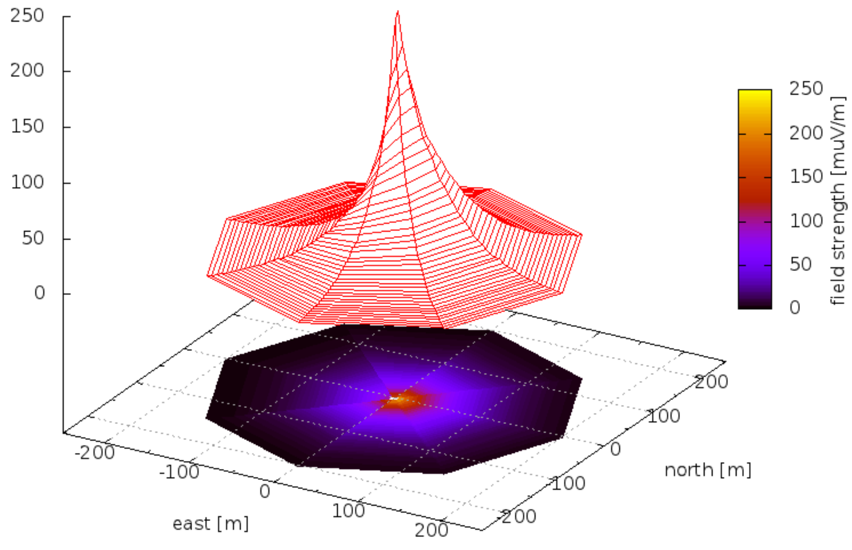


- X_{max} and RMS(X_{max}) provide information about cosmic ray mass
- directly measured by fluorescence detectors, resolution ≈ 20 g/cm²

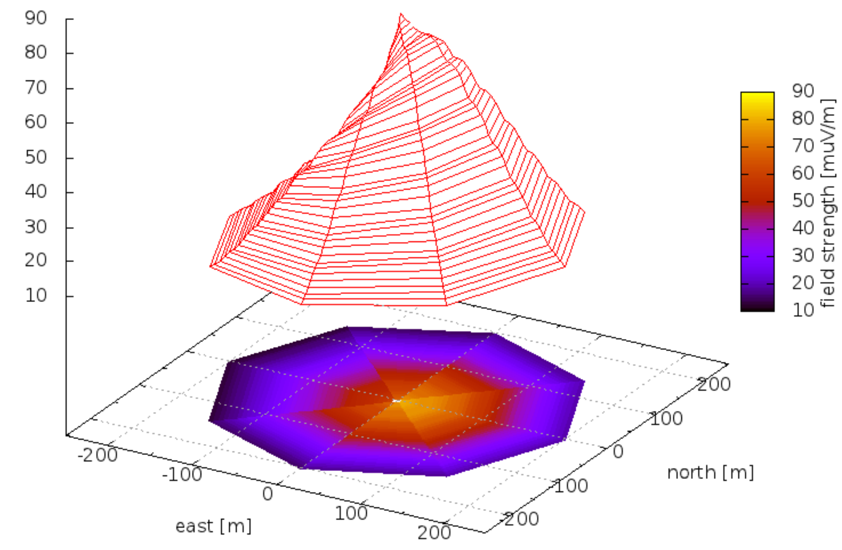
Mass composition in the EAS radio signal

- systematic differences in the radio footprints of light and heavy particles

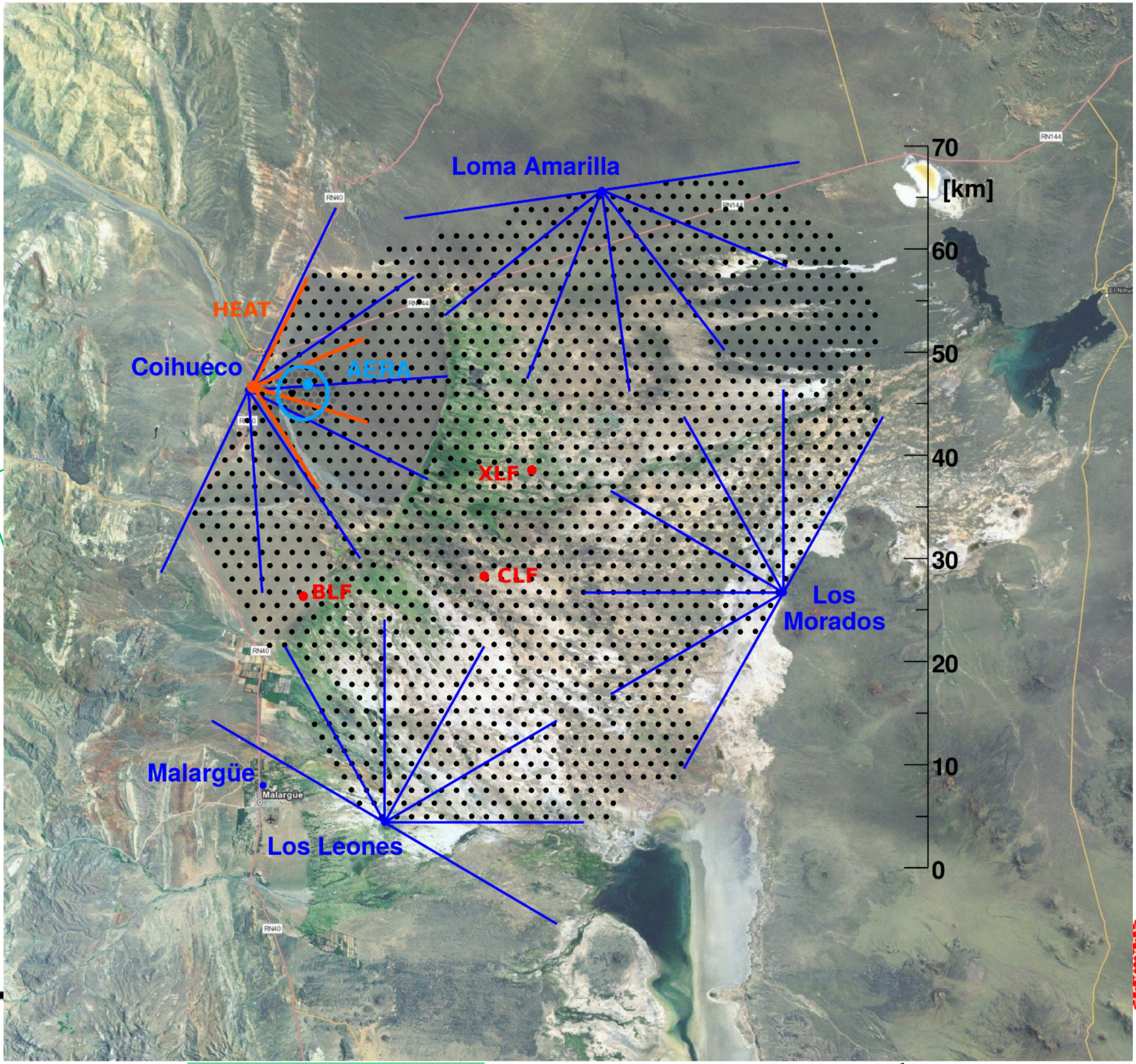
TH et al., ARENA2012



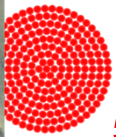
vertical proton shower
at 40-80 MHz
simulated with CoREAS



vertical iron shower
at 40-80 MHz
simulated with CoREAS



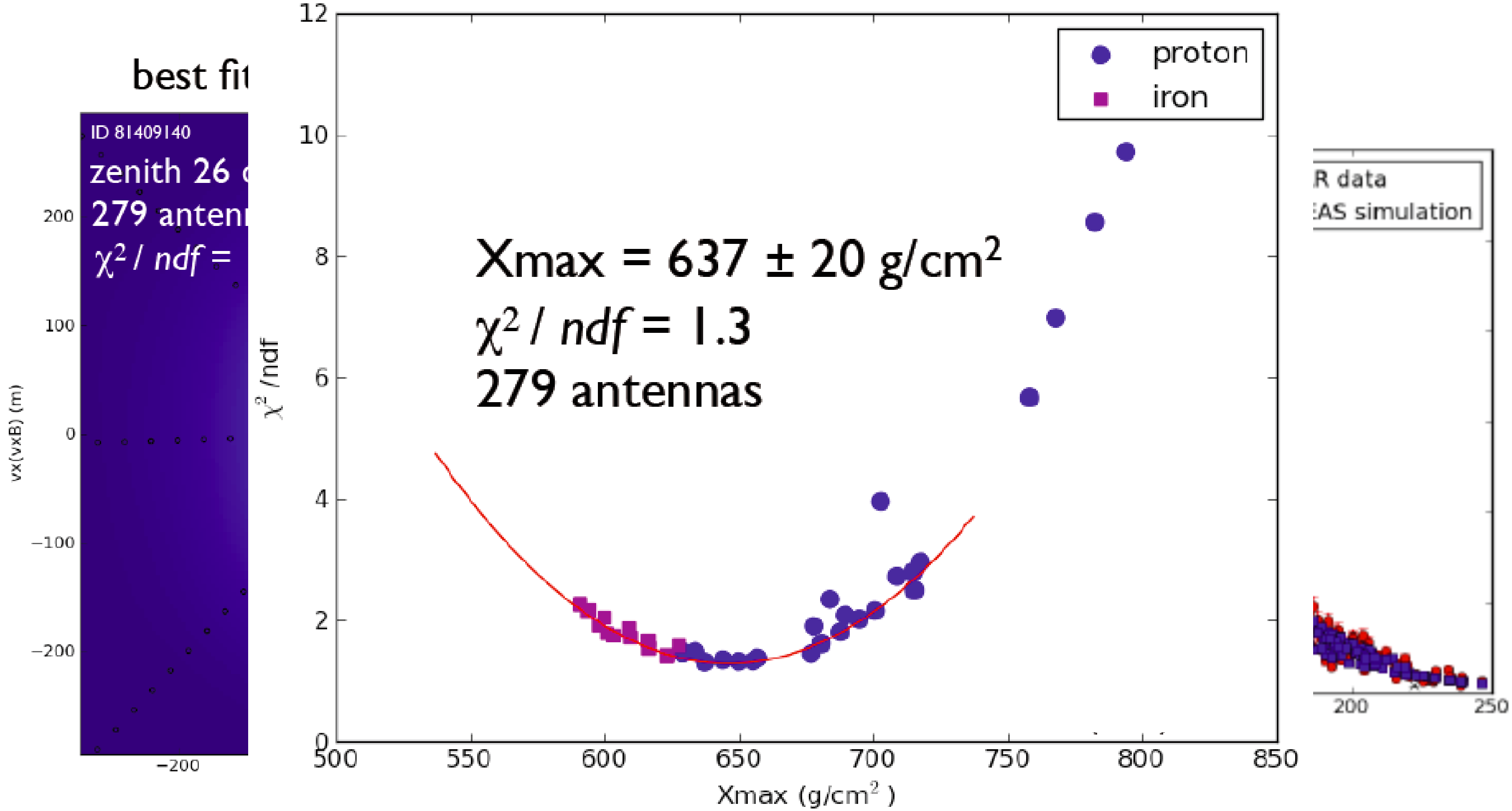
- from prototypes to full-fledged experiments
- sparse arrays (AERA) vs. dense arrays (LOFAR)
- SKA will be extremely dense, and have wide band



