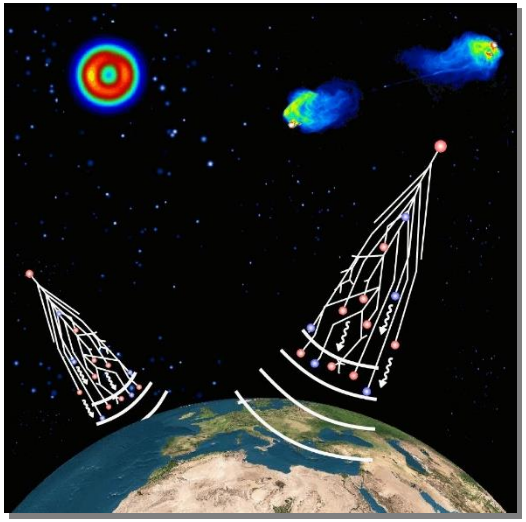
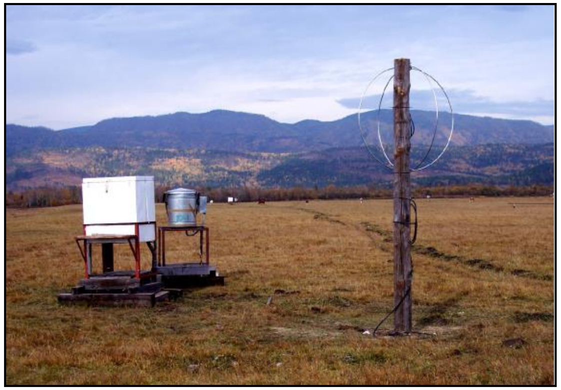
Short review and prospects of radio detection of high-energy cosmic rays

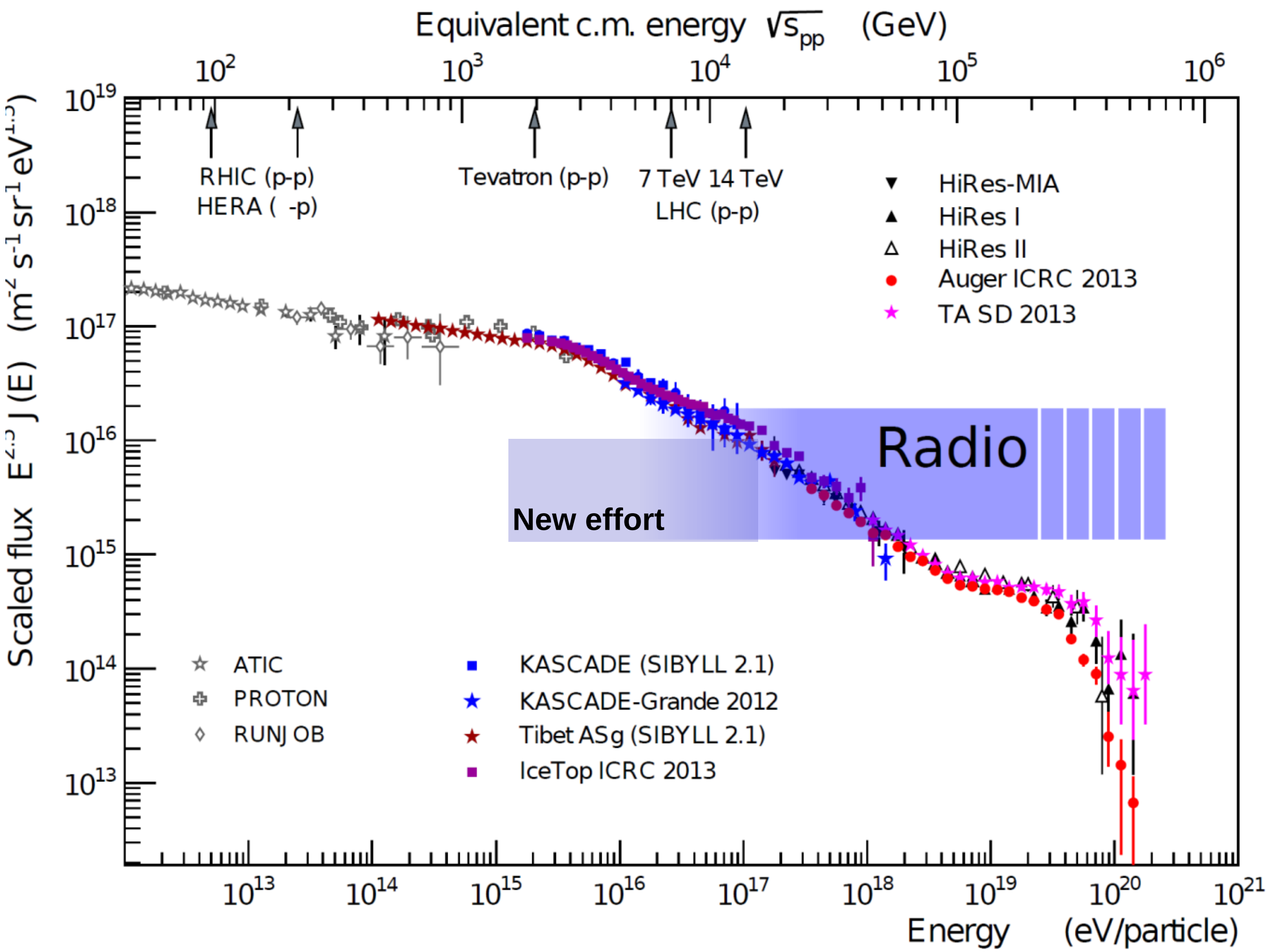




To understand the sources of cosmic rays …

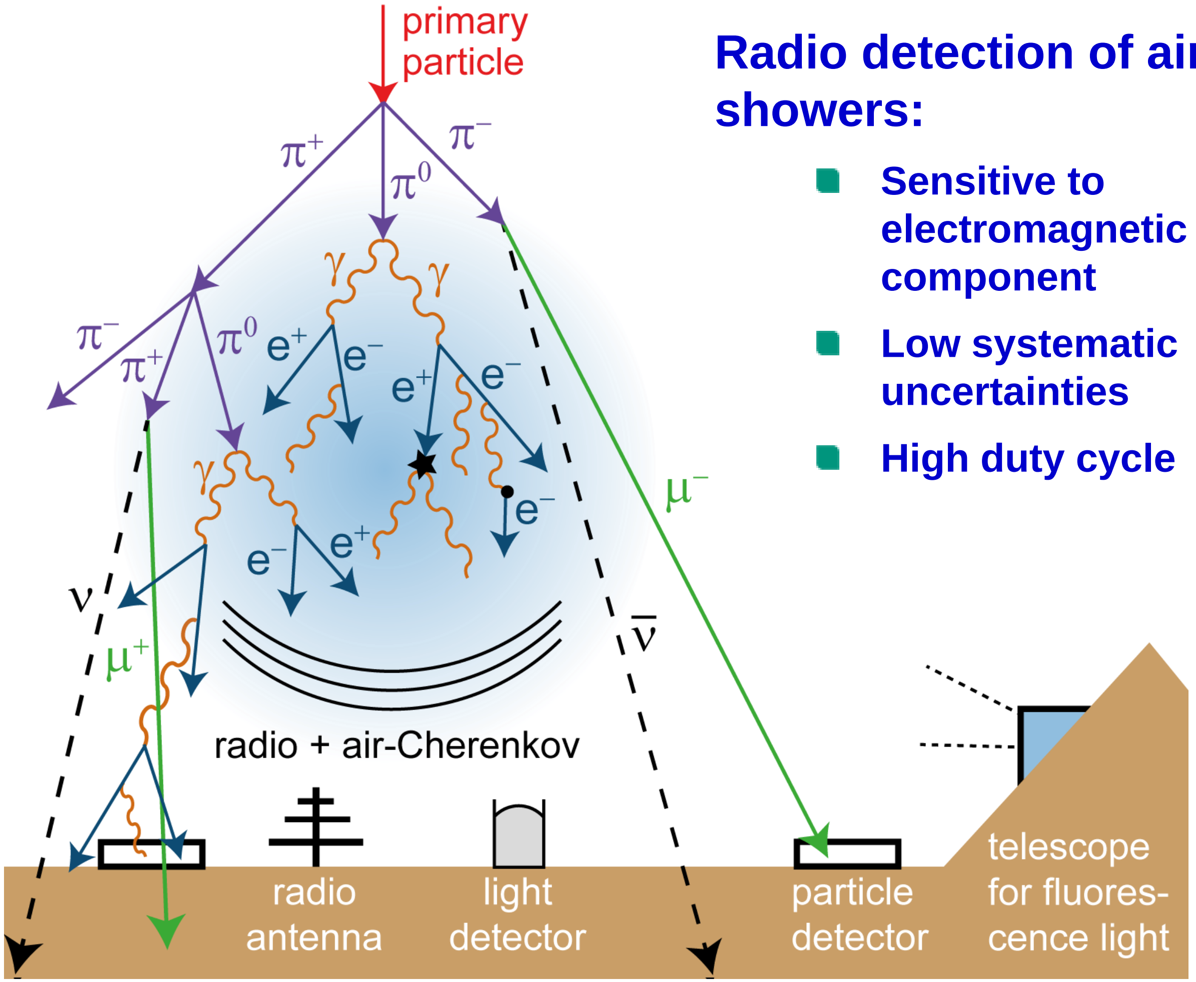
- **we need to know their**
  - **arrival direction**
  - **energy**
  - **and mass**

