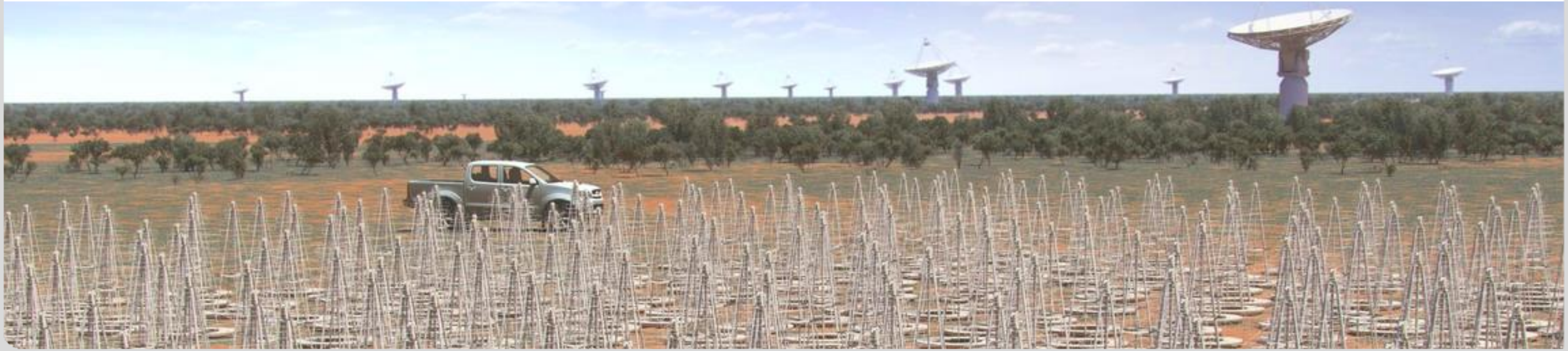
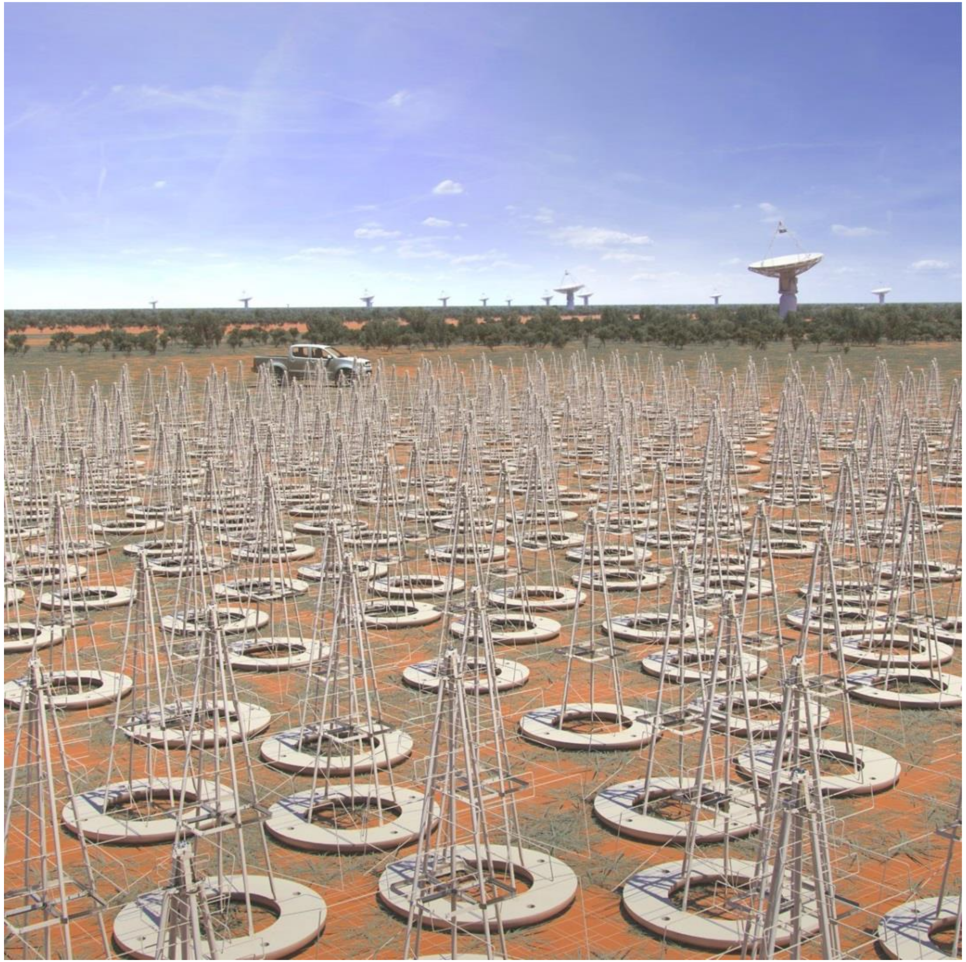
Ultimate precision in cosmic-ray radio detection: The SKA

