Karlsruhe Institute of Technology

A dense radio array with a good muon detector

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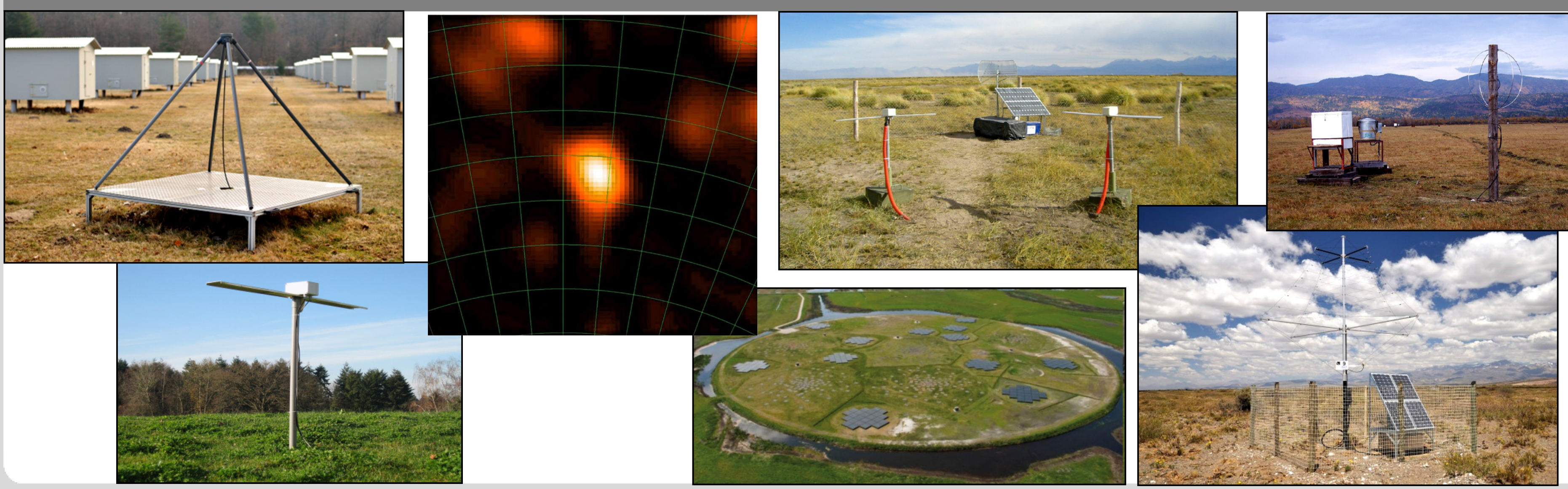
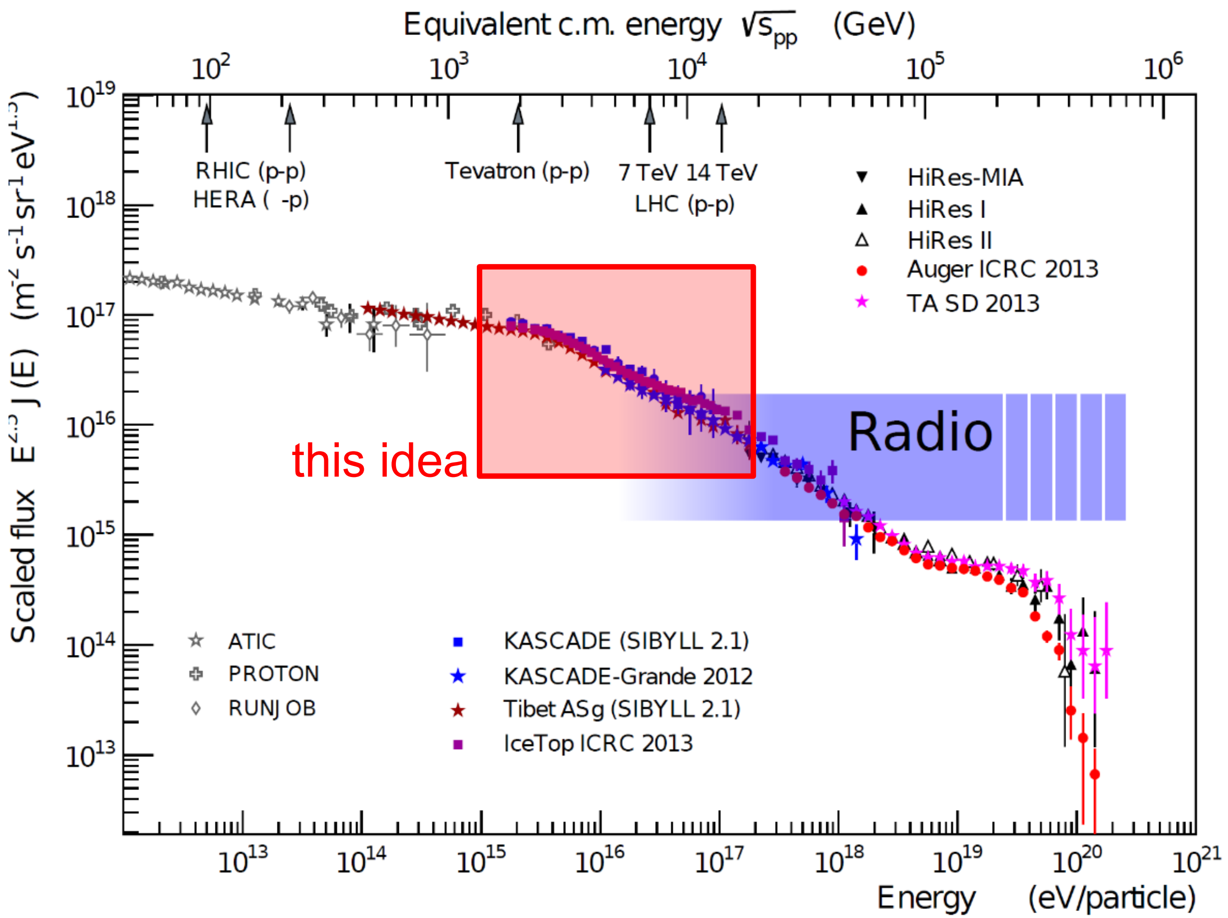