- **we need large statistics**
  - **large effective areas and high duty cycles**



adapted from R. Engel

Measurements of Air Showers



Radio detection of air showers:

- Sensitive to electromagnetic shower component
- Low systematic uncertainties
- High duty cycle

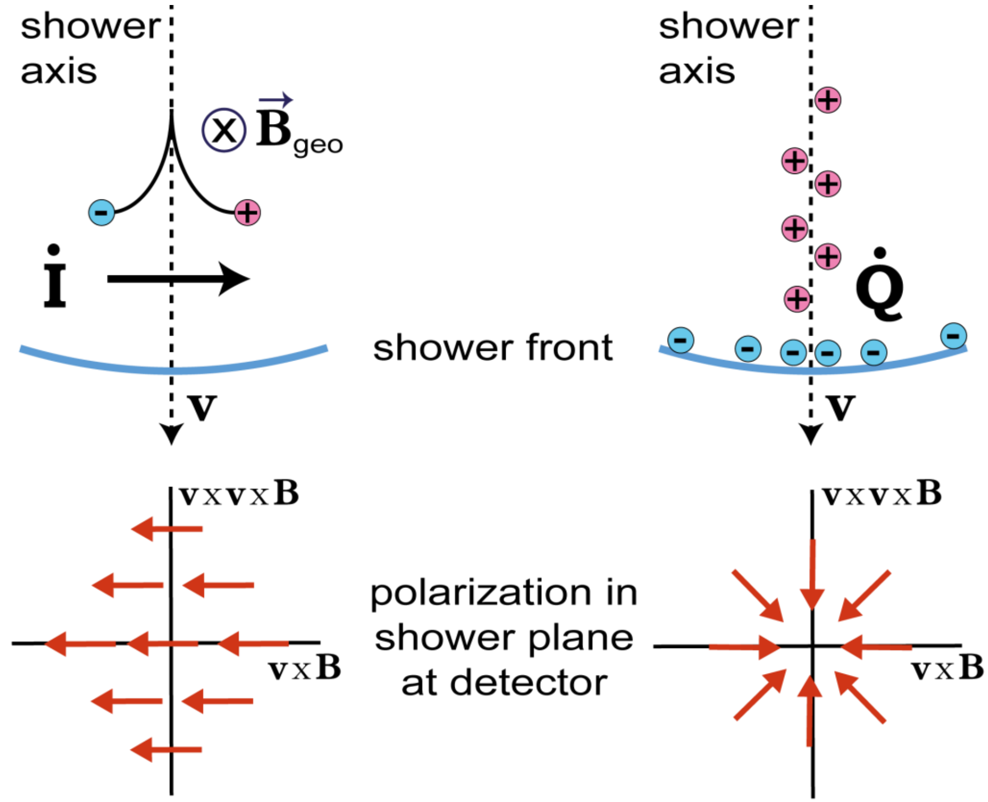
Frank Schröder; Prog. Part. Nucl. Phys. 93 (2017) 1-68 arXiv: 1607.08781

Radio from Air Showers

Detection principle:

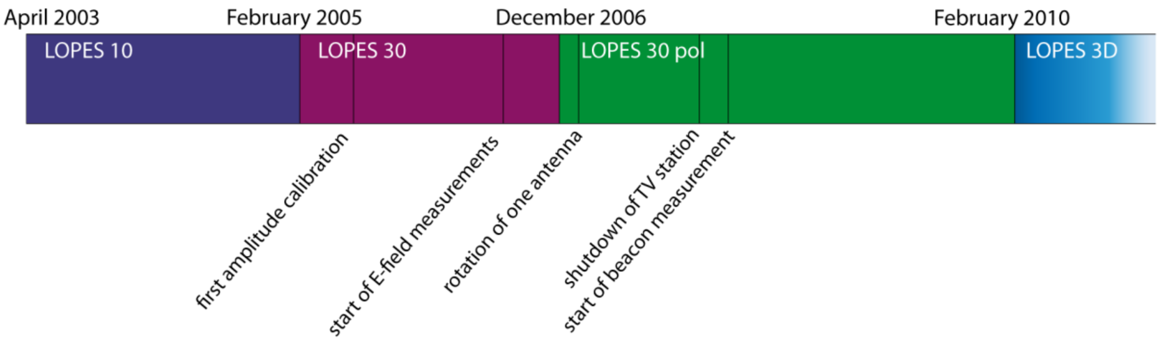
-Geomagnetic deflection of electrons and positrons
-Time-variation of number of charged particles
-Time-variation of charge excess radiation
-and possibly more (refraction index)

➔ lead to coherent emission in atmospheric air showers (initiated by UHECR)
- MHz (GHz) frequency range !
- µV/m-range amplitude
- few ns duration