Tim Huege (KIT) and the SKA focus group on High-Energy Cosmic Particles



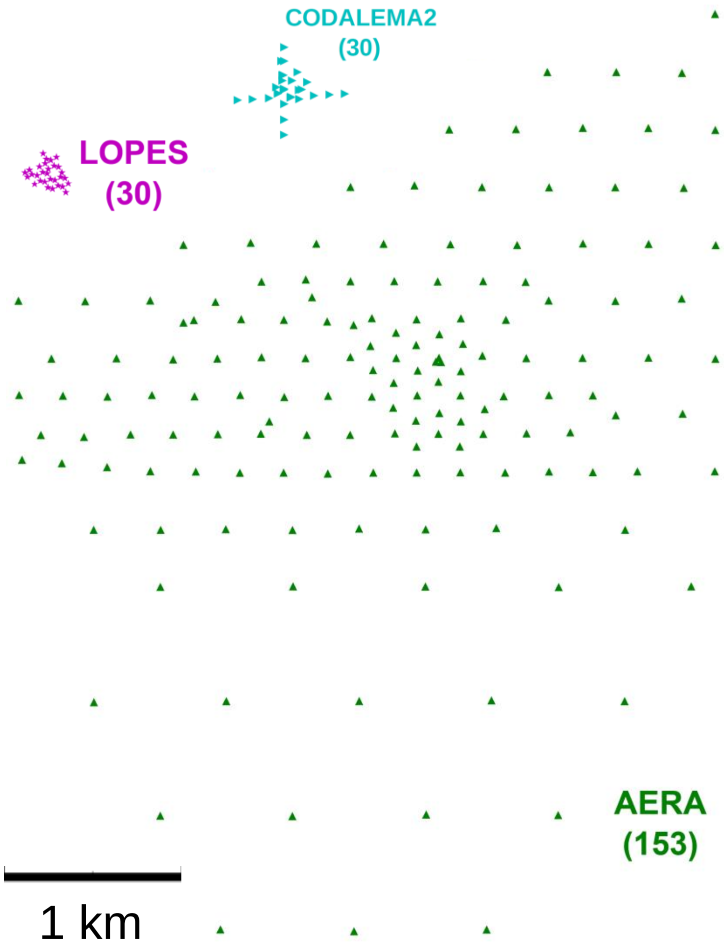
From LOFAR-CR to SKA-CR

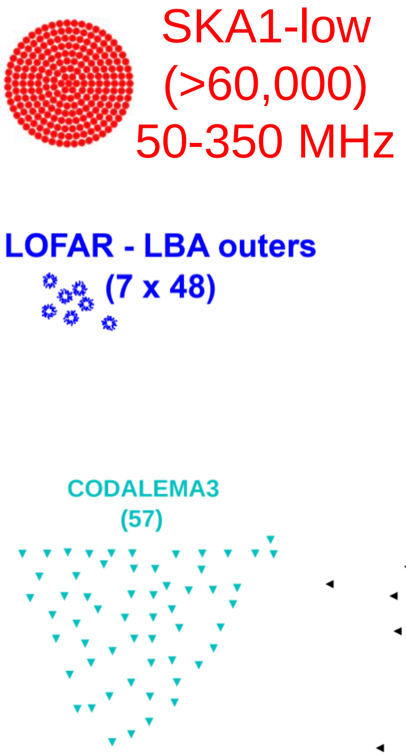


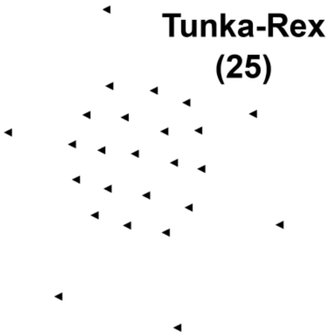
SKA1-low

- 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

Radio-array comparison

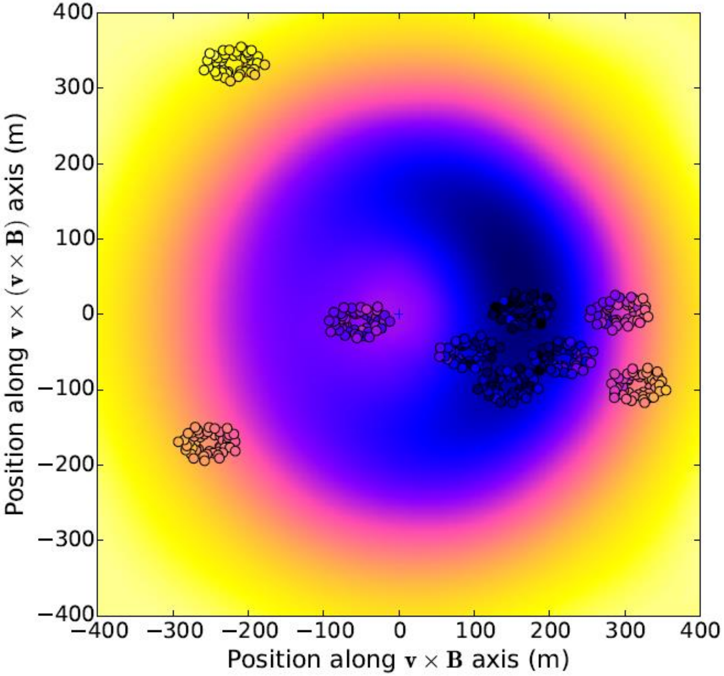


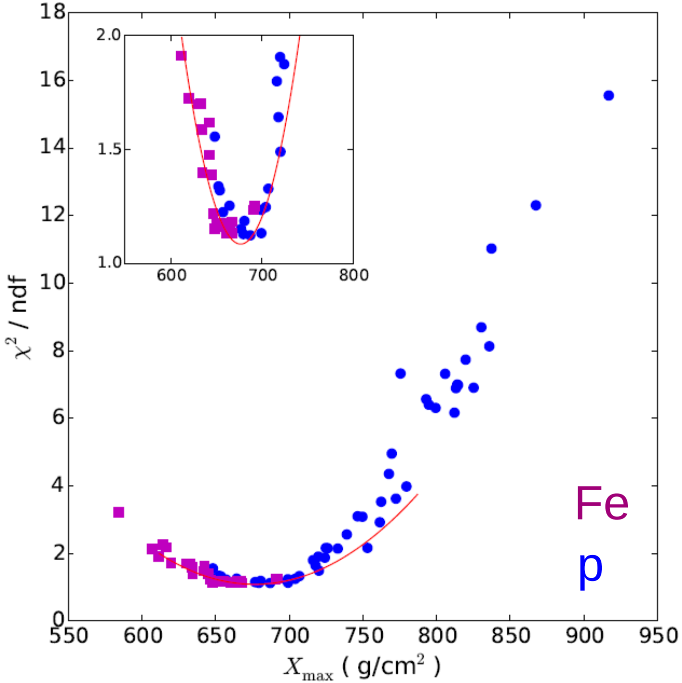




- SKA1-low can measure individual air showers with *extreme* precision
- area of core is roughly 0.5 km^2