SKA1-low (~70,000) 50-350 MHz

T. Huege, Phys. Rep 620 (2016) 1, arXiv:1601.07426

Fit of LOFAR particle and radio data



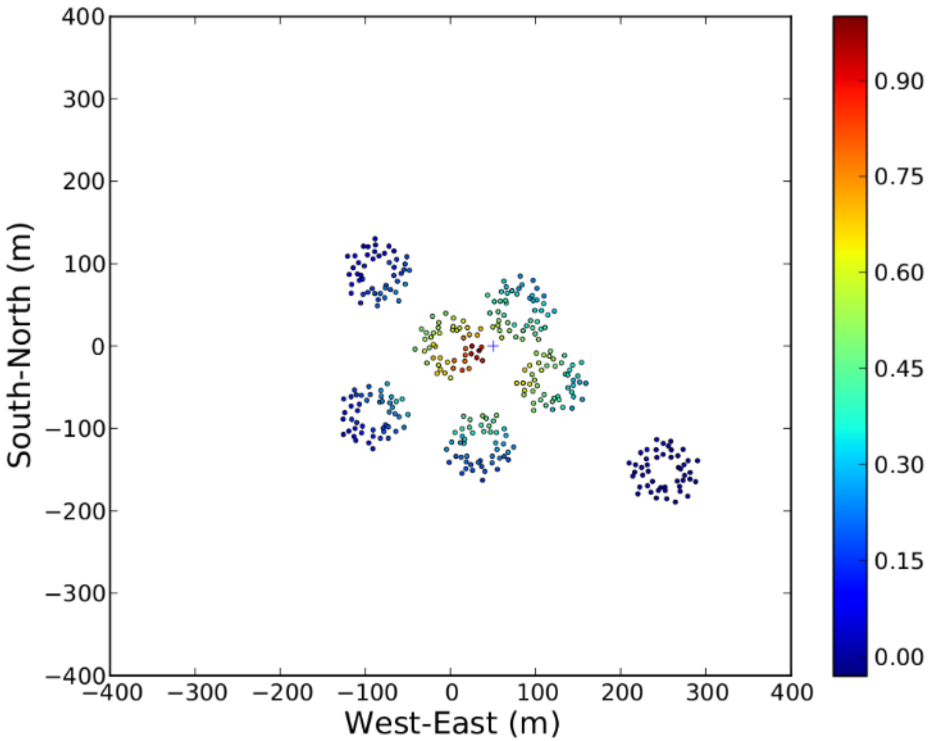
- data fit to CoREAS simulations gives Xmax to ~17 g/cm^2

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

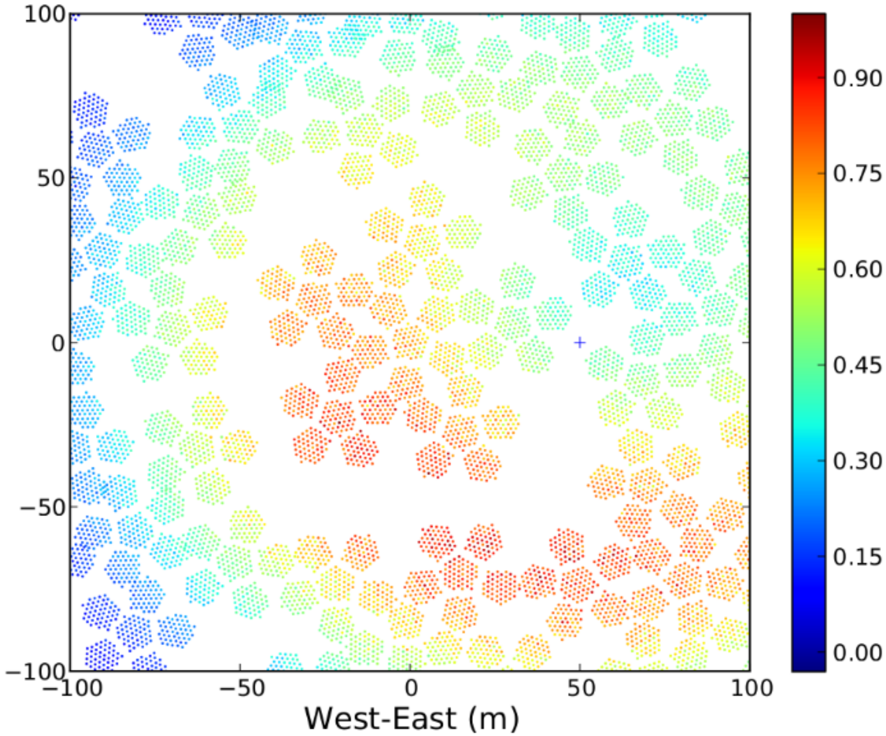
Precision Measurements: SKA

SKA will provide precision measurements

LOFAR, 30-80 MHz



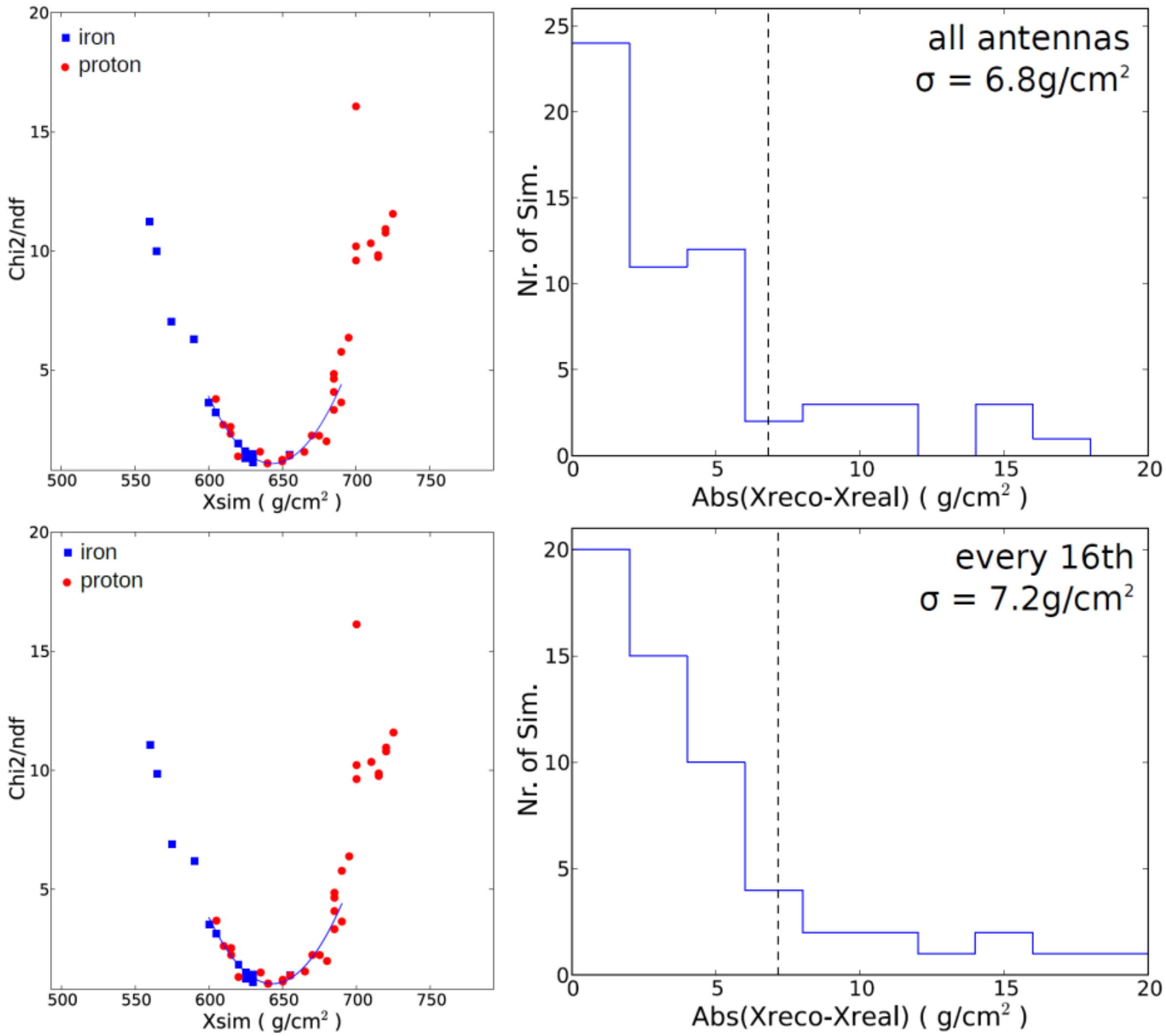
SKA-Low, 50-350 MHz



- any SKA event will be as good as the best LOFAR events, and there is still lots of room for improvement in the reconstruction

A. Zilles et al., arXiv:1702.00283

Precision Xmax studies in transition region

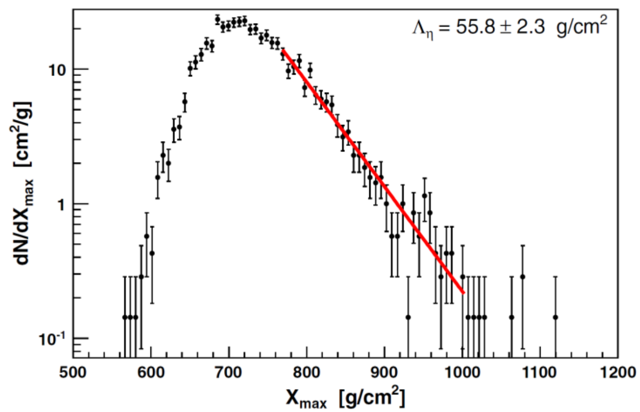


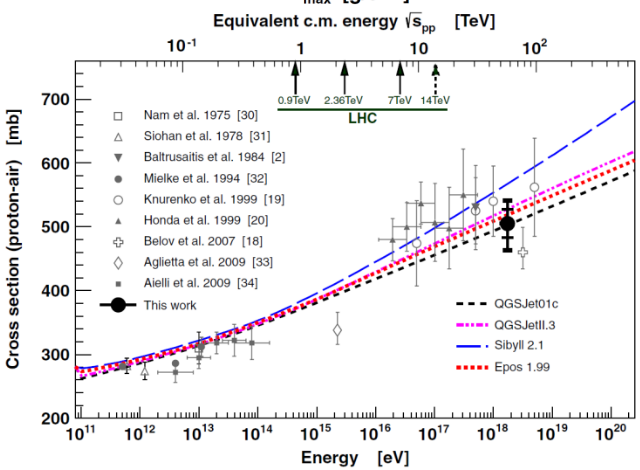
- simulation study predicts intrinsic Xmax resolutions below 10 g/cm^2
- increase of „superb event“ statistics wrt. LOFAR by factor of 100-1000
- do precision mass measurements in transition region