Executive Summary

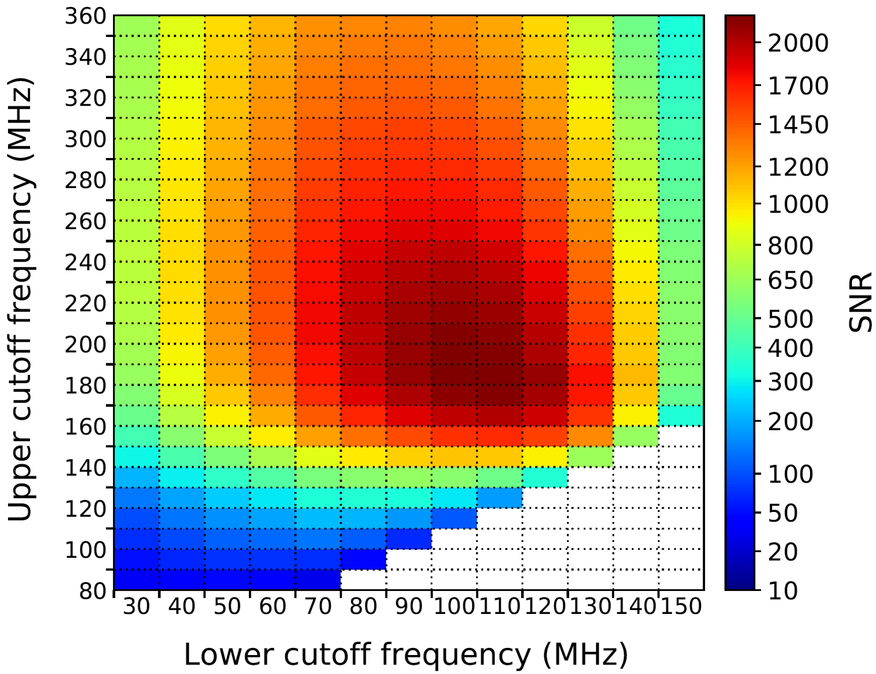
- combine very dense radio array with a good muon detector on ~1 km^2
- study transition region from few times 10^{15} eV to few times 10^{17} eV

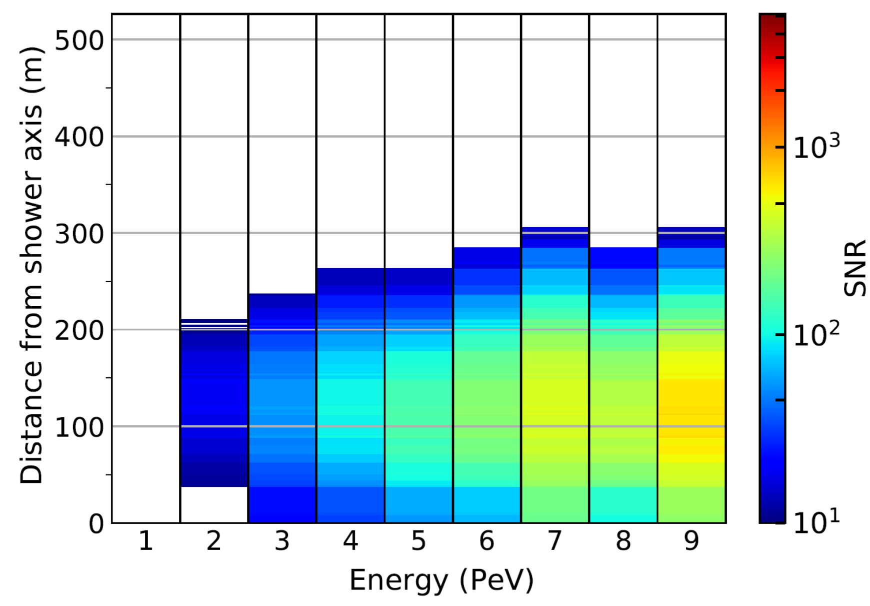


T. Huege, Phys. Rep. 620 (2016) 1
adapted from R. Engel

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

Radio benefits

- accurate (~10%) measurement of energy in electromagnetic cascade
  - atmospheric conditions not critical
  - allows energy-scale calibration from first-principles calculations

    Pierre Auger Collaboration, PRL 116 (2016) 241101
    Gottowik et al., Astrop. Phys. 103 (2018) 87
- Xmax sensitivity from lateral signal distribution („source distance“)
- can be operated with 100% duty cycle
- very complementary to muon measurements

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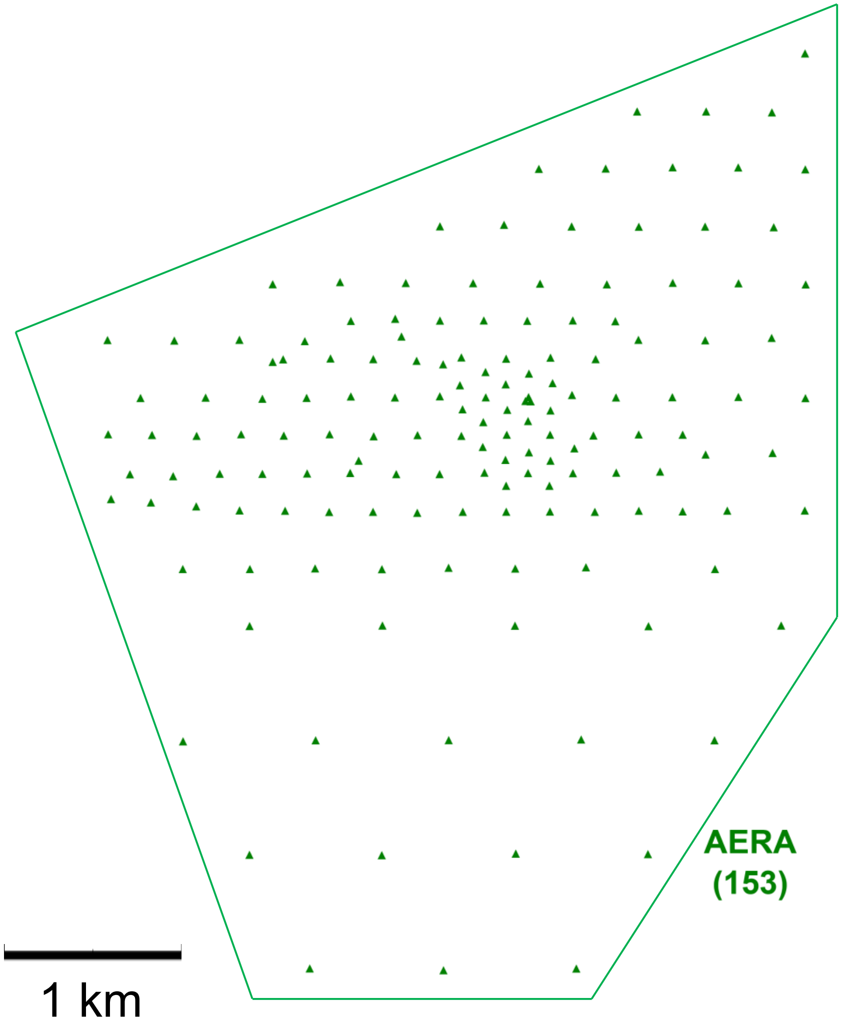
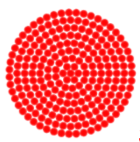
Sparse versus dense radio arrays