Xmax reconstruction from LDF - LOFAR

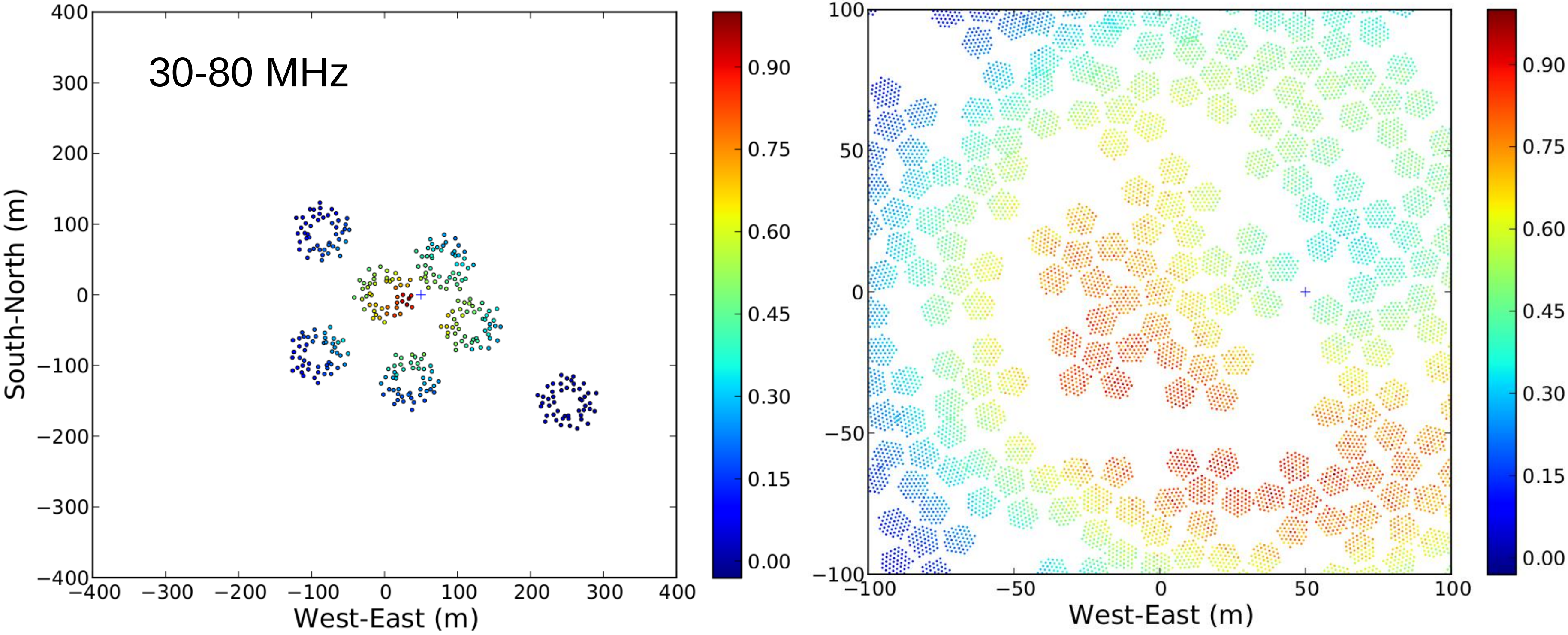




- 2d LDF fit to CoREAS simulations yields mean σ_{Xmax} of ~17 g/cm^2

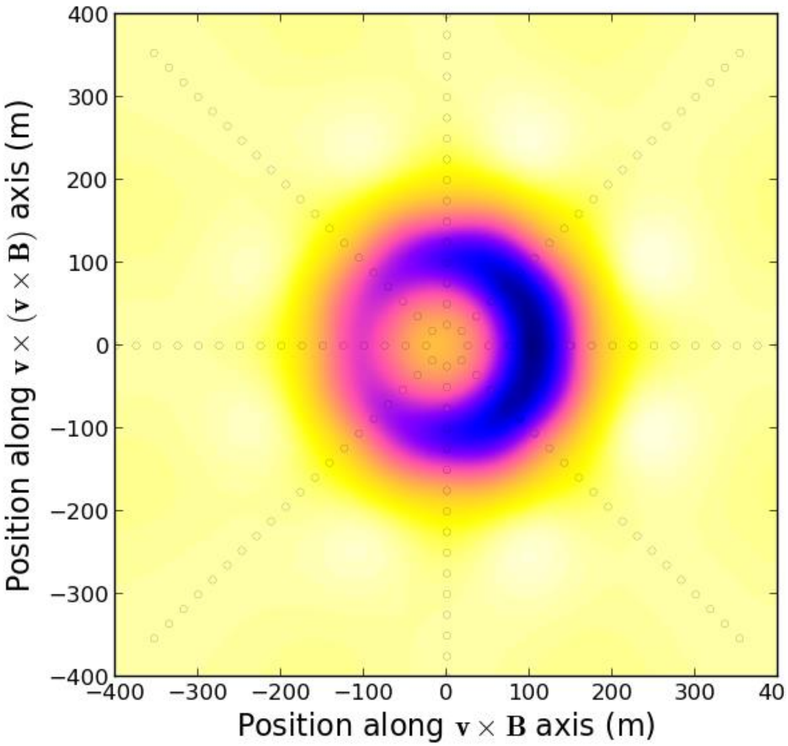
S. Buitink et al., Phys Rev D (2014), arXiv:1408.7001

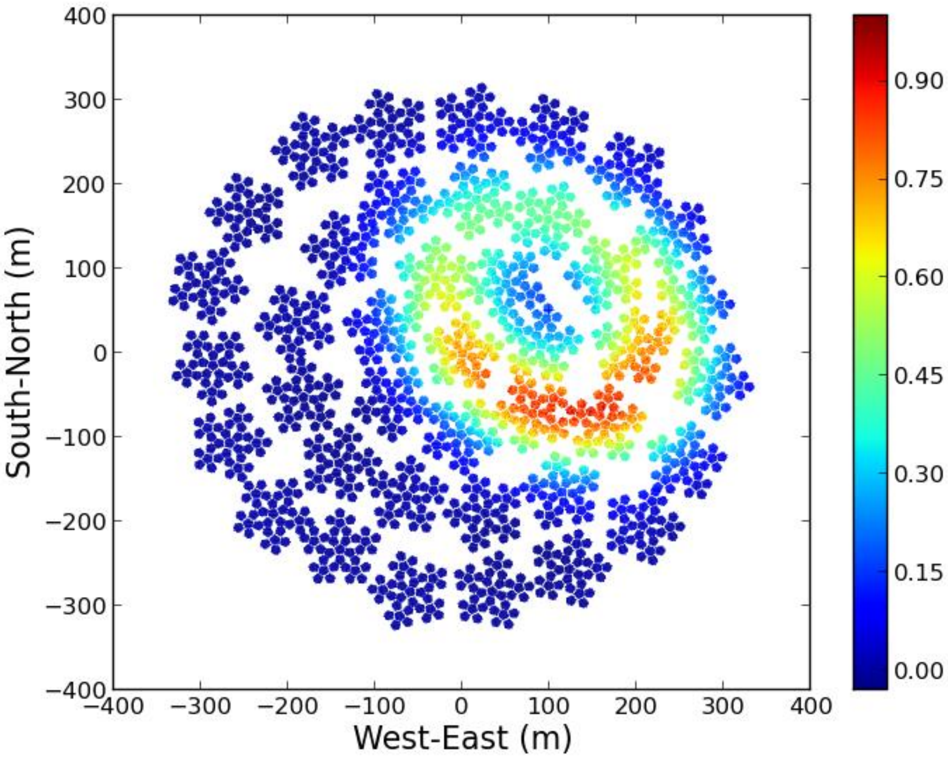
SKA will provide very detailed radio footprint