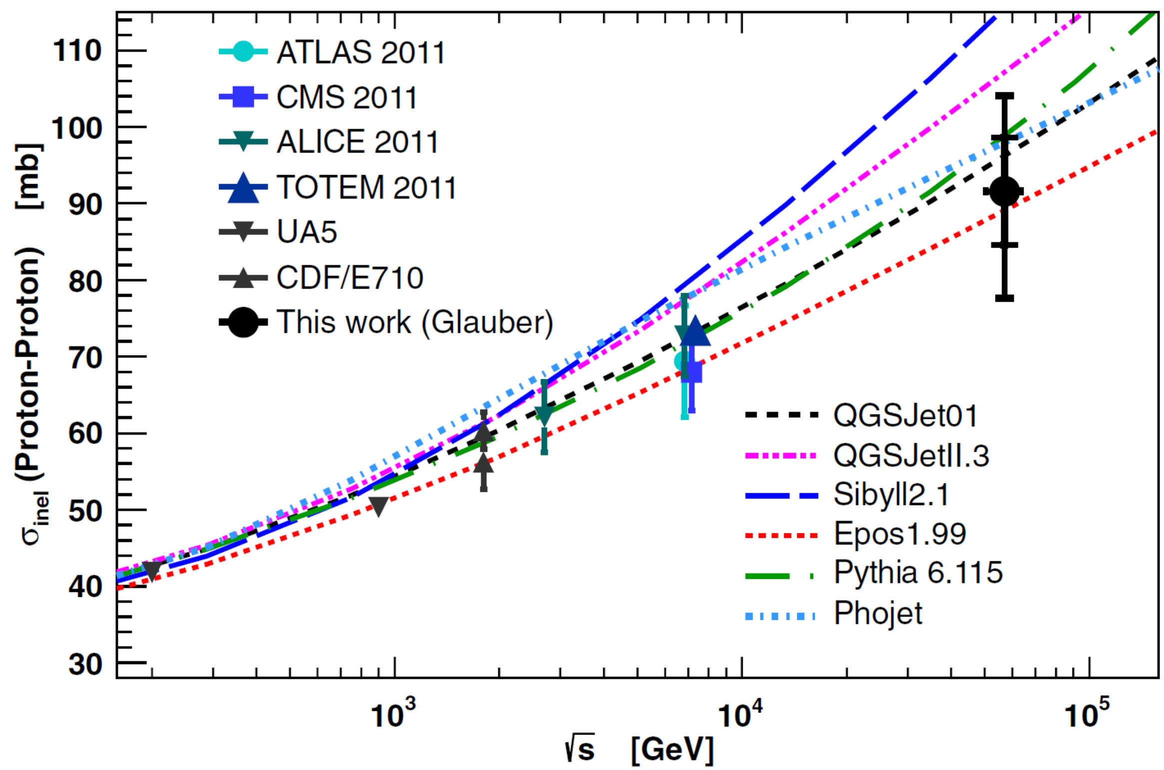
A. Zilles, S. Buitink, T. Huege in prep.

Particle physics beyond-LHC energies

- air shower measurements can be used to study particle interactions
- Auger uses tail of Xmax distributions
- near-field interferometry could possibly do much better!



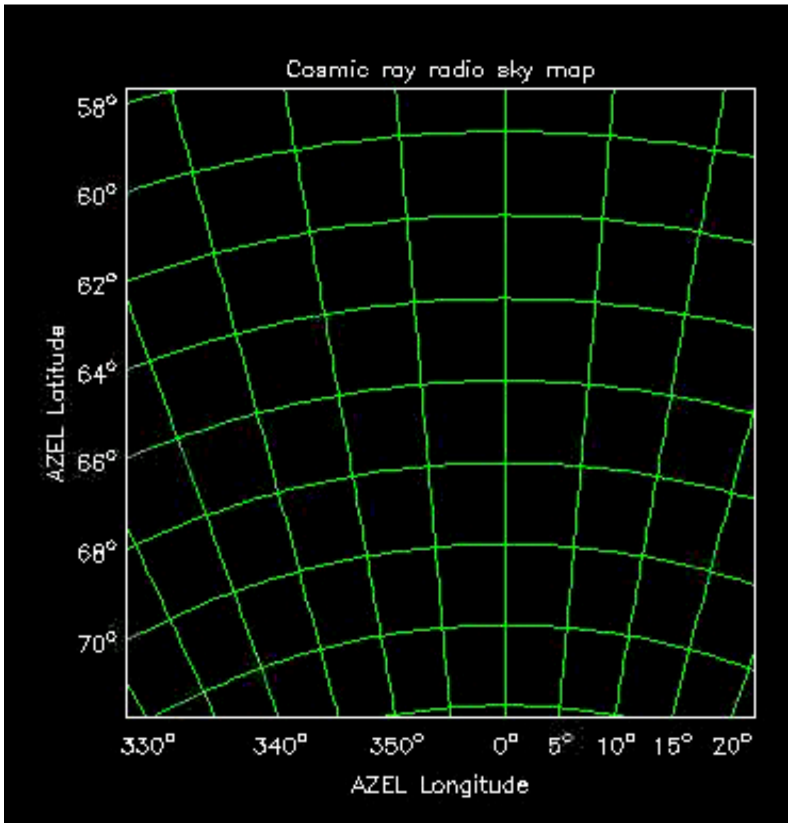




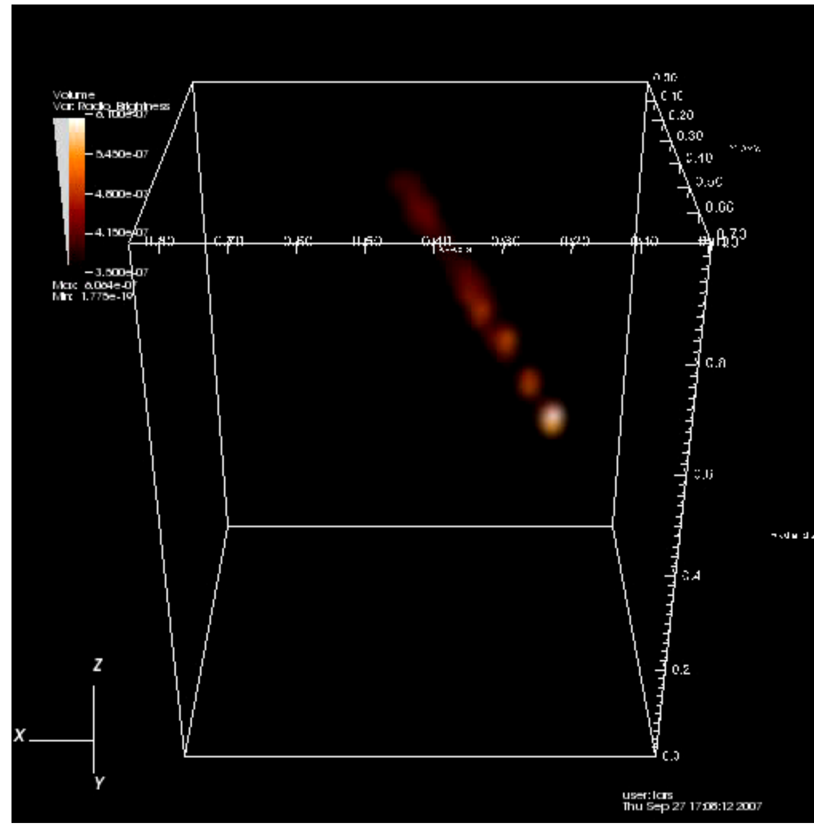
Pierre Auger Collaboration, PRL 109 (2012) 062002

„Tomography of air showers“

- near-field interferometry will yield unprecedented level of detail
  - 4-dimensional distribution of e^+ and e^- in air showers, study shower physics



LOPES, „far-field interferometry“

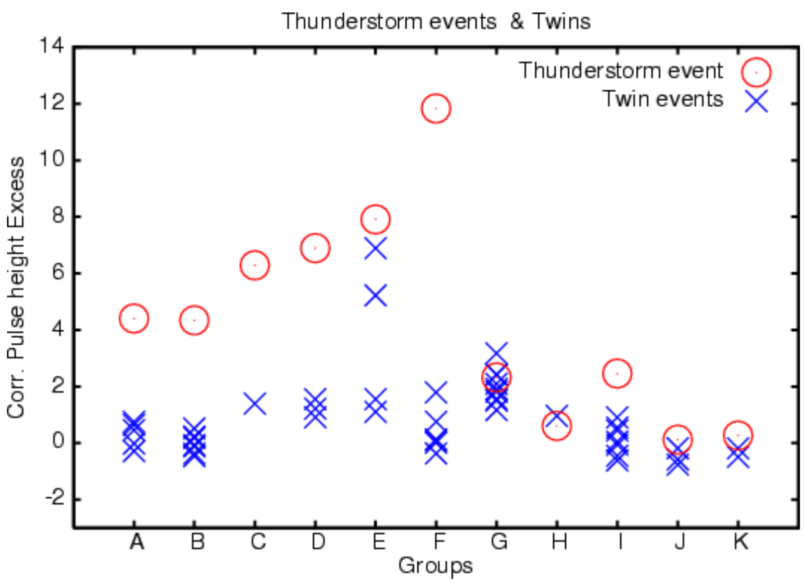


tomography with „near-field interferometry“

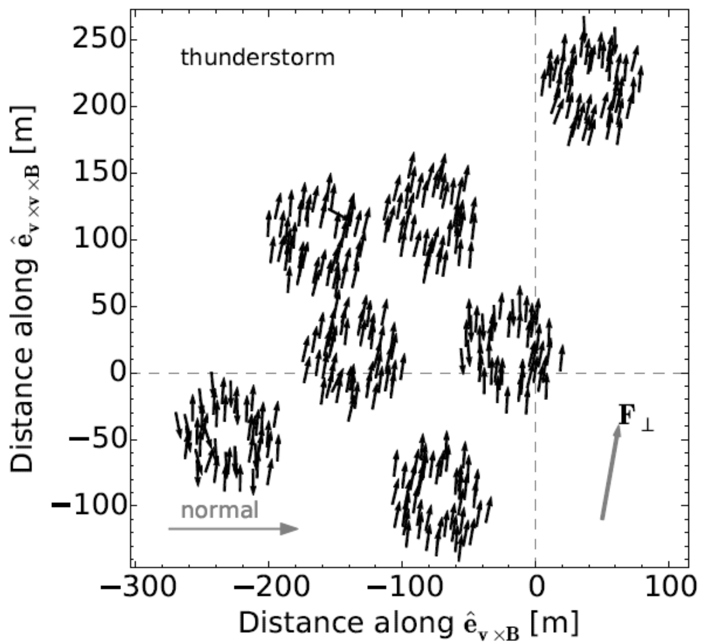
Physics of lightning and connections to EAS