- mostly discussed here: sparse arrays aimed at high energies (AERA, Auger Radio Upgrade)
- but dense arrays for energies up to a few 10^{17} eV have proven very powerful

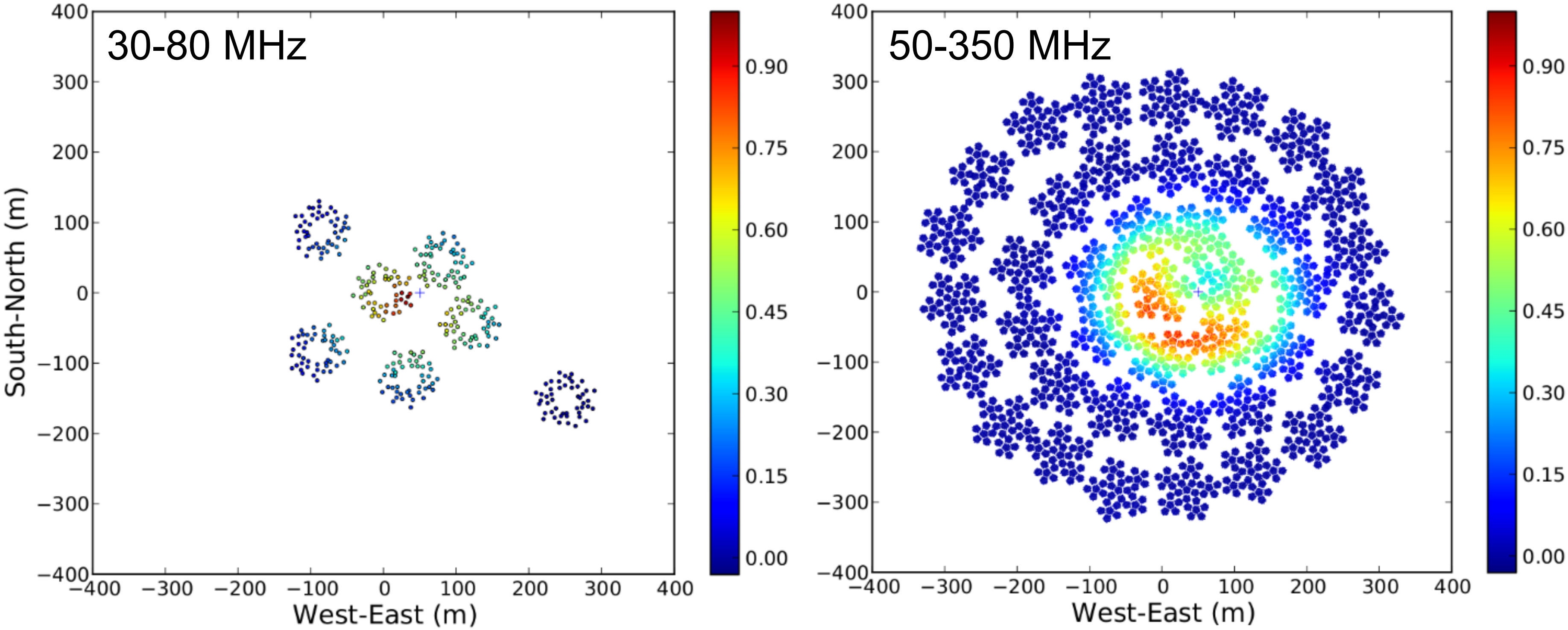


LOFAR - LBA outers



LOFAR and the Square Kilometre Array

- LOFAR achieved an Xmax resolution of ~17 g/cm^2
- the SKA Low-Frequency array could achieve a resolution of ~10 g/cm^2