- **Xmax determination with ~10 g/cm^2 resolution seems feasible!**

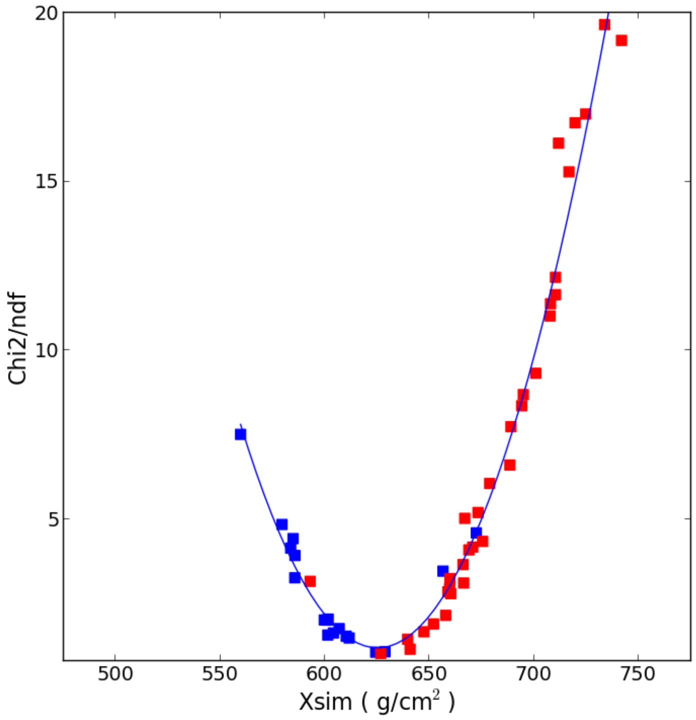
CoREAS simulation study on Xmax precision