Karlsruhe Institute of Technology

- atmospheric electric fields influence EAS radio emission
- LOFAR deduced thunderstorm electric fields from CR data



Buitink et al. (LOPES Coll.), A&A 467 (2007) 385

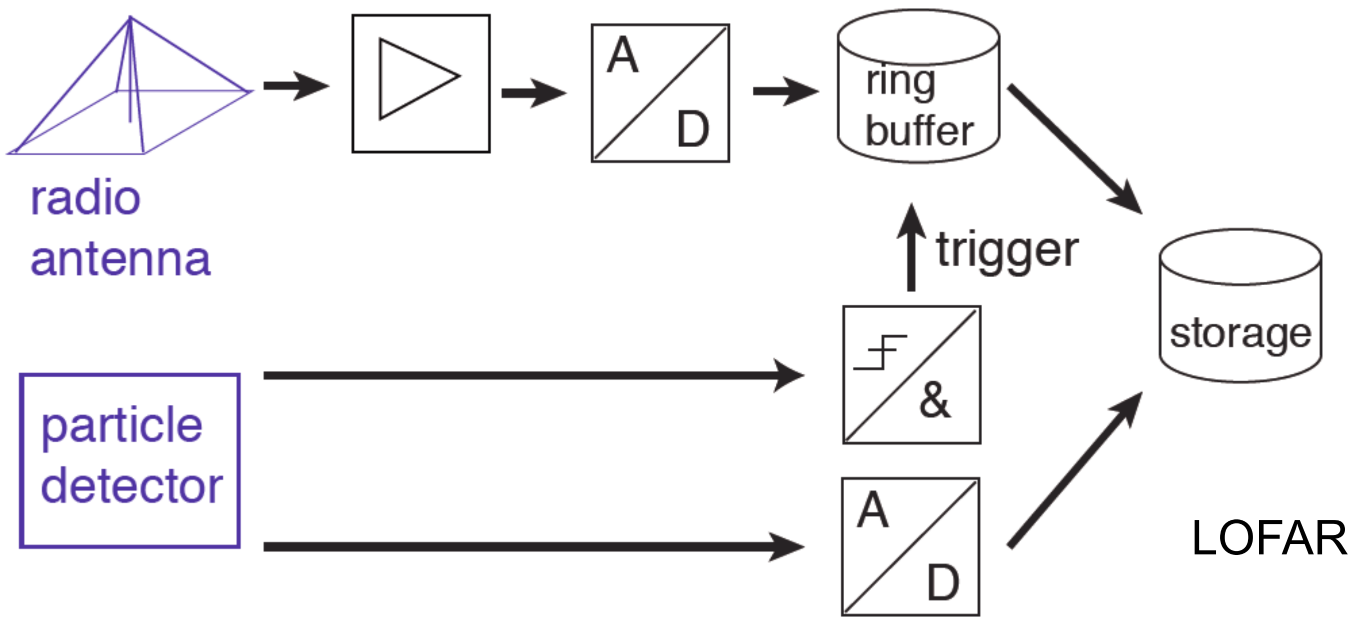


Schellart et al. (LOFAR Coll.), PRL (2015)

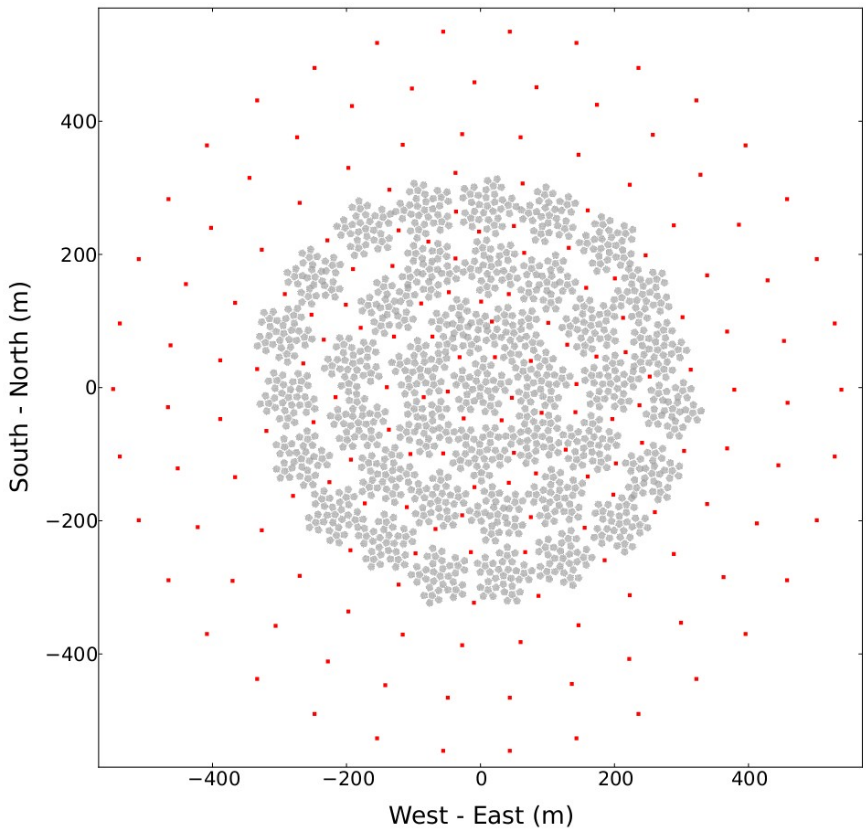
Engineering Requirements

Technical requirements for SKA-EAS

- read out ~50 μs of **8 bit raw data** of **individual antennas** upon trigger
  - trigger to come from dedicated small particle detector array
- ring buffers allow piggy-backing to normal observations
  - 100% commensality
- concept has been successfully implemented in LOFAR