A. Zilles et al. PoS(ICRC2017)360

- bring particle detectors to SKA as a CR trigger

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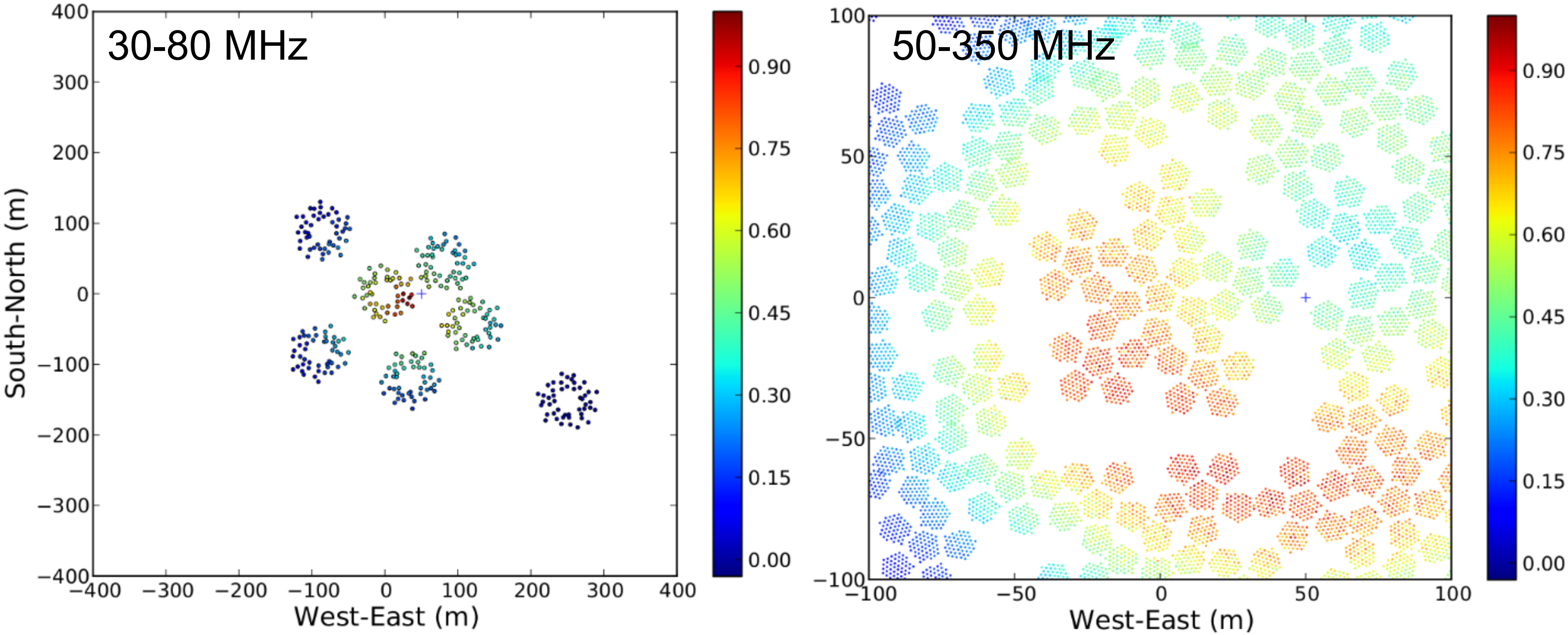
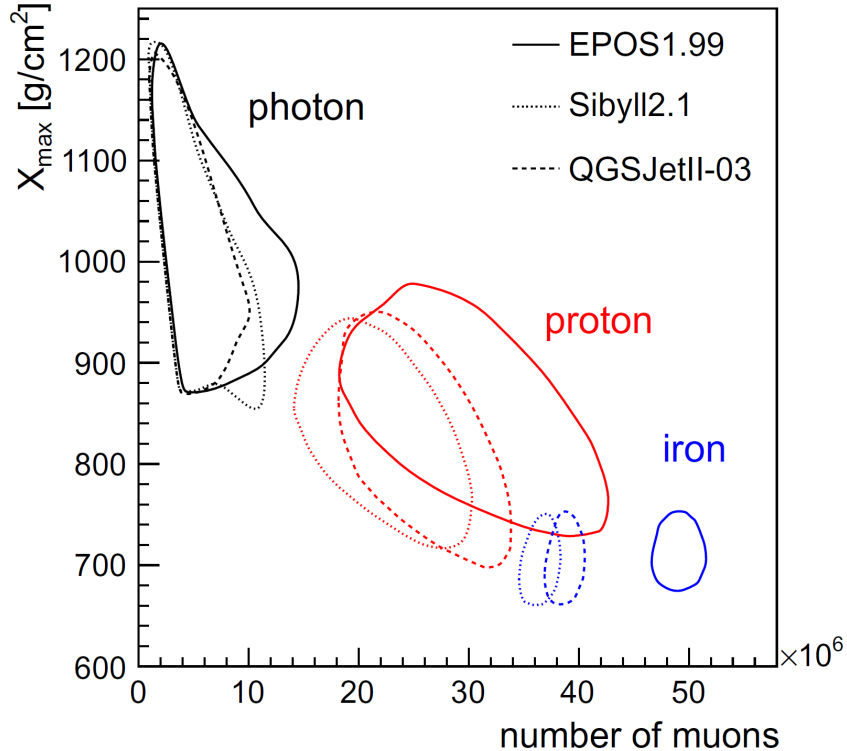


A. Zilles et al. PoS(ICRC2017)360

- bring particle detectors to SKA as a CR trigger

SKA as a cosmic ray detector has drawbacks

- is superior Xmax resolution alone useful? probably not
- combination with muon information could be very useful! but deploying muon detectors at the SKA seems completely unrealistic
- the major cost in SKA is in the (here unused) real-time correlation
- antenna density and other parameters (dynamic range, …) are not optimized for cosmic ray detection