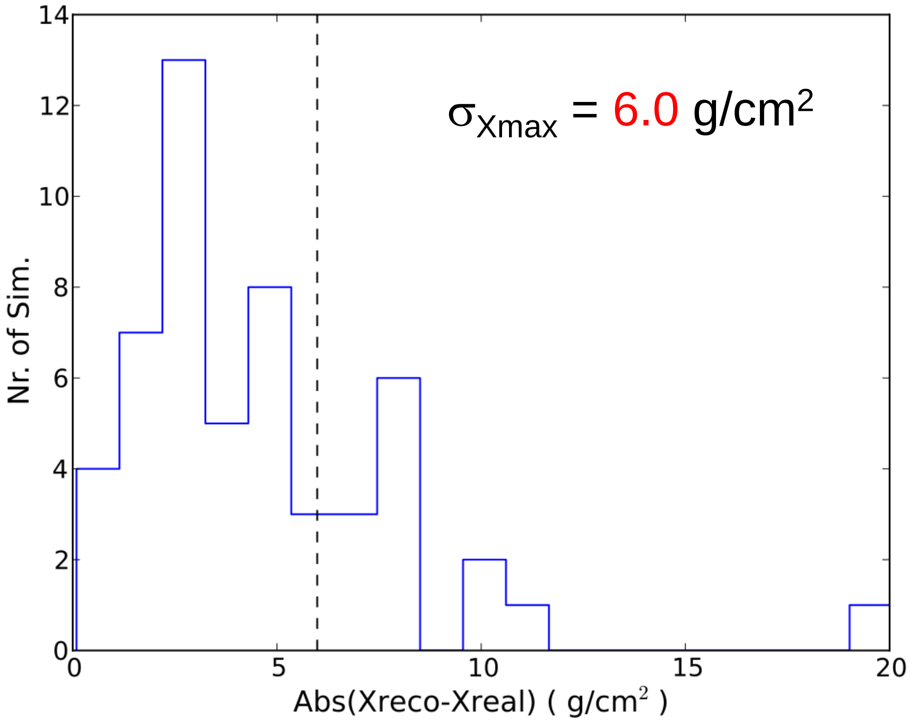




- take one simulation, add noise, pretend it is a measurement

CoREAS simulation study on Xmax precision

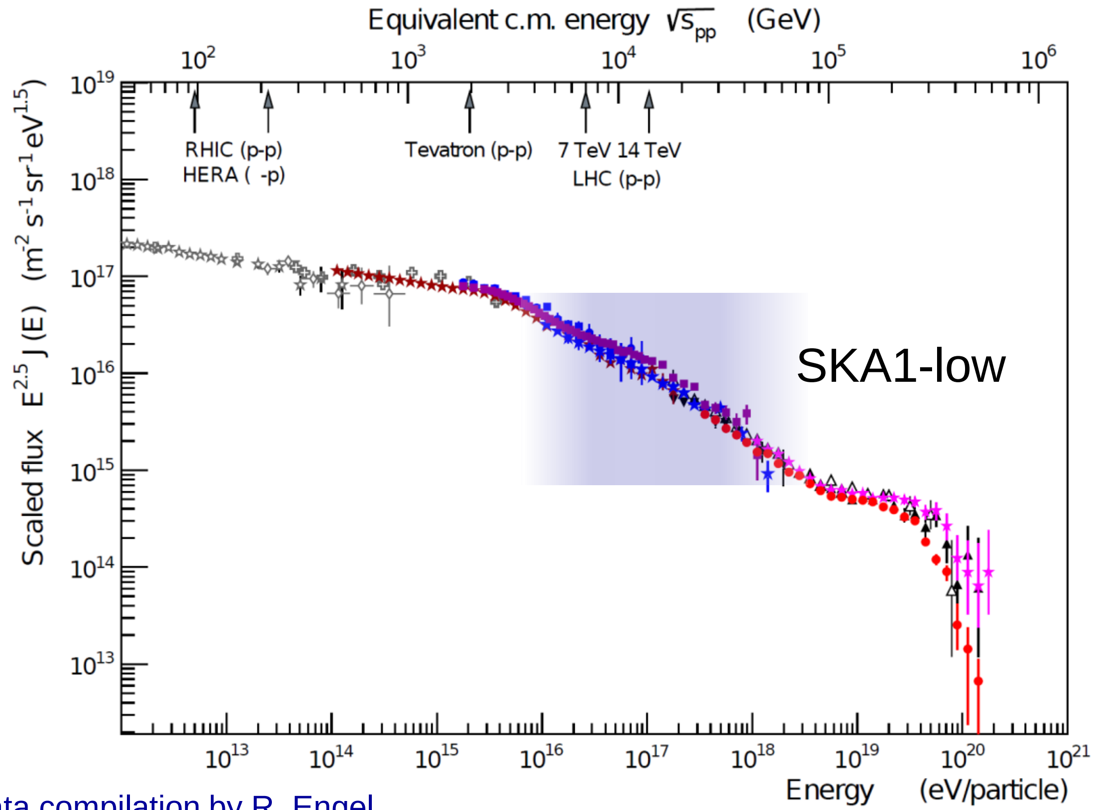




- reconstruct fake data with other sims, take Xmax offset, repeat

Science Potential

High-precision composition measurements



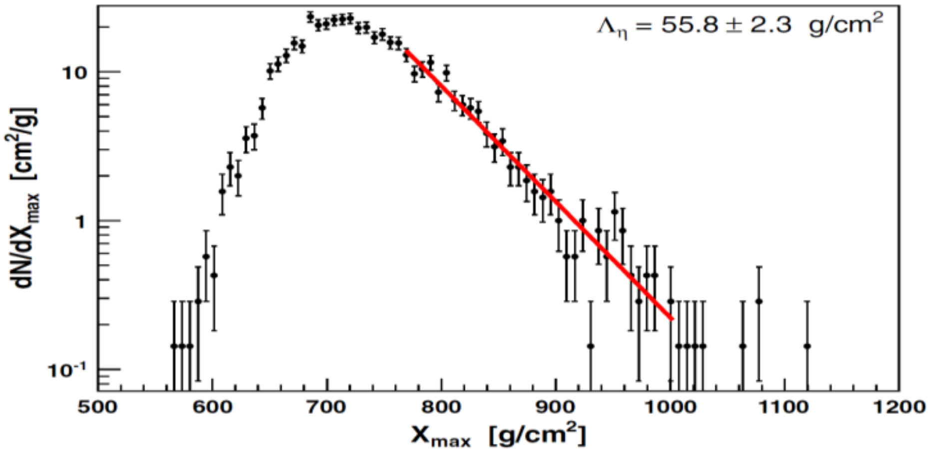
Data compilation by R. Engel

- very precise mass composition studies from ~10^{16} to ~10^{18} eV
- possibly decompose in individual elements, in particular p vs. He
- study transition from Galactic to extra-galactic origin
- composition-sensitive anisotrpy?

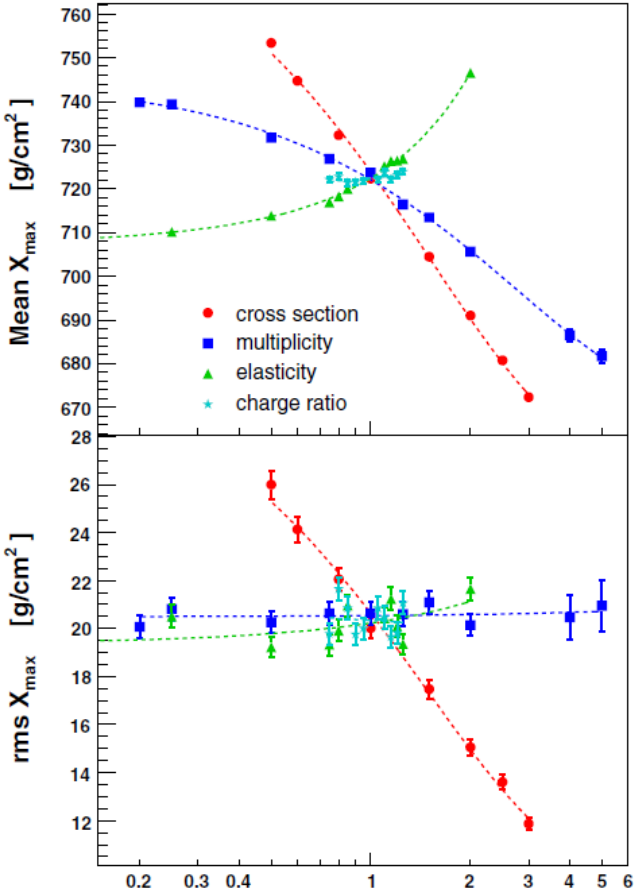
Tim Huege <tim.huege@kit.edu>

Particle and shower physics via Xmax

- hadronic particle production cross sections
- multiplicity of secondaries in interactions
- elasticity (E_leading/E_tot)
- pion charge ratio