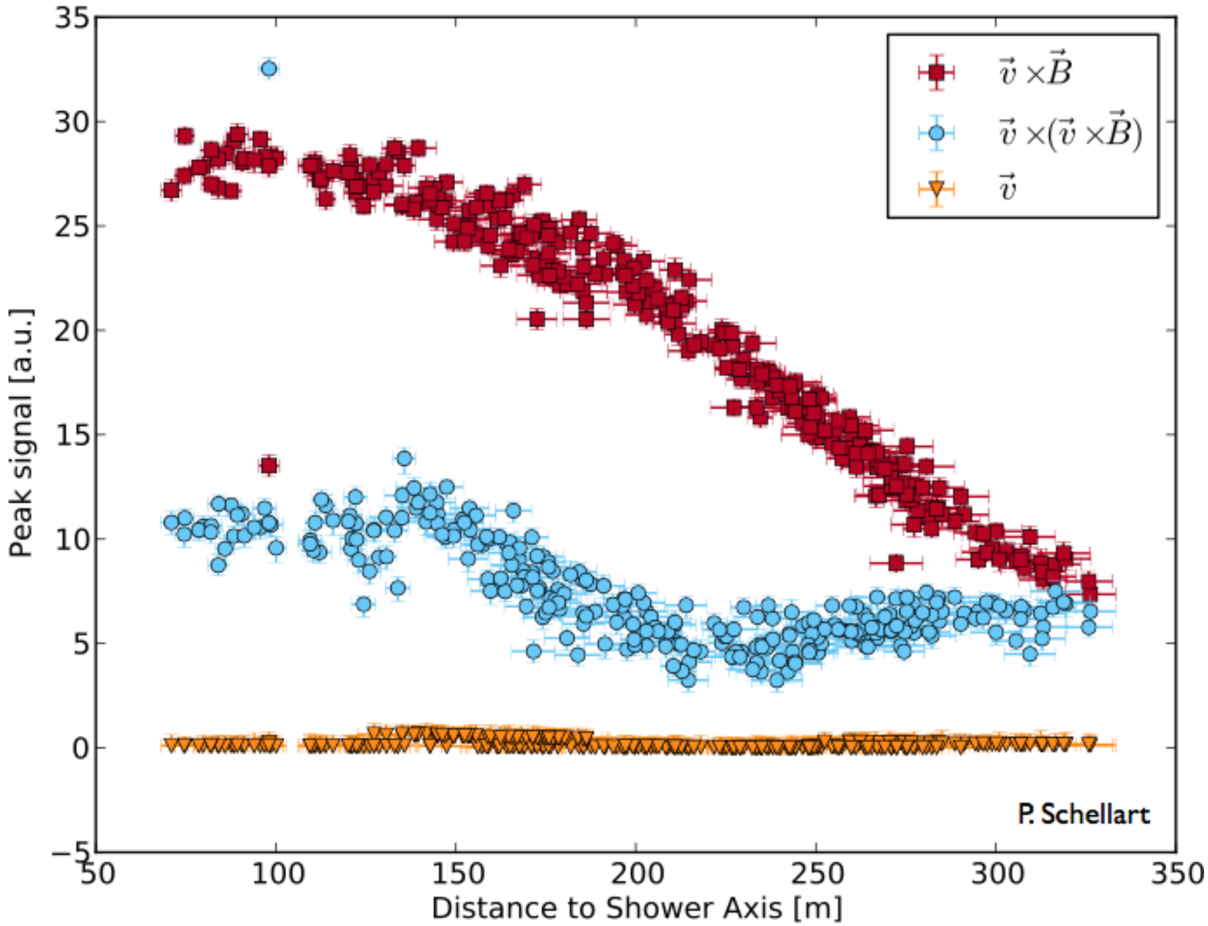


Engineering change: triggering array



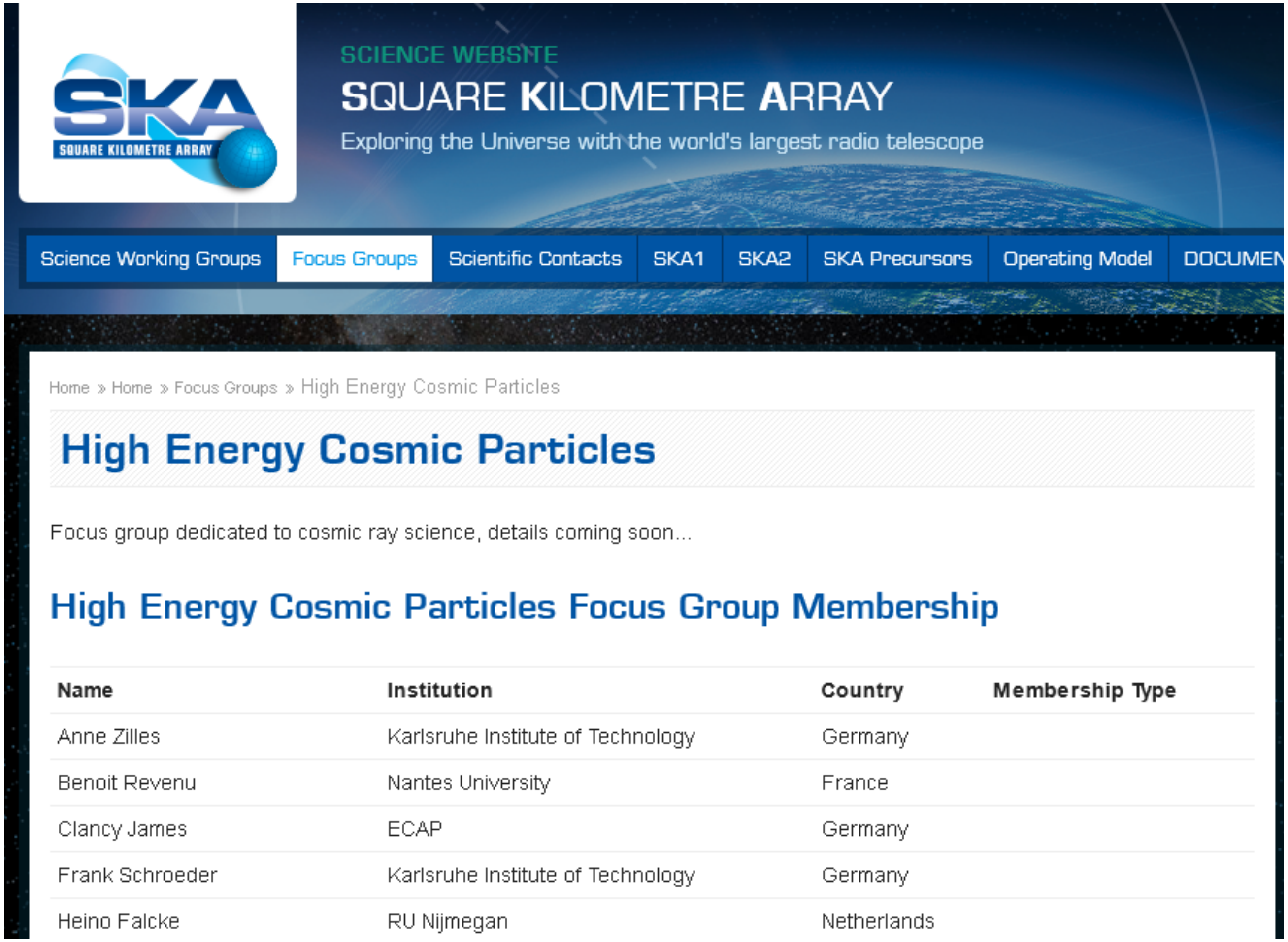
- particle detector array ensures efficient and pure trigger
  - ~10,000/a above 10^{17} eV
- should become efficient at ~10^{16} eV, average distance ~50-100 m
  - possibility: 180 scintillators from KASCADE array, 3.6 m^2 each
- extend fiducial area outside the SKA1-low core, area ~1 km^2
- read-out as for antennas, analogue over optical fibres, digitize centrally
  - low RFI (no clock distribution, …)

NB: A great tool for low-level diagnostics



- single-antenna data allowed LOFAR to fix problems such as swapped cables, defective connectors, timing issues, …

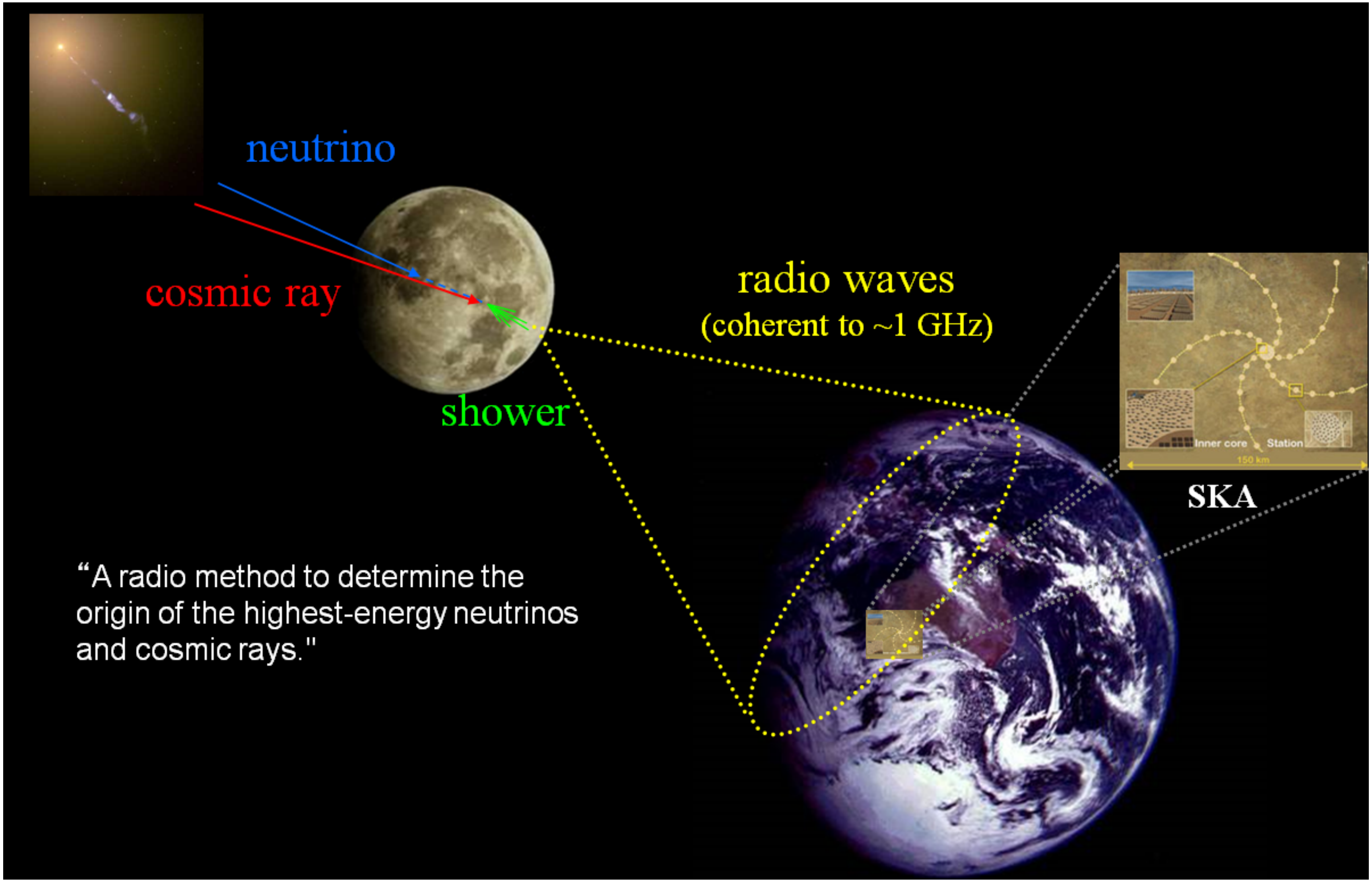
State of the project



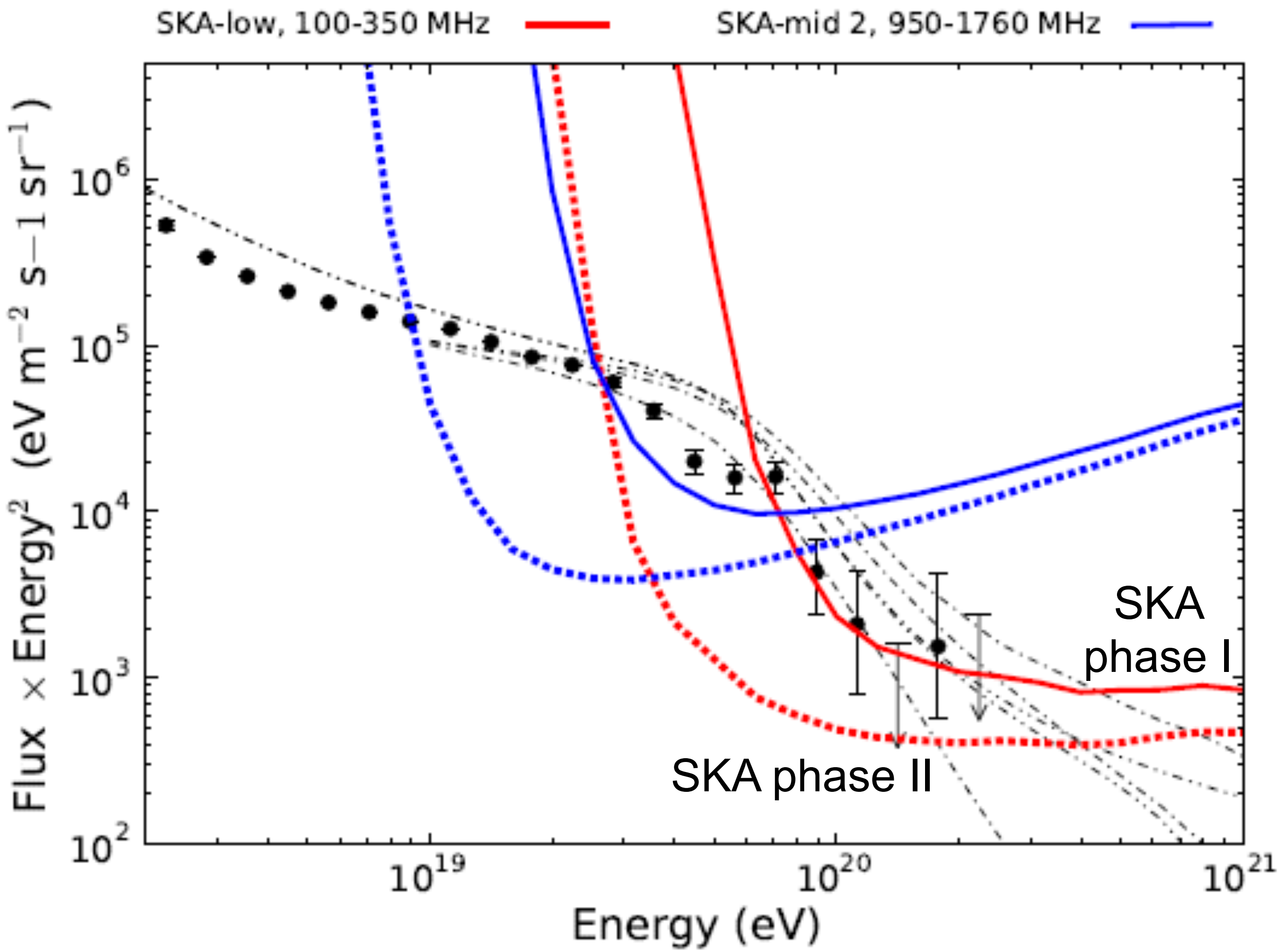
- „SKA focus group“
- detailed „Engineering Change Proposal“ under consideration
- „Custom Experiment Policy“ being developed
- no decision in current cost reduction phase