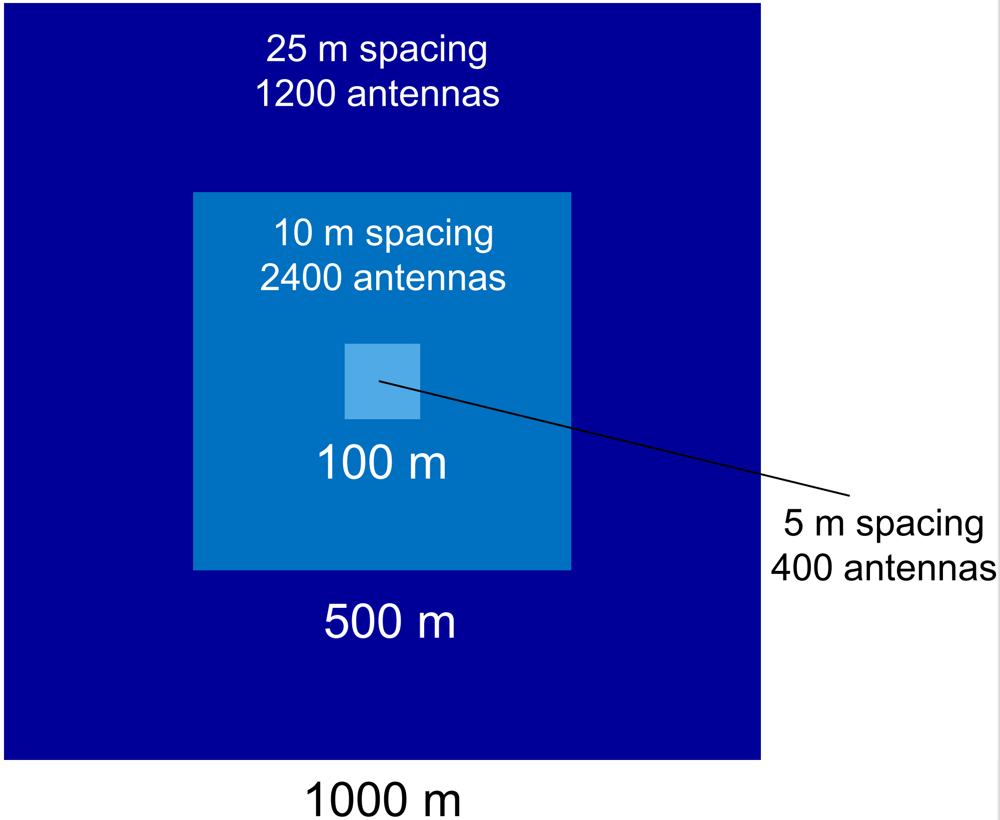


Kampert & Unger, Astrop. Phys. 35 (2012) 660

Bring the antennas to the muon detectors …

- put a very dense radio array at an existing muon detector
  - deploy of order 1000-5000 antennas on 1 km^2
  - graded array for different energy regimes
  - only „dumb“ readout, cabled setup possible
  - probably trigger externally
- obvious option: in the infill of the Pierre Auger Observatory
  - AMIGA muon detectors
  - AERAlet (433 m) or denser sub-array of surface detectors
  - overlooked by HEAT fluorescence detectors

oversimplified ad-hoc example



NB: these are really circles ;-)

How expensive are individual detectors?

- antenna can be cheap, e.g. 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, cables, …)
- sub-1000$ for antenna plus digital electronics seem feasible
- project of order <5 MUSD

Conclusion

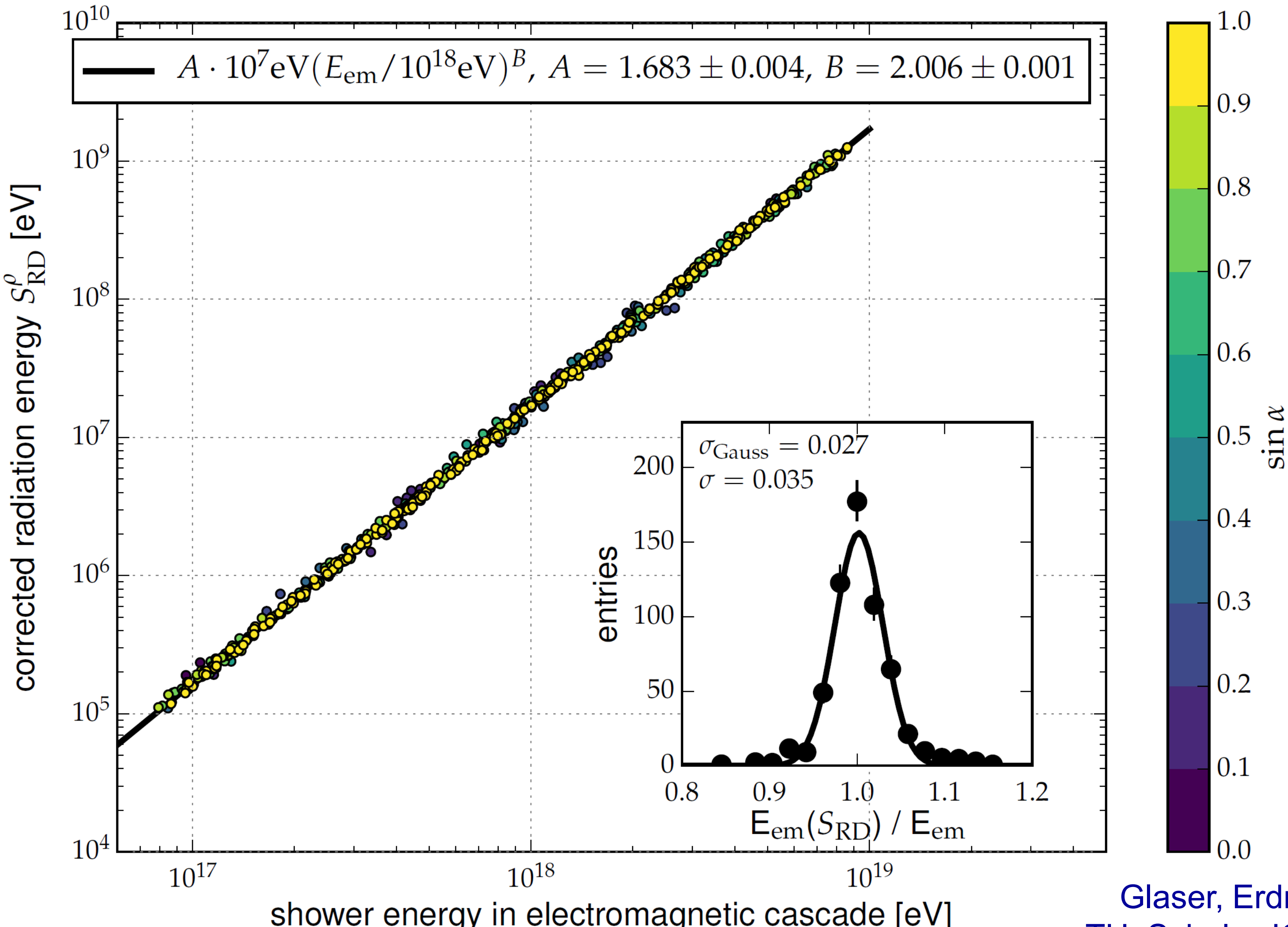
- we now know pretty well what radio can do
- sparse arrays allow measurements at highest energies
- dense arrays yield very accurate information at lower energies
  - energy in electromagnetic cascade with 10% resolution
  - Xmax as good as 10 g/cm^2
- it might be worthwhile to combine a very dense radio array (~1000-5000 antennas on 1 km^2) with a high-quality muon detector
  - composition-sensitive anisotropy in the transition region
  - precision studies of air shower physics

Backup Slides

Other considerations

- obviously should be properly simulated, tools exist
- detection-dependent energy threshold: anisotropy studies challenging
- RFI-quiet site would be preferred (Auger infill region is not quiet)
- current radio analysis approaches do not use all available information
  - phase information (interferometry)
  - wavefront curvature
  - polarization
- technically feasible; real question to discuss: is it worth doing?