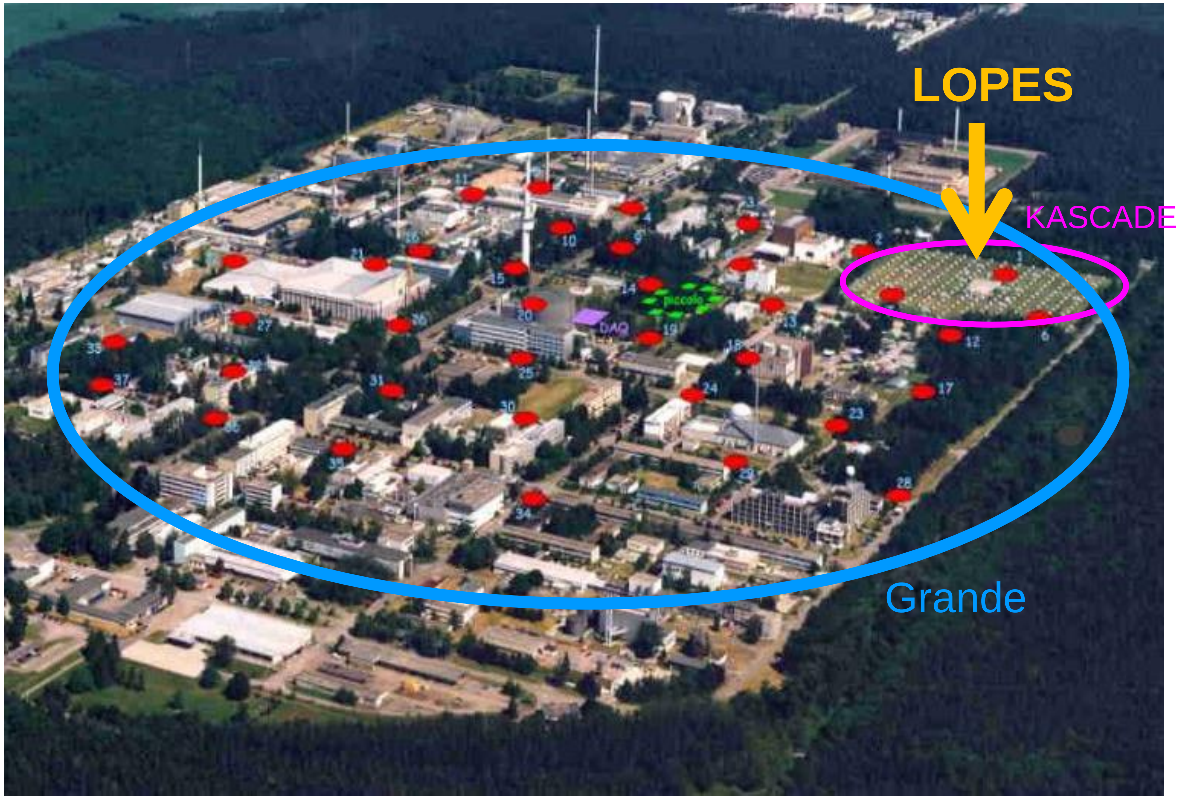


geomagnetic effect ~ 90%   Askaryan effect ~ 10%

LOPES



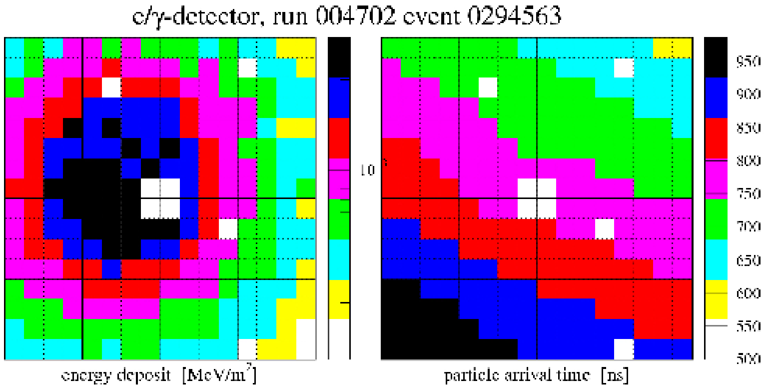
LOPES collaboratio
-) KASCADE-Grande
-) U Nijmegen, NL
-) MPIfR Bonn, D
-) Astron, NL
-) IPE, FZK, D



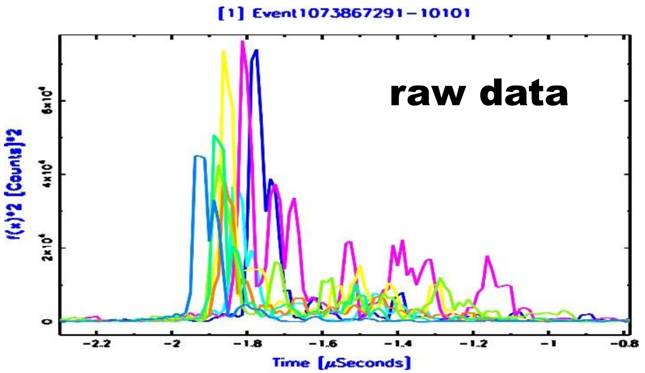
➔Development of a new detection technique!