SKA Lunar

The highest energies: SKA-Lunar



SKA lunar could pinpoint UHECR sources



J. Bray et al., PoS(AASKA14)144, arXiv:1408.6069

- increased sensitivity of SKA for the first time makes energies with established CR fluxes accessible to Lunar technique
- search for sources at highest energies

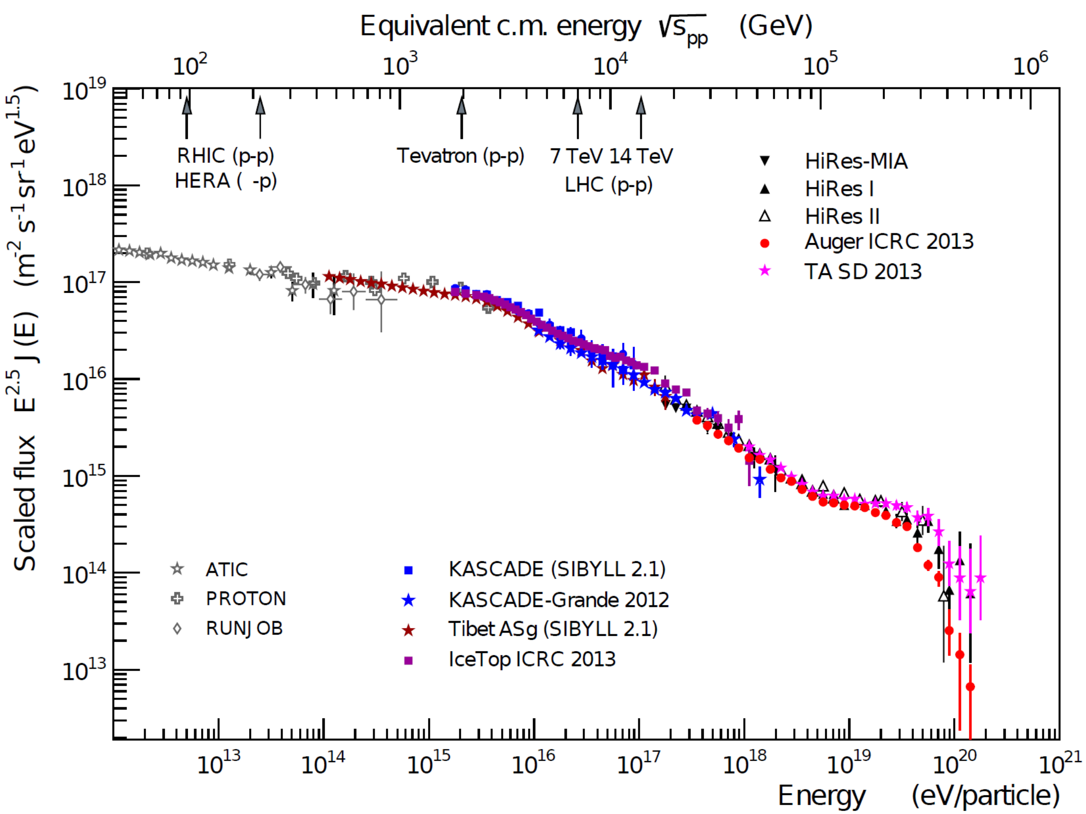
Conclusions

- SKA1-low can be enabled for cosmic ray detection
  - 100% commensal observations
- the science potential lies in precision measurements
  - mass composition in the transition region
  - particle interactions and air shower physics
  - air showers and thunderstorms
- an engineering change proposal is under consideration

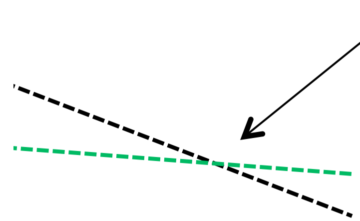
Backup Slides

Transition from Galactic to extragalactic CRs

- needs precise mass composition studies from 10^{17} to 10^{19} eV
- SKA will be able to measure Xmax there with unprecedented precision

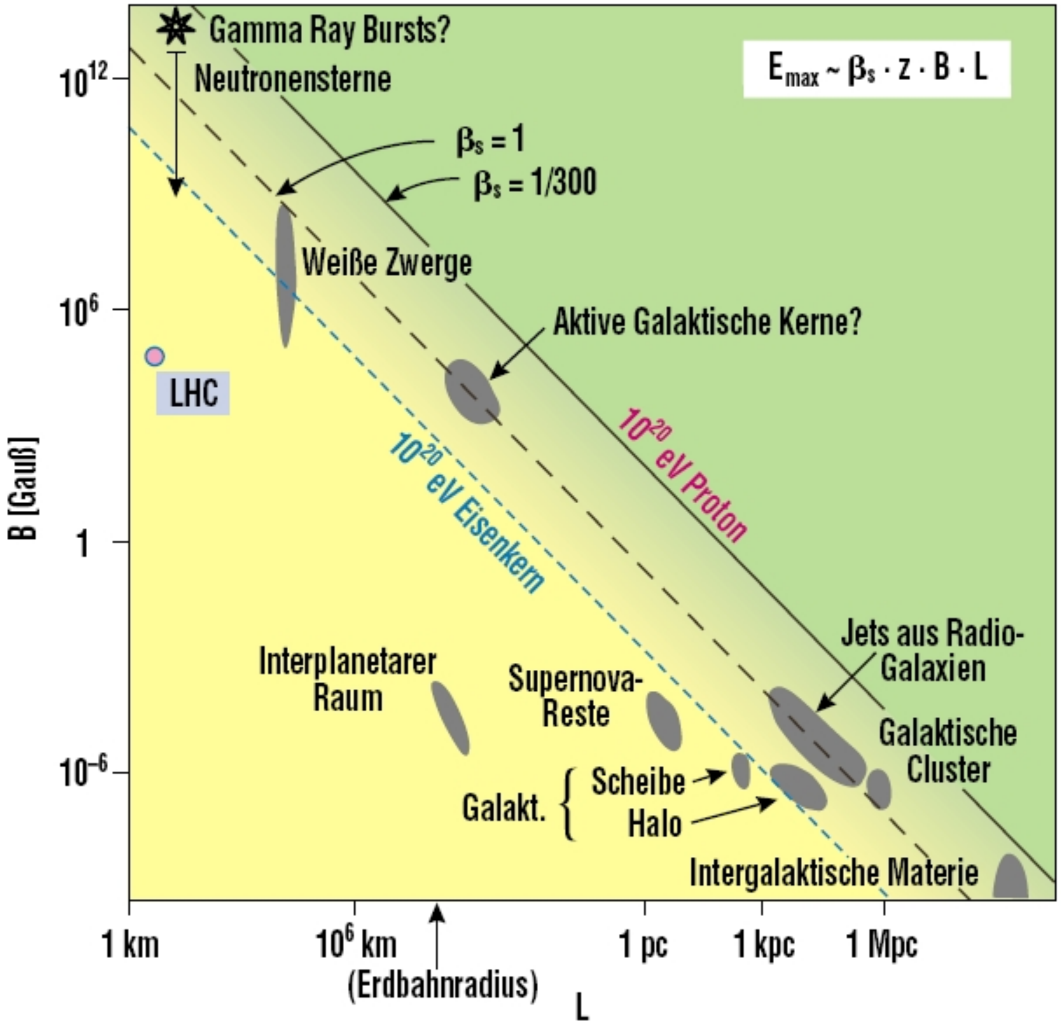


„Ankle“ at 3 10^{18} eV transition from galactic heavy particles to extragalactic protons?



KASCADE-Grande Collaboration, Phys. Rev. D 87 (2013) 081101(R)