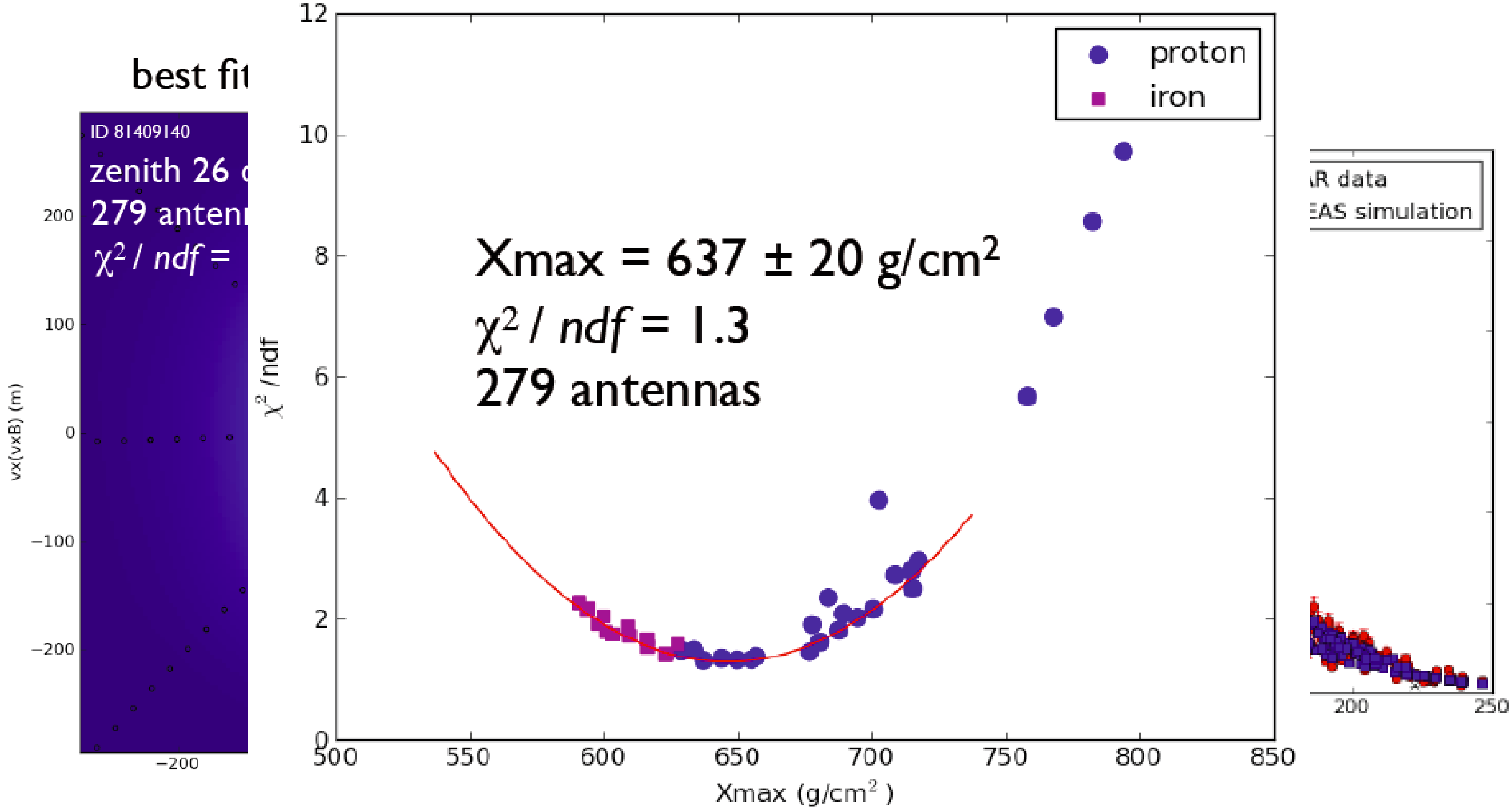
Radiation energy and electromagnetic energy