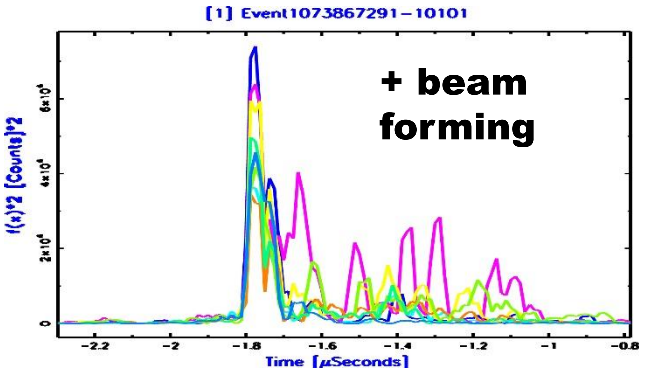
LOPES: Proof of principle

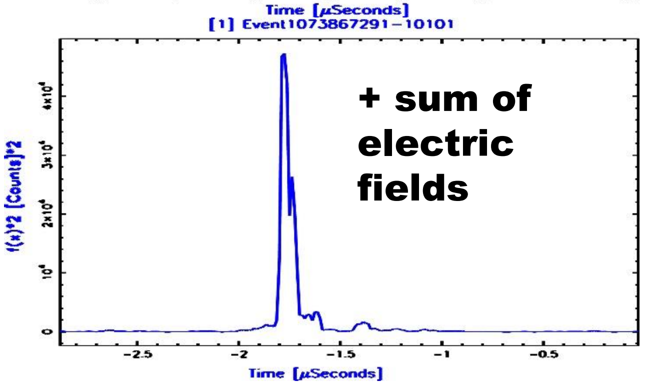
1. KASCADE measurement



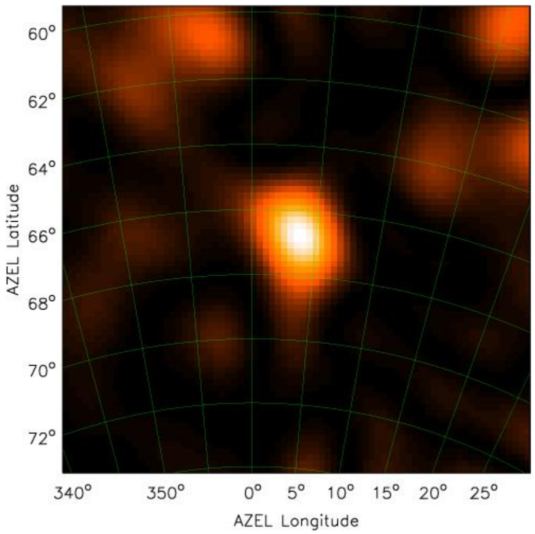
2. Radio data analysis



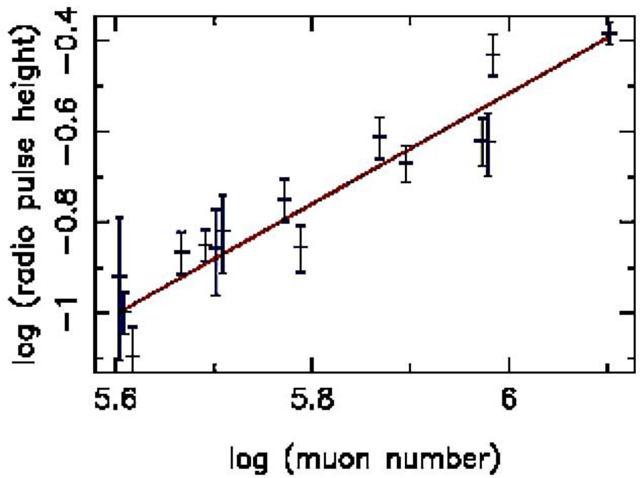




3. Skymapping



4. Many events



LOPES collaboration, Nature 425 (2005) 313

Radio from Air Showers

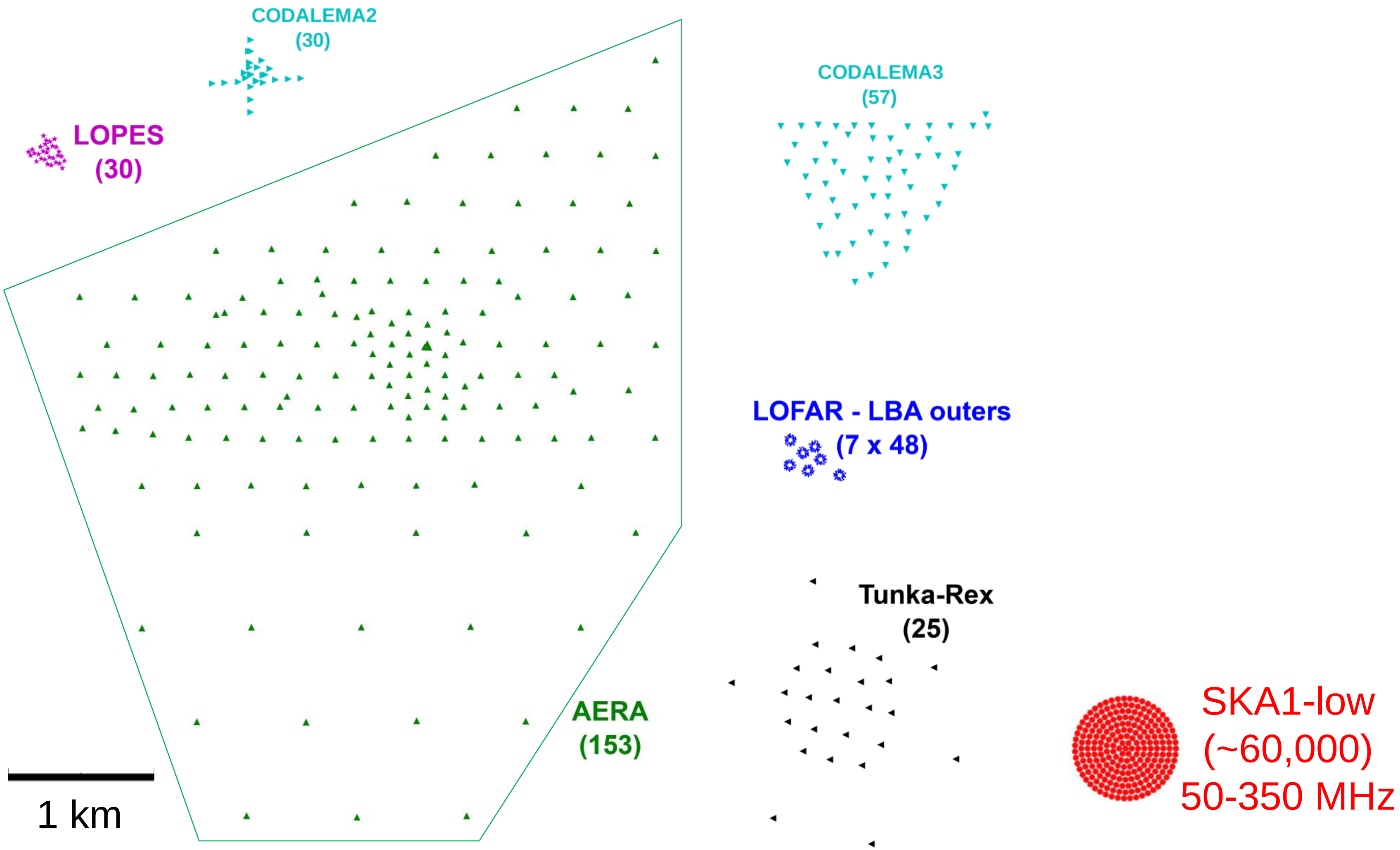
Thousands of cosmic-ray events unambiguously detected by

LOPES
CODALEMA
Radio Prototypes@Auger
LOFAR
AERA
TREND
ANITA
Tunka-Rex

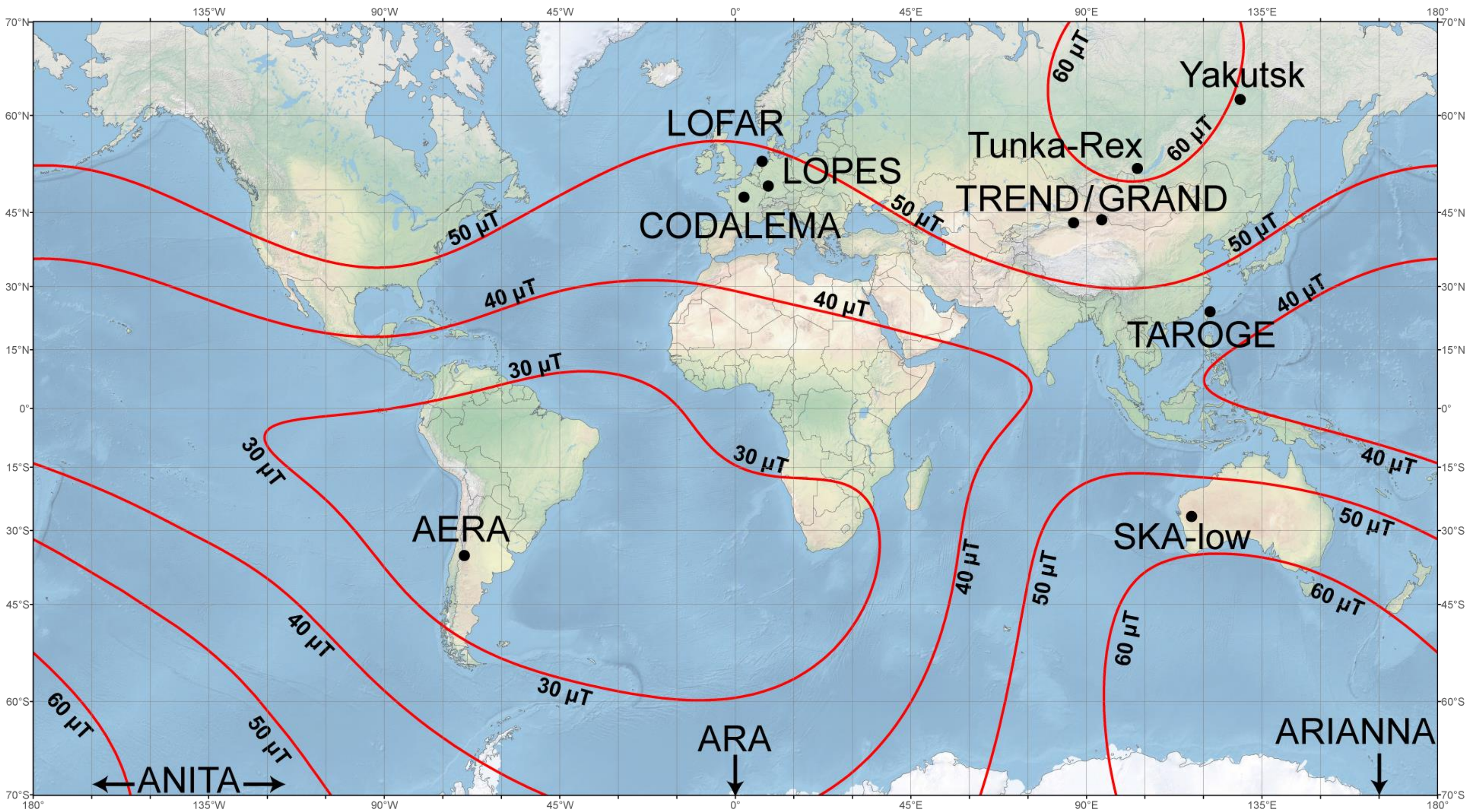
(and of course the historical experiments, partly re-analyzed: MSU, Yakutsk, e.g.)

➔Now: do we fully understand the signals?