Pierre Auger Collaboration, PRL 109 (2012) 062002

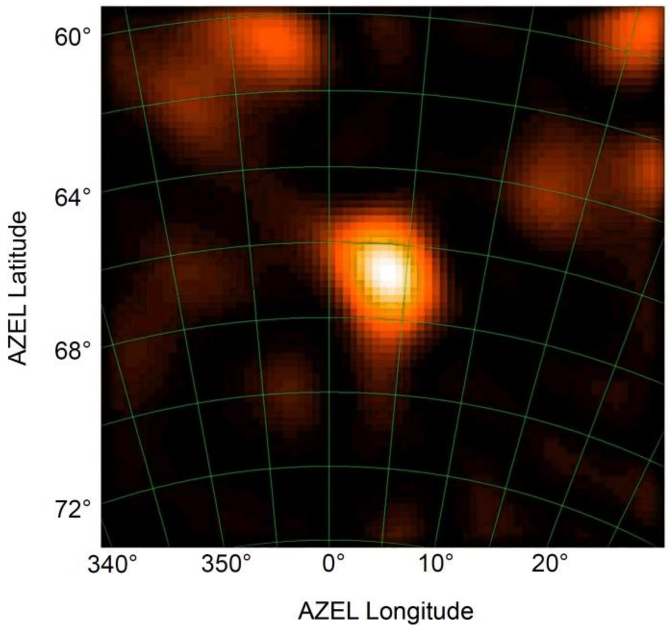


Ulrich, Engel, Unger, PRD 83 (2011) 054026

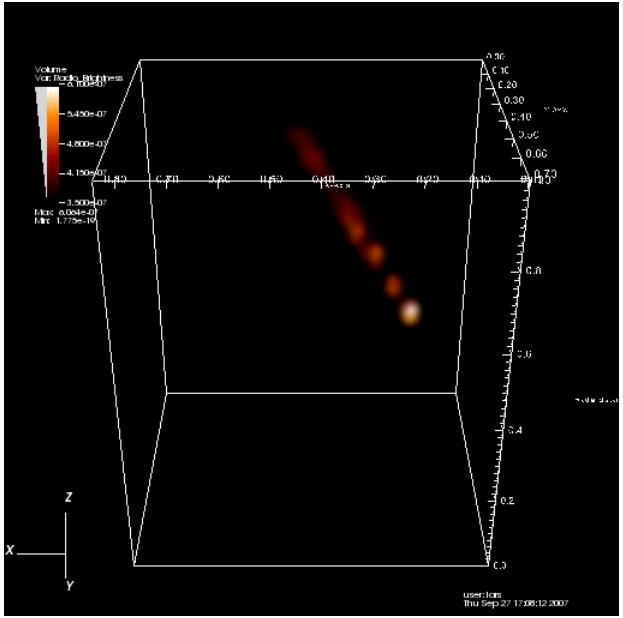
Tomography of electromagnetic cascade

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

LOPES Coll., Nature 2005



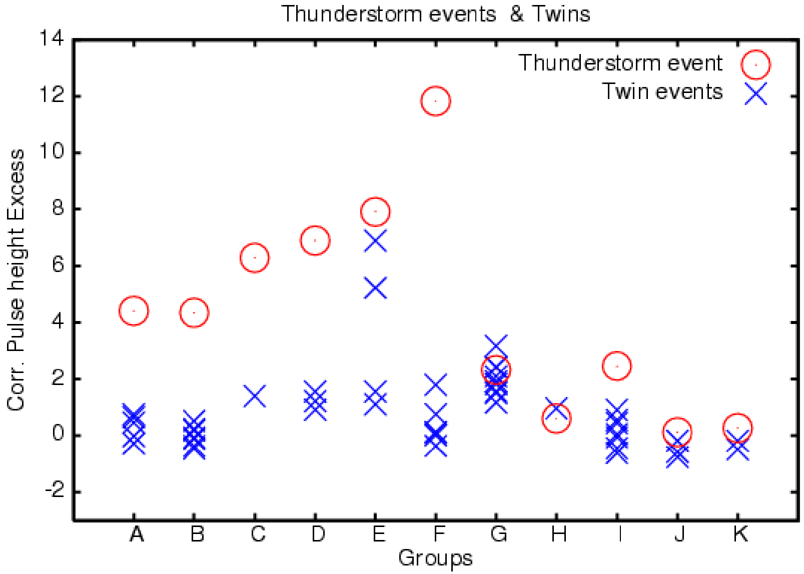
LOPES, „far-field interferometry“



tomography with „near-field interferometry“

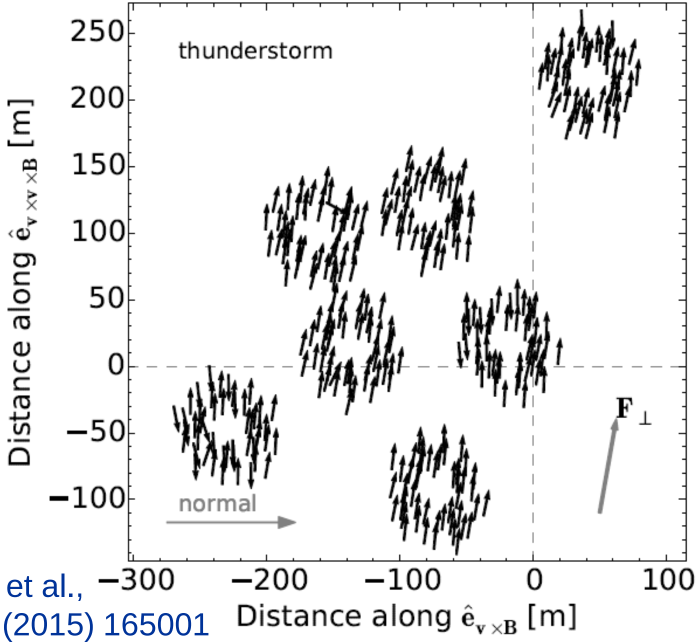
Physics of thunderstorms and connections to EAS

- atmospheric electric fields influence EAS radio emission



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

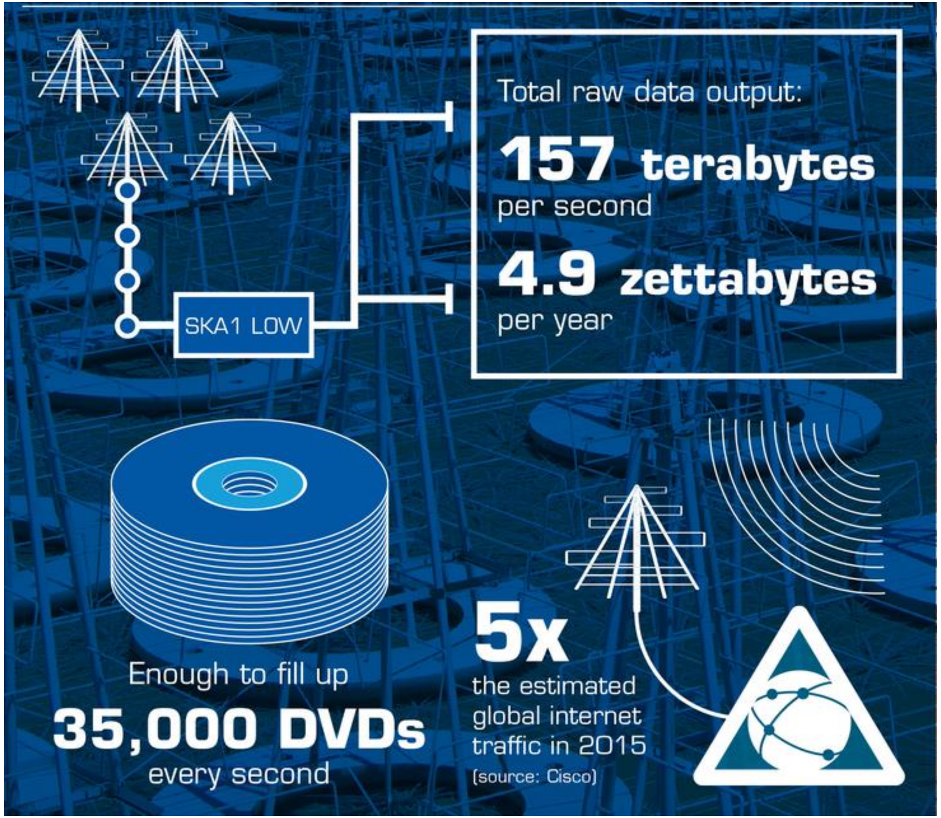
- LOFAR deduced thunderstorm electric fields from CR data



Schellart et al., PRL 114 (2015) 165001

How to make it work …

Baseline-SKA is unsuitable for CR detection



- raw data rate much too high, so signals from individual antennas are combined and beam-formed on the fly
- but: buffers will be available, used on station-level for search for astronomical transients, e.g. fast radio bursts

Engineering change proposal for CR detection

Enabling detection of cosmic ray air showers with SKA-low

T. Huege[1], J.D. Bray[2], S. Buitink[3], R. Dallier[4,5], R.D. Ekers[6], T. Ensslin[10], H. Falcke[15,7], N. Hashim[13], A. Haungs[1], C.W. James[8], K. Mack[12], L. Martin[4,5], J. Rautenberg[11], B. Revenu[4], O. Scholten[9,3], R. Spencer[2], F.G. Schröder[1], S. Tingay[14] and A. Zilles[1]

[1]KIT; [2]Univ. of Manchester; [3]Vrije Universiteit Brussel, Belgium; [4]Subatech, Nantes; [5]Station de radioastronomie de Nançay; [6]CSIRO ATNF; [7]ASTRON; [8]Univ. of Erlangen-Nuremberg; [9]Univ. of Groningen; [10]Max-Planck-Institut für Astrophysik, Germany; [11]Bergische Universität Wuppertal, Germany; [12]University of Melbourne, Australia; [13]Kenyatta University, Kenya; [14]ICRAR, Curtin, Australia; [15]Radboud Univ. Nijmegen