- 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

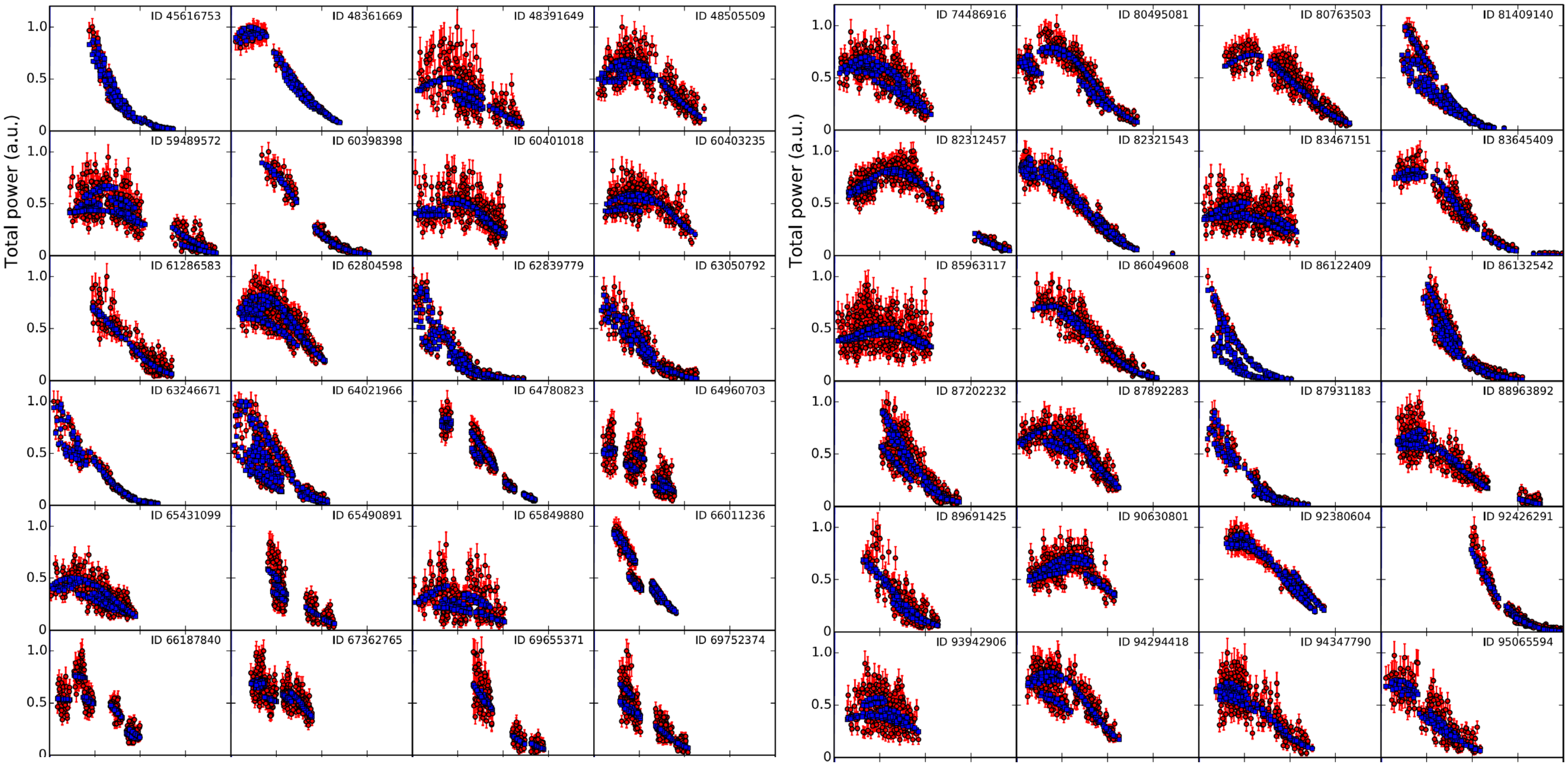
Fit of LOFAR particle and radio data



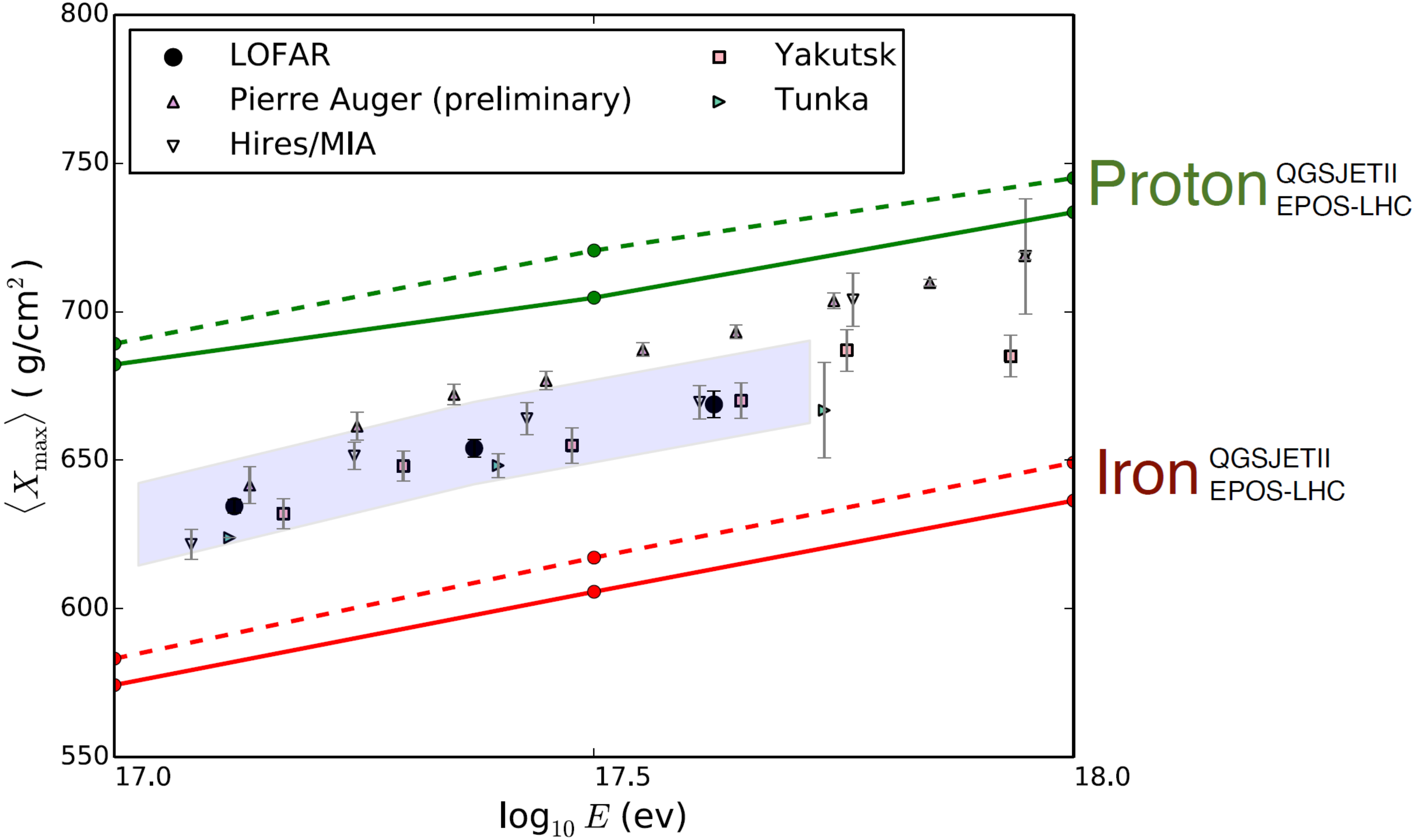
- data fit to CoREAS simulations gives Xmax to ~17 g/cm^2