Comparison of experiments to scale



Location of selected experiments and geomagnetic field



Underlying map (Mercator projection):
Main Geomagnetic Field Total Intensity with contour intervals of 10 µT according to US/UK World Magnetic Model - Epoch 2015.0

developed by NOAA/NGDC & CIRES
http://ngdc.noaa.gov/geomag/WMM

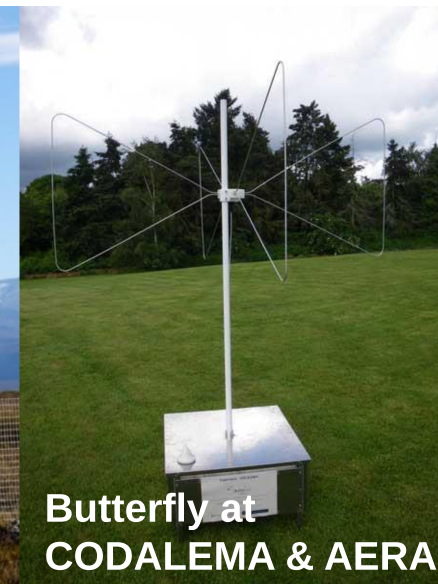
Map reviewed by NGA and BGS
Published December 2014

Overlayed: **Location of radio experiments for cosmic-ray air showers**
added on underlying map by Frank G. Schröder
Karlsruhe Institute of Technology (KIT), Germany

Prog. Part. Nucl. Phys.
93 (2017) 1-68
arXiv: 1607.08781

Different Antenna Types

- **Many working solutions at different experiments**
  - **LOPES, CODALEMA, Yakutsk, LOFAR, AERA, Tunka-Rex, …**
- **Typical band today: 30-80 MHz (other bands under investigation)**



Connection particle array – radio array:

Radio detection technique is presently in the step from developing phase to maturation!

Calibration (understanding) radio emission

- **Dependencies of radio signal**
- **Validity of simulation codes**
- **Understanding emission mechanism(s)**

Capability of the radio detection technique?

Sensitivity and resolution to

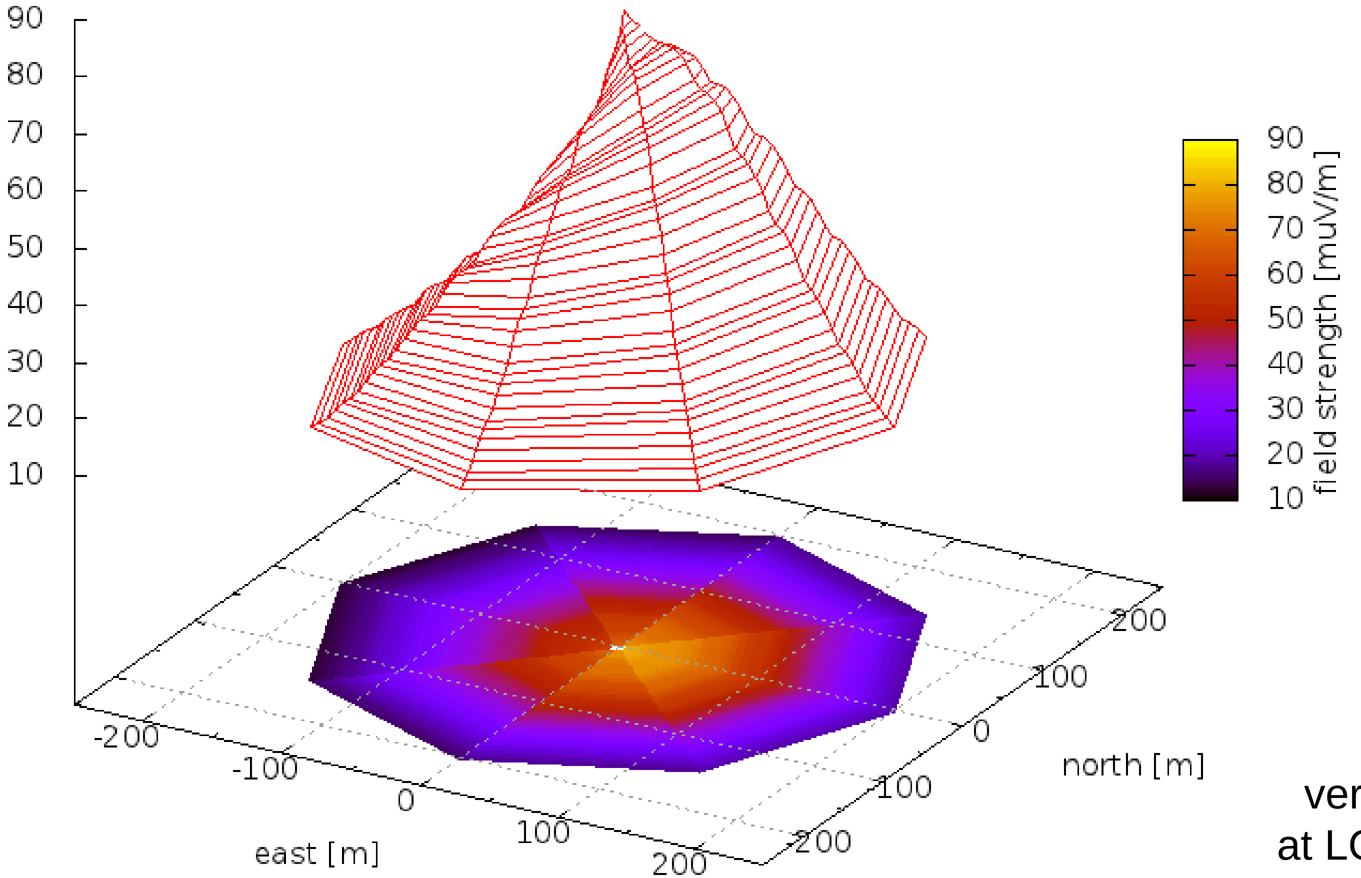
primary energy?
arrival direction?
composition ?

EAS radio detection for CR (and neutrino) measurements:

stand alone or hybrid technique?

Hybrid with particle arrays, not fluorescence technique (duty cycle).