Hillas Diagram

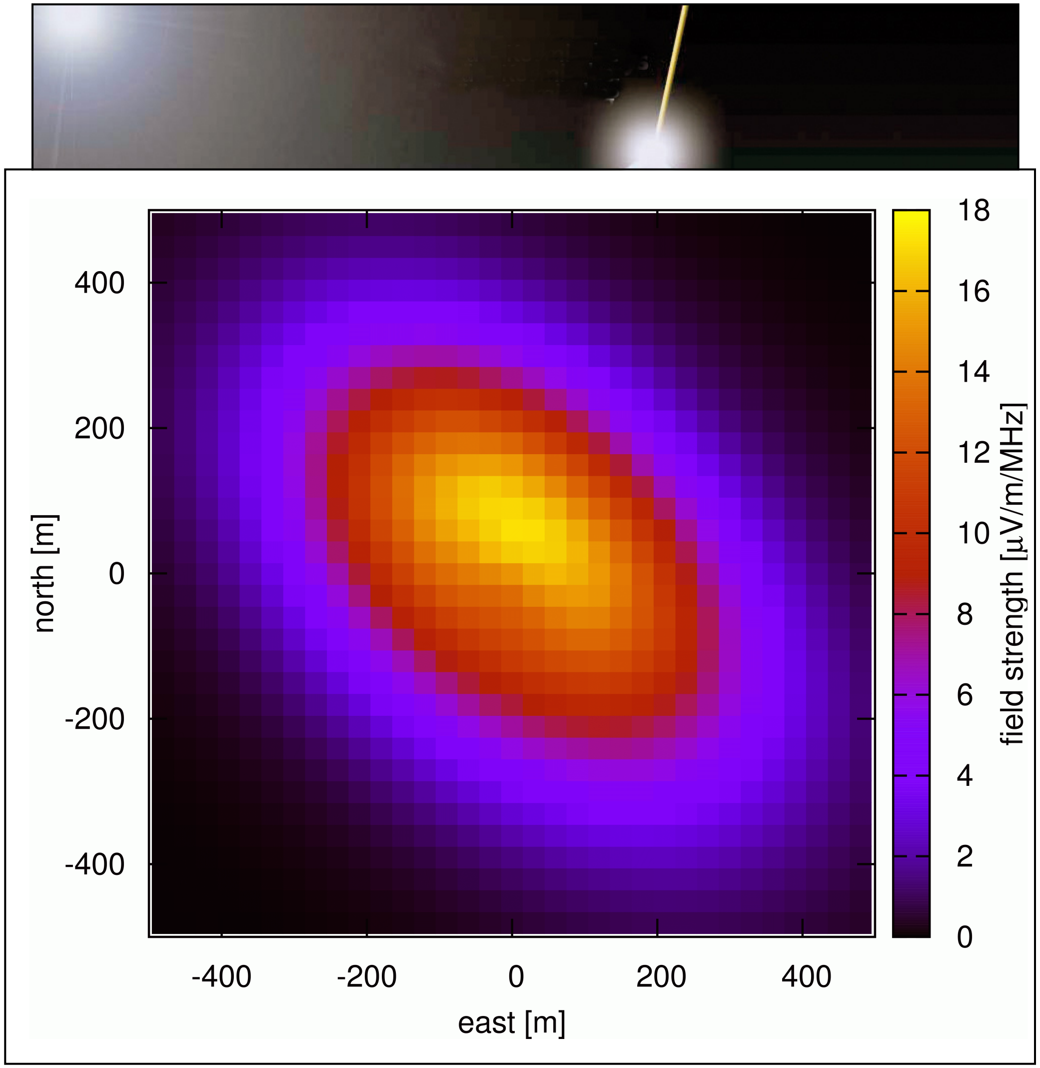


Tim Huege <tim.huege@kit.edu>

Extensive air showers (EAS) and their detection

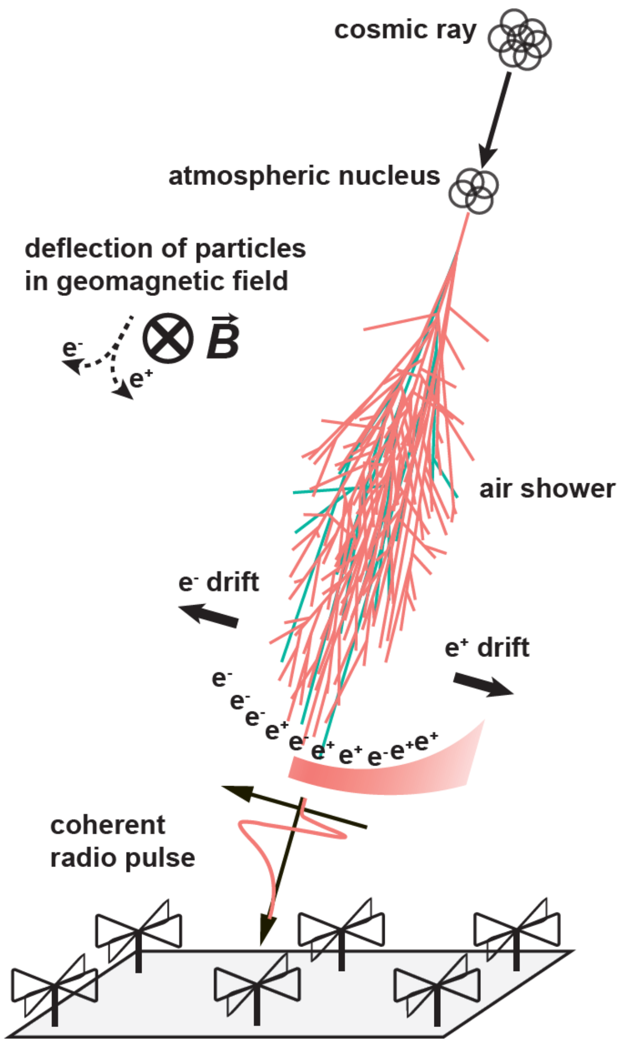
Karlsruhe Institute of Technology

- cosmic ray interacts with nucleus in atmosphere
- cascade of secondary particles evolves
  - particle detectors register particles at ground
  - optical telescopes measure energy deposit via N_2 fluorescence
  - radio detectors measure short (<100 ns) coherent radio pulses in radio pulses in a limited area

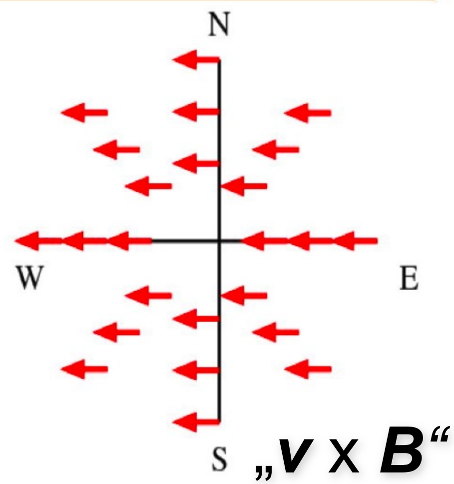


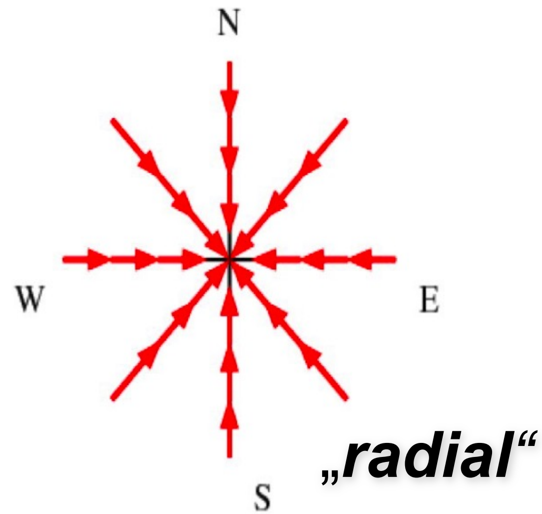
Radio emission physics is understood

Karlsruhe Institute of Technology



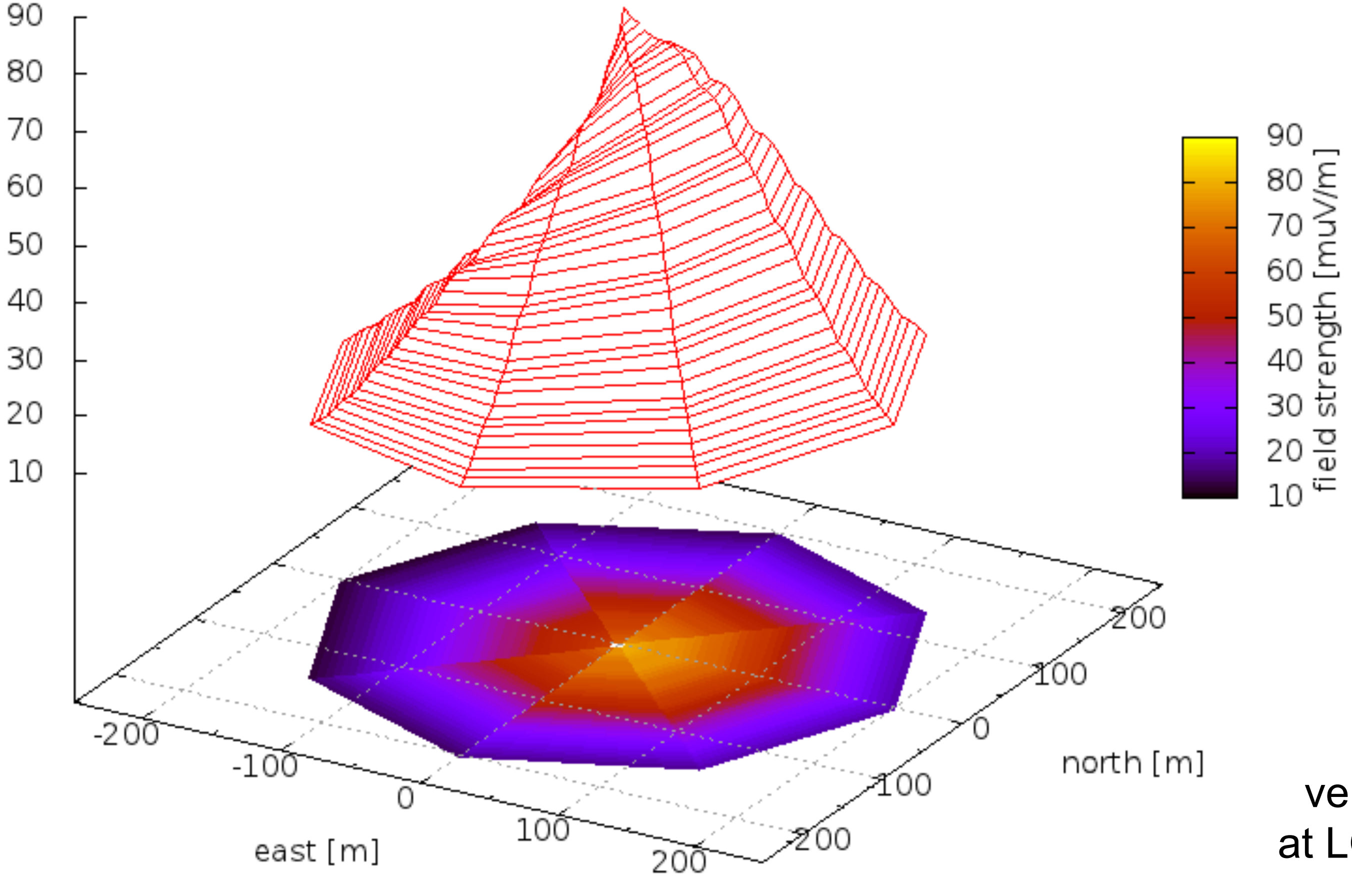
- *time-varying* transverse currents in geomagnetic field
- *time-varying* net charge excess („Askaryan effect“, at level of ~15%)





- + coherence effects (spatial distribution)
- + Cherenkov-like time compression due to atmospheric refractive index gradient