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

Wealth of information in dense measurements

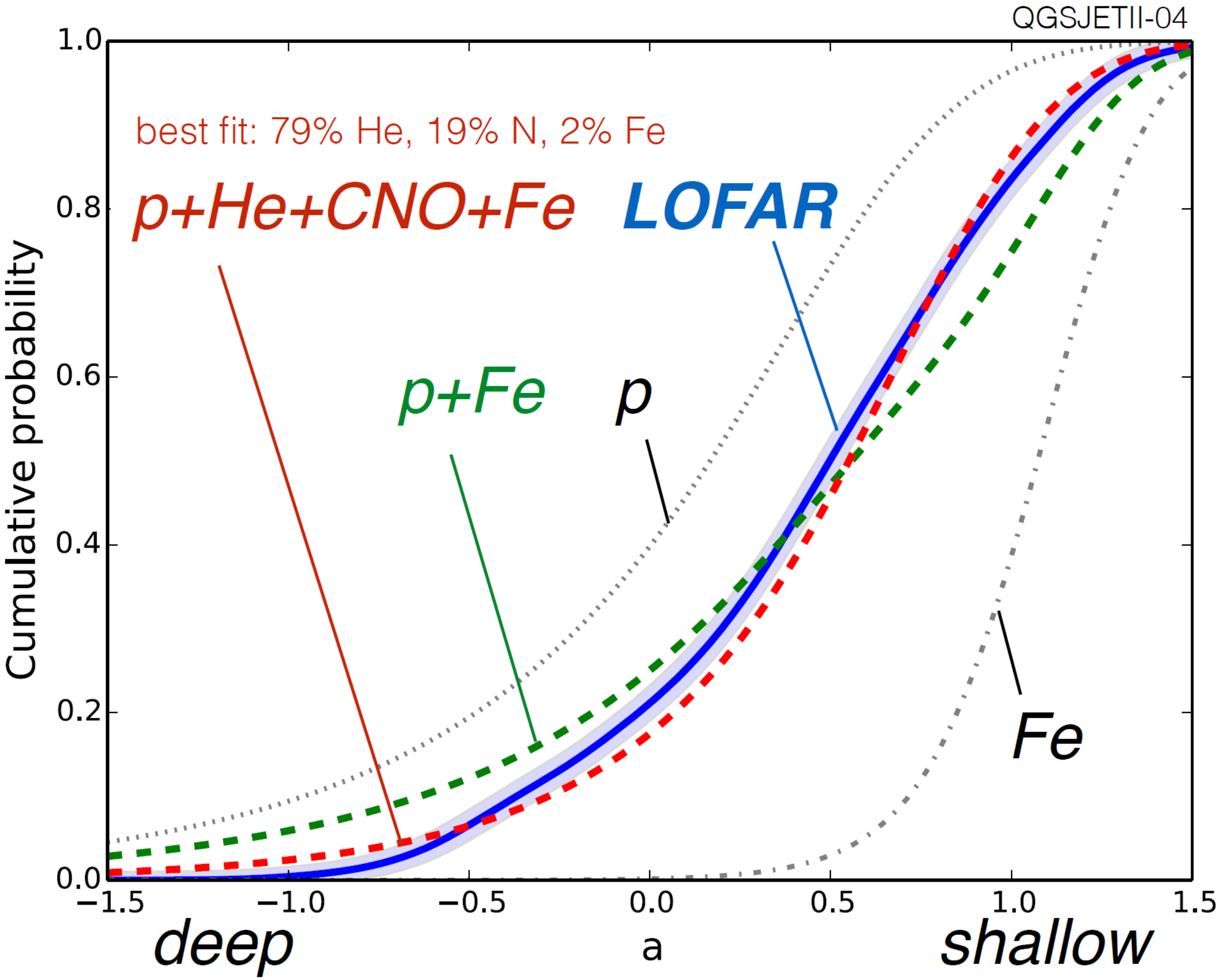


Lofar <Xmax> results



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

LOFAR unbinned analysis



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

- compare measured distribution of

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

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

Very dense arrays - Square Kilometre Array

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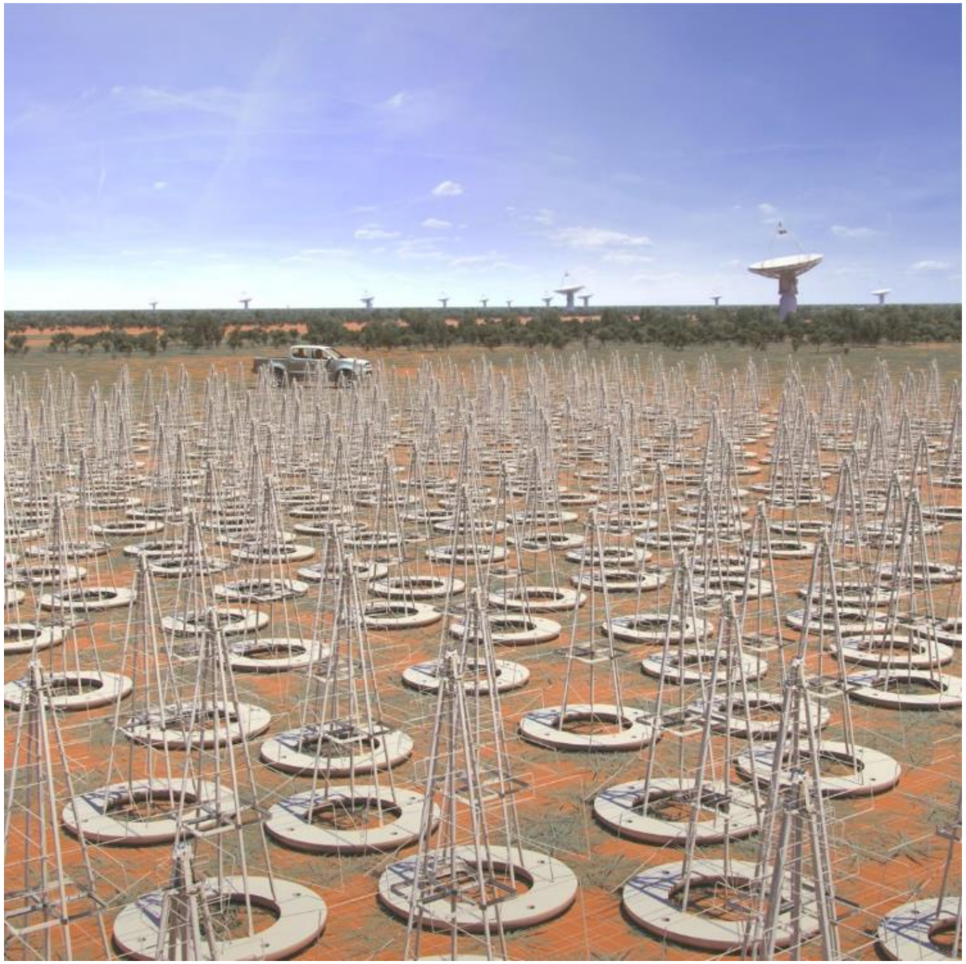

- in the final design stages
- to be built in western Australia
- first science 2020
- planned completion 2023
- >70,000 dual-polarized antennas within 750 m diameter
- bandwidth 50-350 MHz
- can be used for air shower detection with minor additions
- precision measurements in energy range of ~$10^{16.5}$ to $10^{18.5}$

TH et al., ARENA2016 conference, arXiv:1608.08869

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