Complexity of radio footprint

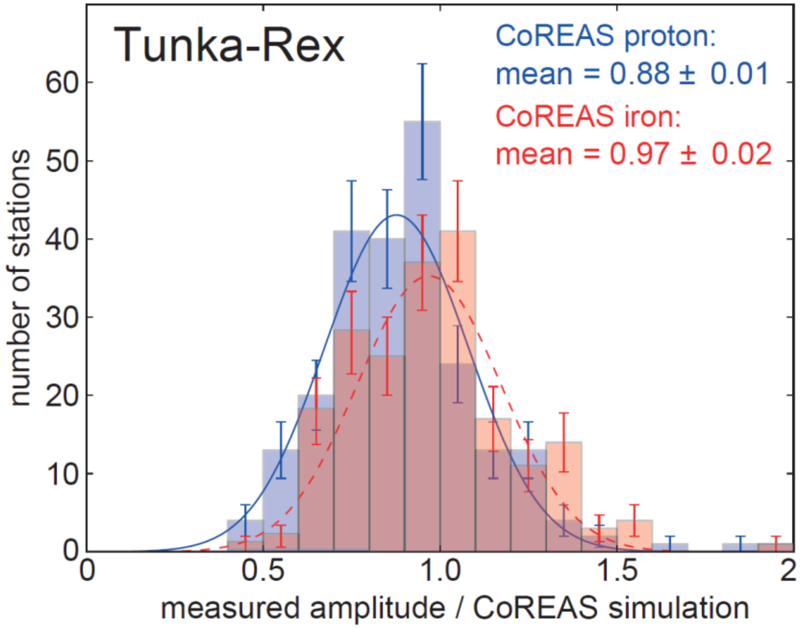


vertical iron shower
at LOPES frequencies
simulated with CoREAS

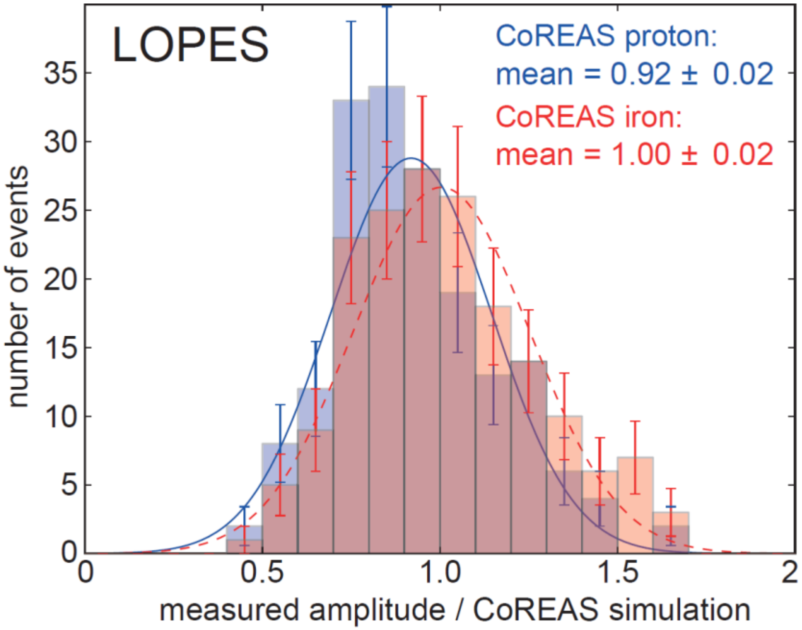
T.Huege et al., ARENA2012

Testing simulations of radio emission

- **Perfect agreement within experimental uncertainties of absolute scale (15-20%)**
- **Differences between various simulations codes < 10%
→ still difficult to test**

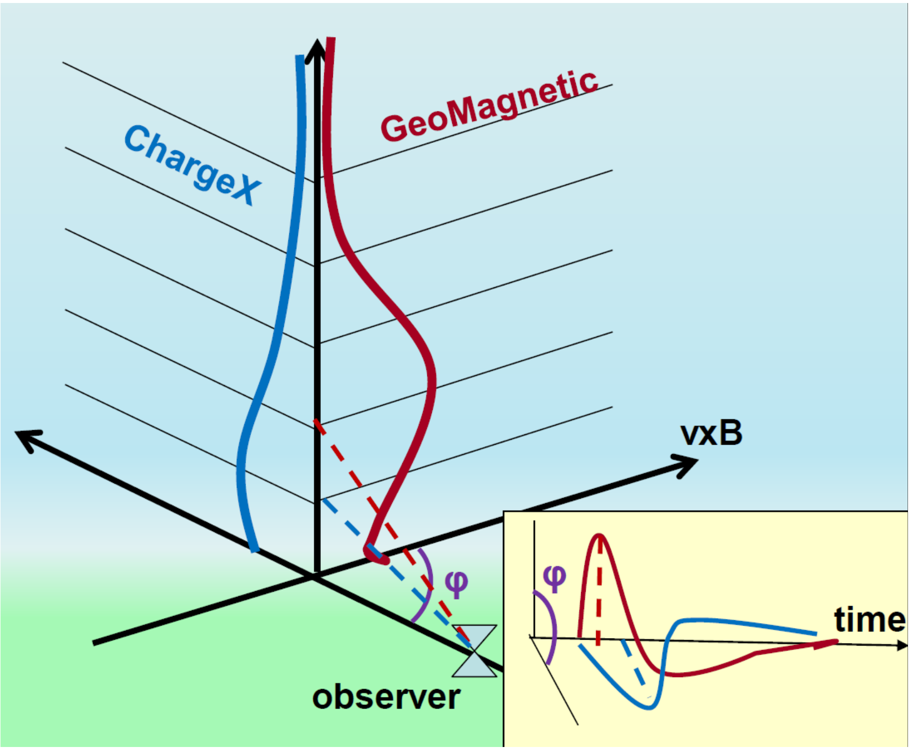


PLB 763 (2016) 179

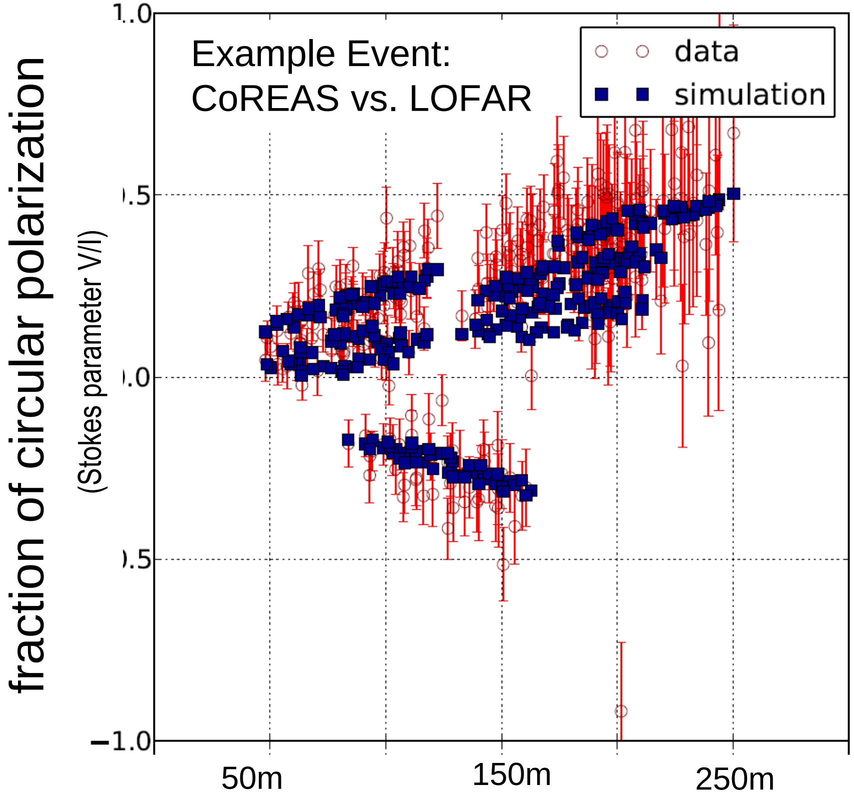


LOFAR confirms slightly elliptical polarization

Precise LOFAR measurements reveal different emission regions for both processes.



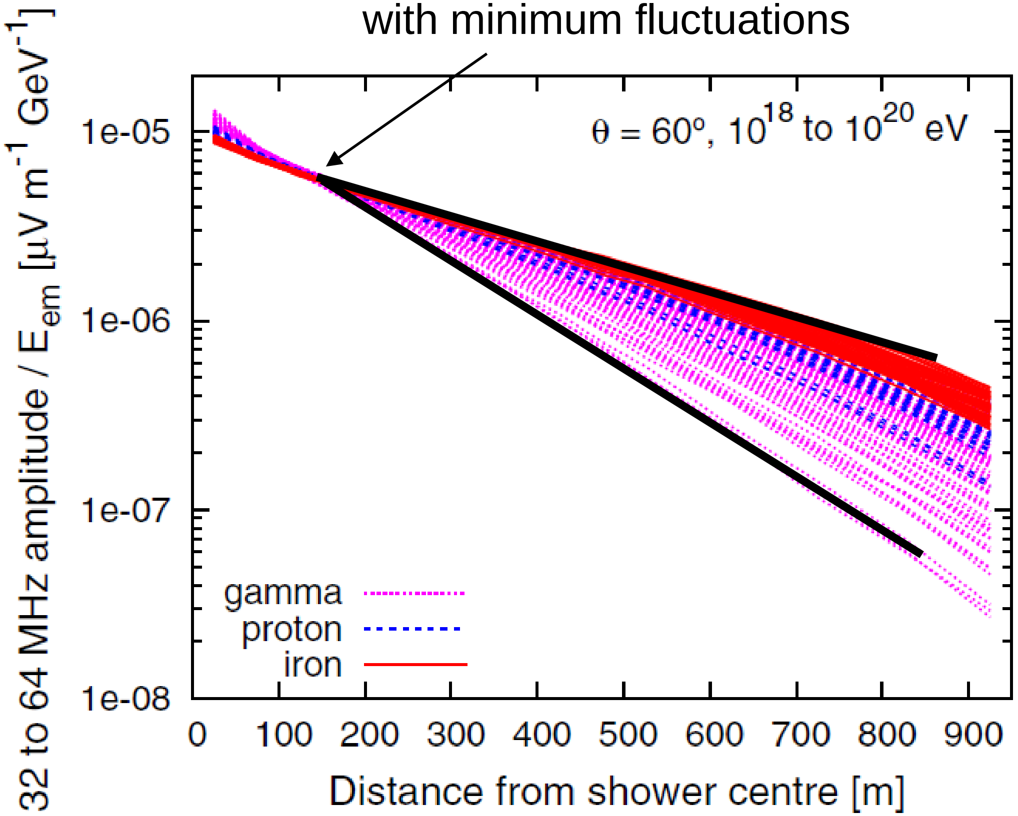
O. Scholten, et al. (LOFAR), PoS (ICRC2017) 324