Complexity of radio LDF



vertical iron shower
at LOPES frequencies
simulated with CoREAS

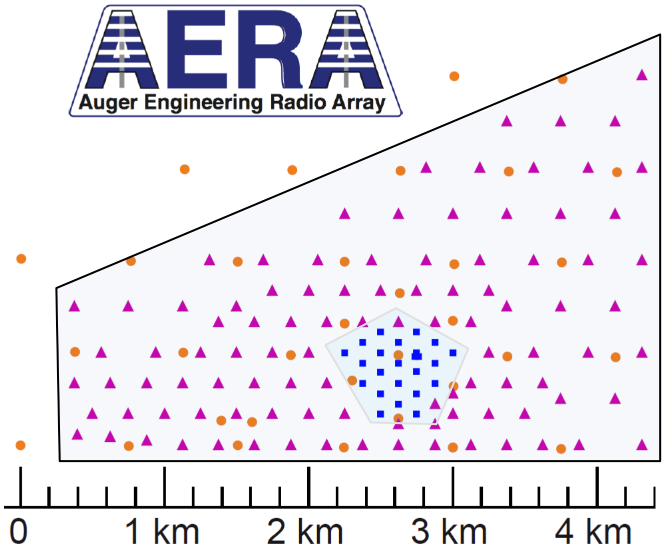
TH et al., ARENA2012

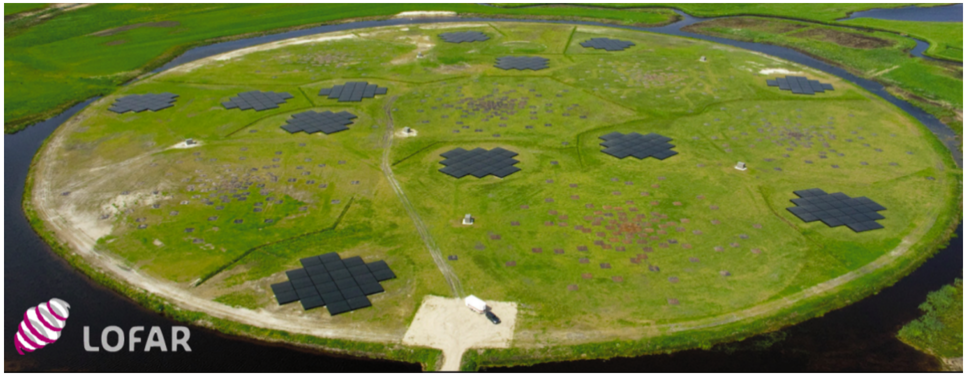
Radio detection of cosmic ray air showers

- prototyping phase is over (LOPES, CODALEMA, …)
- we clearly understand the radio emission
- different paths can now be followed

cover large areas (>10 km^2), sparse antenna arrays

measure individual air showers very precisely with dense antenna arrays



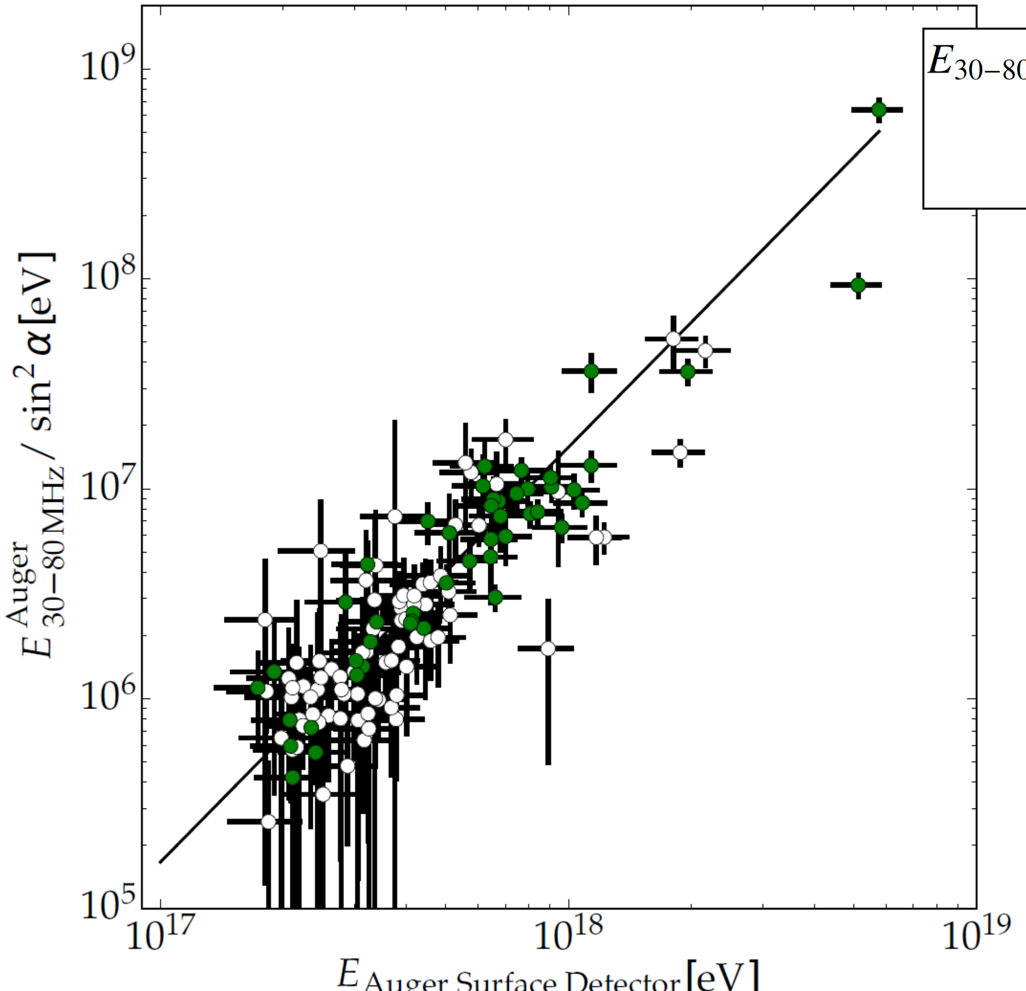


Energy scale from first principles

- 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 uncertain hadronic interaction simulations) can be calibrated from first principles!

„Radiation energy“ as energy estimator



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

- 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

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

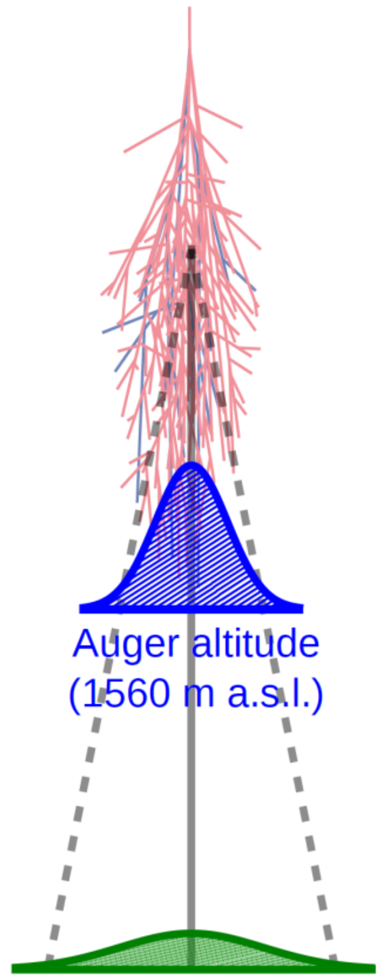
Radiation energy and energy-scale calibration

Radiation Energy

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

Amplitude at optimal lateral distance

$$A$$

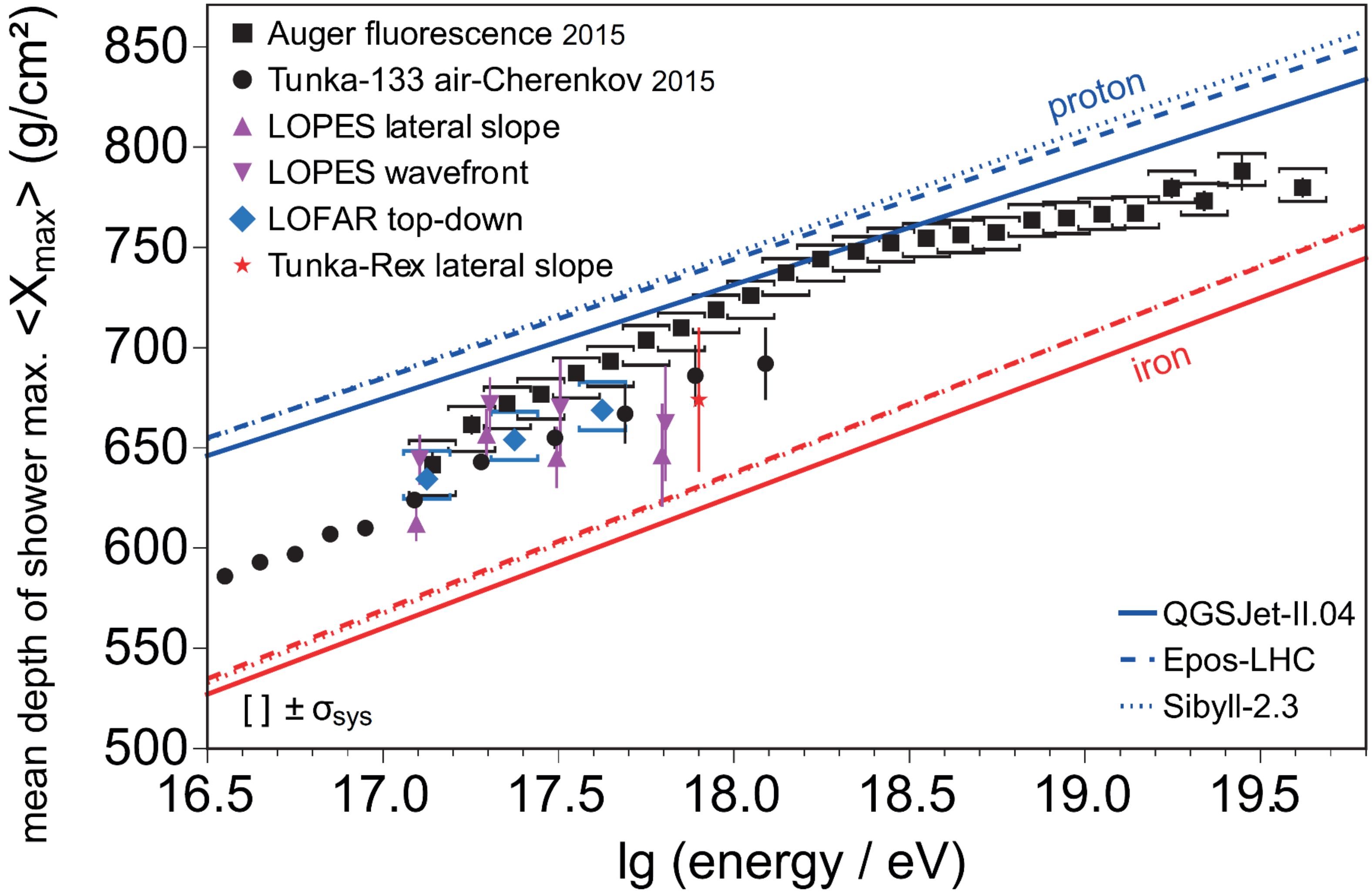


The Radiation Energy reflects the calorimetric energy of the air shower. It is independent of observation altitude.

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.

Xmax measurements with radio detectors



F.G. Schröder, Prog. Part. Nucl. Phys. 93 (2017) 1-68, arXiv:1607.08781