July 15, 2015

1 Executive summary

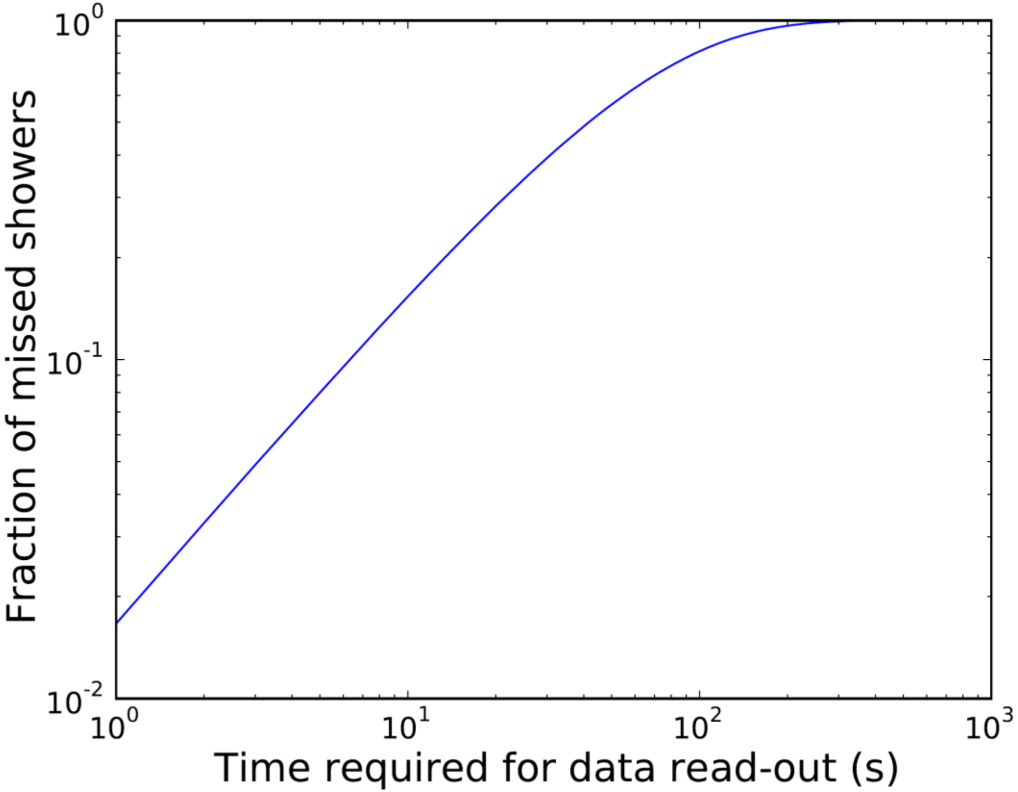
With a modest effort, the core of SKA-low can be enabled for the detection of cosmic ray air showers. The homogeneity and high density of radio antennas in the core as well as the large bandwidth from 50 to 350 MHz would make SKA-low the most precise cosmic ray radio detector in the world. SKA-low would be able to study the mass composition of cosmic rays in the region of transition from Galactic to extragalactic cosmic rays, particle physics beyond the reach of the LHC, and potential relations between cosmic rays and thunderstorm physics. Cosmic ray observations would be 100% commensal with other SKA-low observation modes and would also provide a valuable tool for low-level diagnostics, especially for transient RFI. The necessary design changes would essentially be two-fold: a) Continuously buffer the raw data at individual antennas in the SKA-low core for the time that is needed to receive trigger information on the arrival of a cosmic ray air shower. b) Deploy a particle detector array (funded by the proponents) that meets SKA-low RFI/EMI requirements, is integrated in the SKA design with respect to power and data readout, and provides the trigger for the readout of the antenna buffers. The feasibility of this approach has already been demonstrated successfully within LOFAR [1].

- an initial engineering change proposal was rejected – during descoping process
- a new, improved ECP was submitted in July 2015, decision pending, currently in stage 4 of 6

Antenna buffering

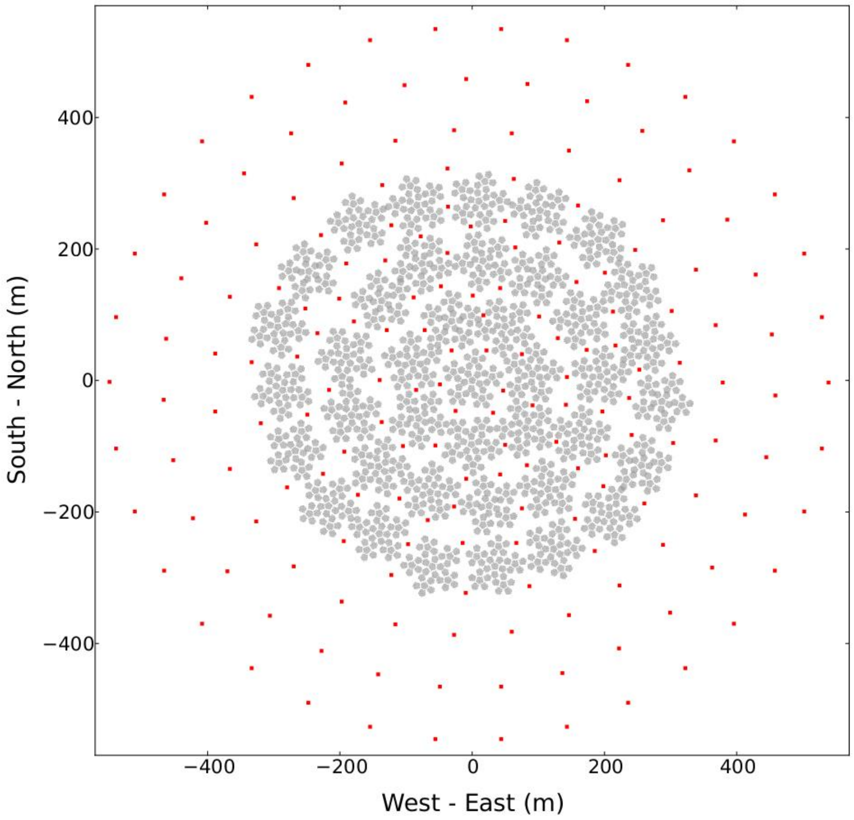
- air shower detection needs individual-antenna signals
  - continuously buffer individual-antenna raw-data
    - 800 MHz sampling
    - at least 8 bit, preferably 12 bit dynamic range
    - buffer depth determined by trigger latency (10 ms)
    - 1.4 TeraBytes of buffer for 60,000 antennas
    - in parallel with any other buffering activities (100% duty cycle)
  - read out 50 microseconds upon an external air shower trigger
    - 7.2 GigaBytes per event for 60,000 antennas