LOFAR, PRD 94 (2016) 103010

Expected energy sensitivity of radio detection

energy determination at distance with minimum fluctuations



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

- Radio-Emission is coherent
- Energy sensitivity via electric field strength
- Radio signal (electric field) scales with primary energy:

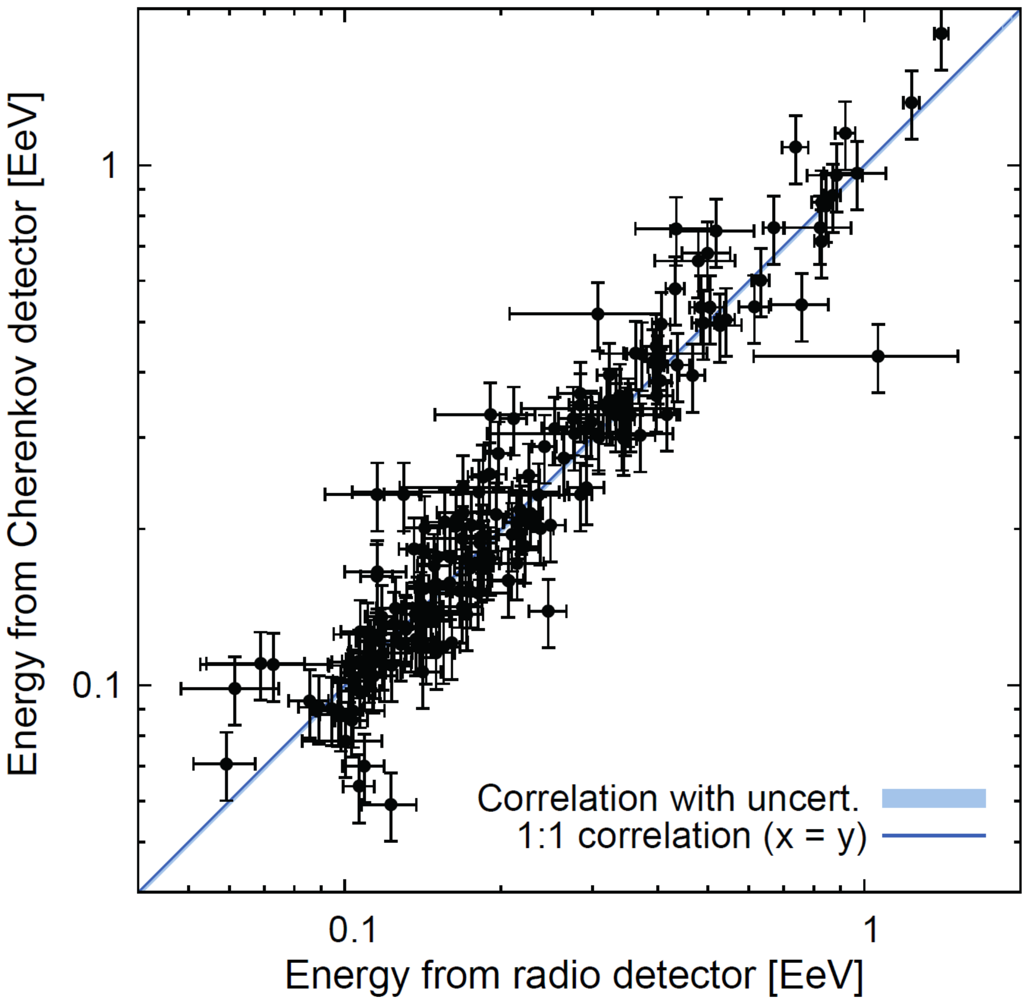
$$\varepsilon_\nu \sim E_0^{\approx 1}$$

➔ **Power of electric field scales approximately quadratically with primary energy !**

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

linear scaling & characteristic distance for best energy estimate

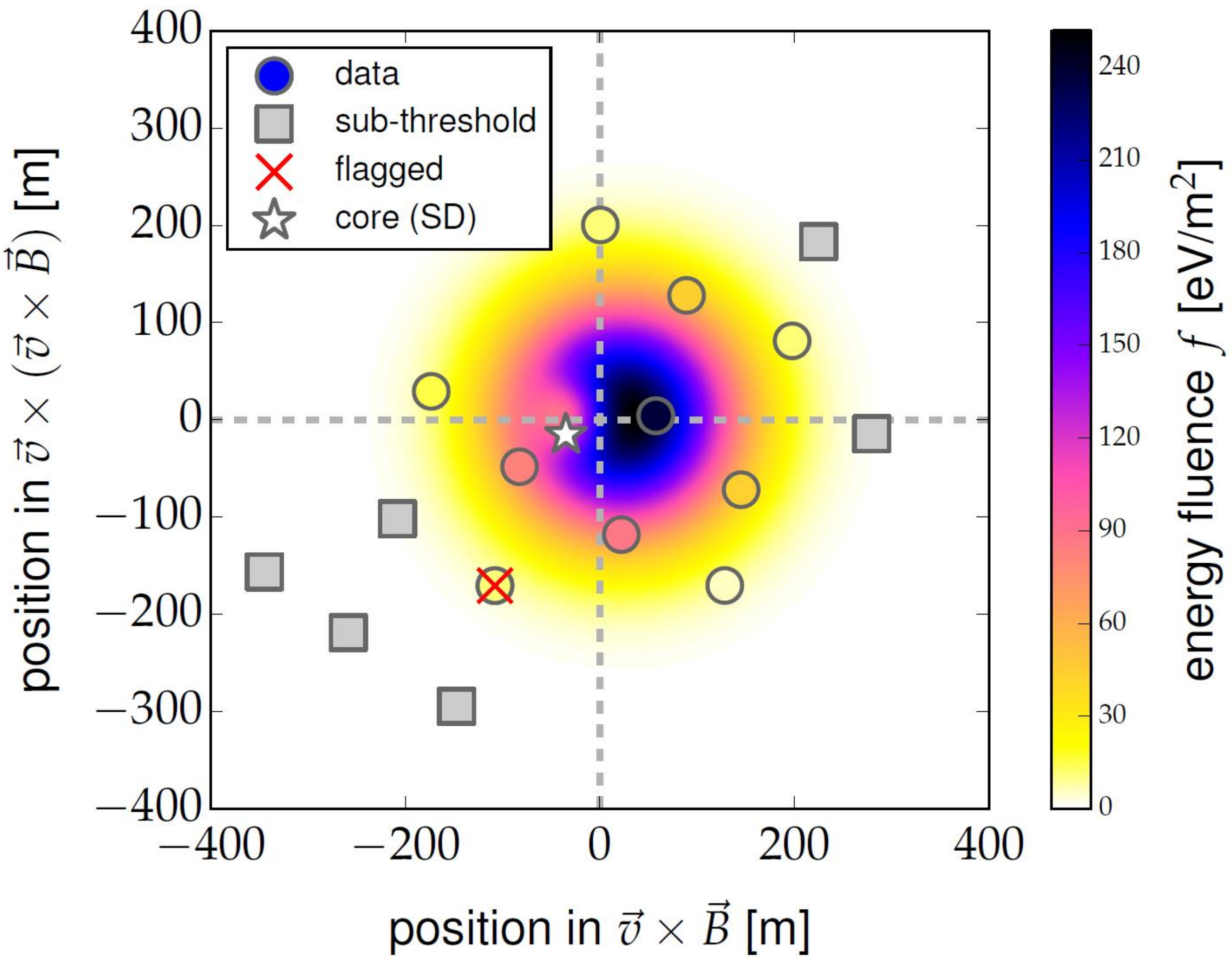
Tunka-Rex energy reconstruction



- **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.