Deadtime versus read-out time



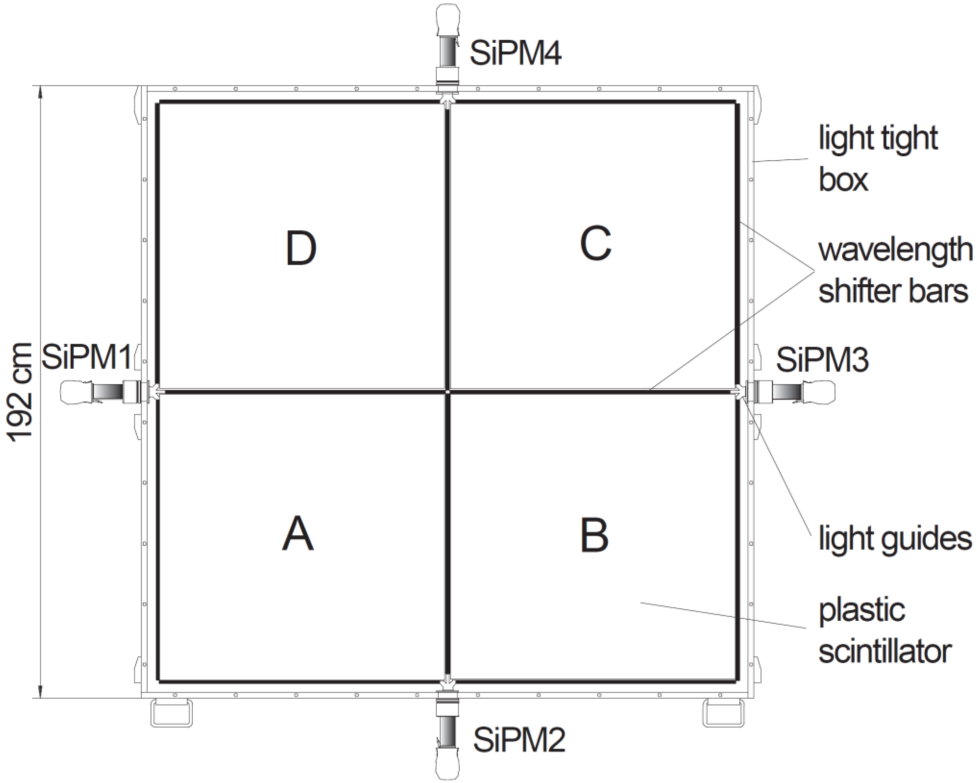
- estimated rate: 1 shower per minute at 10^{16} eV
- resulting average data rate of 120 Mbyte/s is small compared to other SKA data streams – but Poissonian distribution!
- bursts of 2.4 GigaByte/s for 3 s of each minute will lead to ~3% deadtime

Triggering particle detector 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
- 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, …)

Particle detector array – details



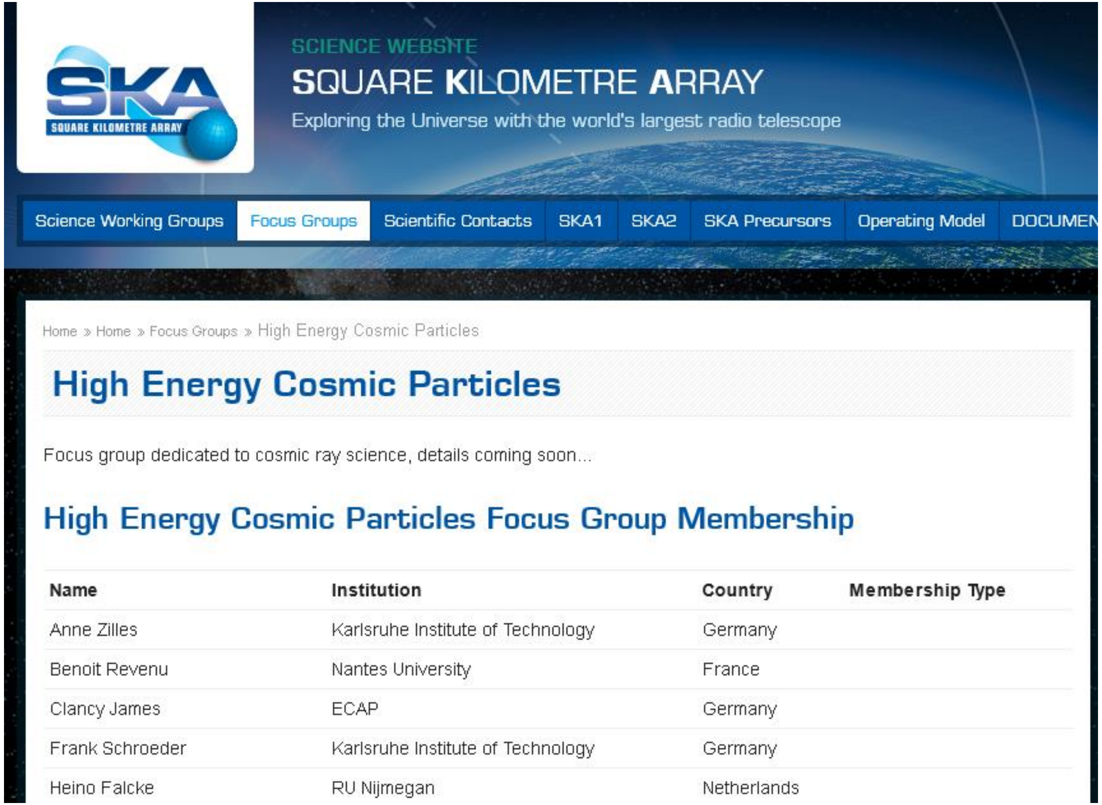
- 180 particle detectors of 3.6 m^2 area and 3 cm thickness are available from KASCADE
- worth 1,000,000 EUR, will be provided by the proponents
- need 720 additional readout channels (4 per Scintillator), cf. 120,000 existing ones
- need 720 SiPMs, ensure RFI-quietness
- possibly shield/bury part of detectors for muon separation

Diagnostic benefits for SKA

- monitoring of transient sky
- low-level diagnostics on antenna level
  - broken antenna elements
  - mismatched cabling, swapped polarisations
  - timing precision
  - directivity pattern

Current status

State of the project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Home » Home » Focus Groups » High Energy Cosmic Particles

High Energy Cosmic Particles

Focus group dedicated to cosmic ray science, details coming soon...

High Energy Cosmic Particles Focus Group Membership

Name	Institution	Country	Membership Type
Anne Zilles	Karlsruhe Institute of Technology	Germany	
Benoit Revenu	Nantes University	France	
Clancy James	ECAP	Germany	
Frank Schroeder	Karlsruhe Institute of Technology	Germany	
Heino Falcke	RU Nijmegan	Netherlands	

- have become an „SKA focus group“
- have submitted a detailed „Engineering Change Proposal“, in review stage 4 of 6
- are on a tight schedule, first data expected 2020
- R&D work on particle detectors re readout, … to start soon

Conclusion

- SKA1-low can be enabled for cosmic ray detection
  - 100% commensal observations
- it would be a unique radio detector („ultimate detail in measurements“)
- 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