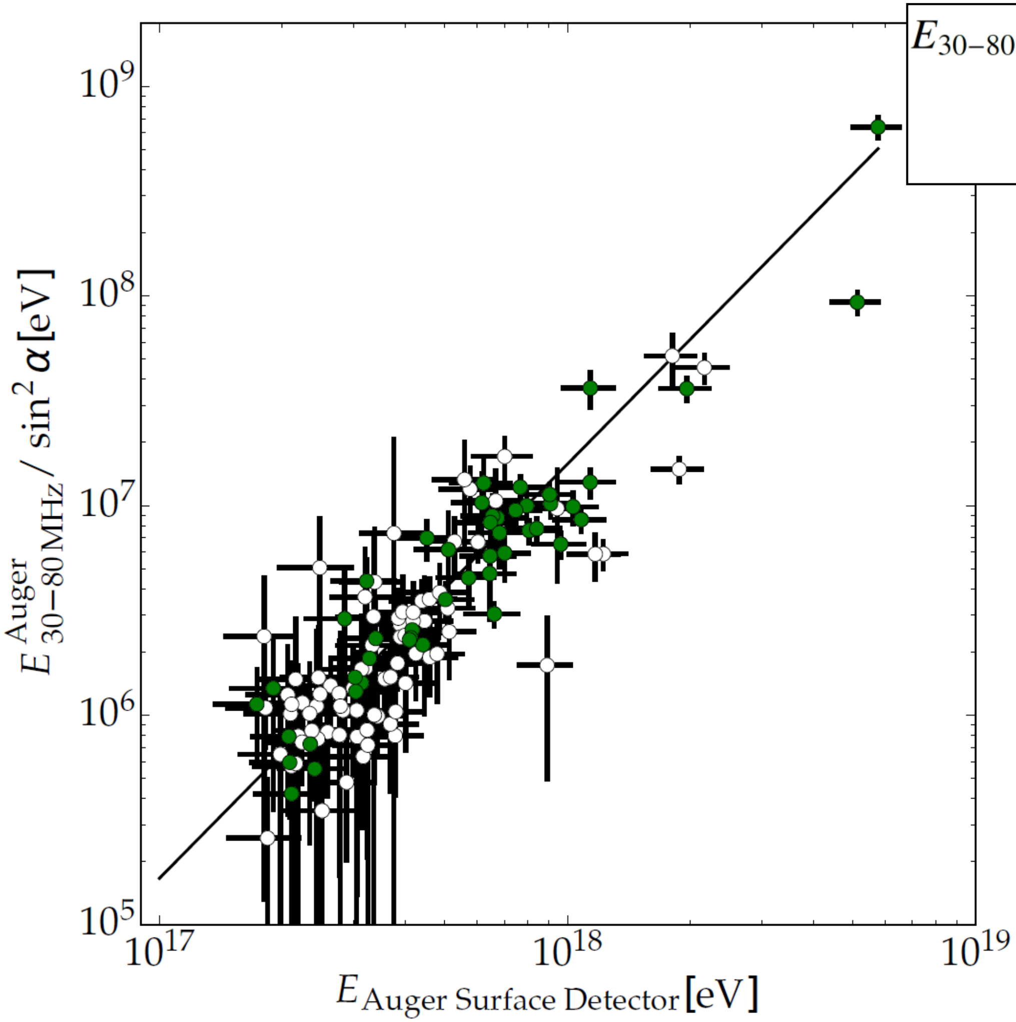
AERA energy reconstruction – radiation energy



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



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

- **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**

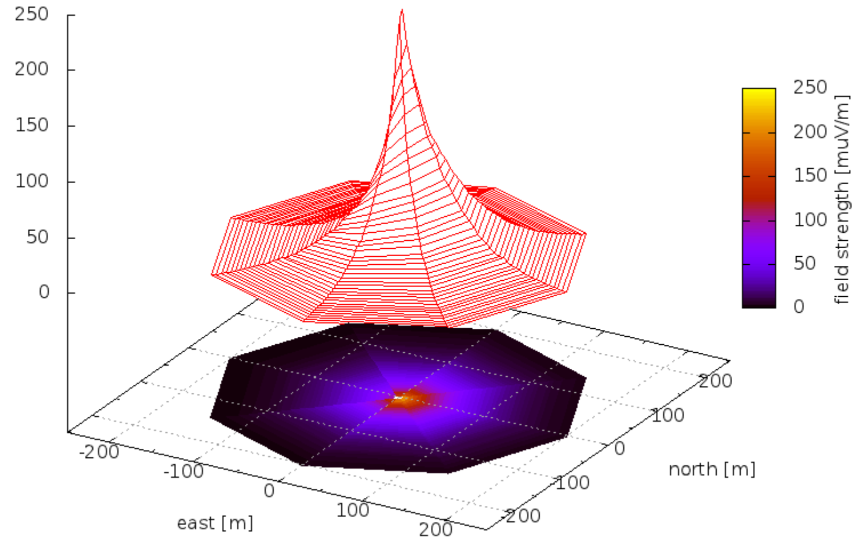
energy determination from first principles!

- **Absolute energy scale**

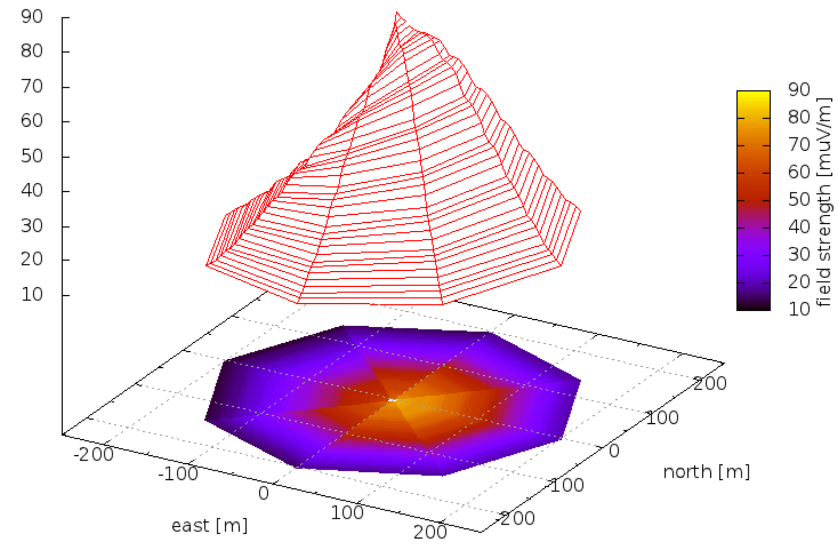
Piere Auger Coll., Phys Rev. Lett. (2016), arXiv:1605.02564.

Lateral distribution as probe for composition

- **forward beaming of emission: geometrical distance from source (X_{max}) to observer influences emission pattern**



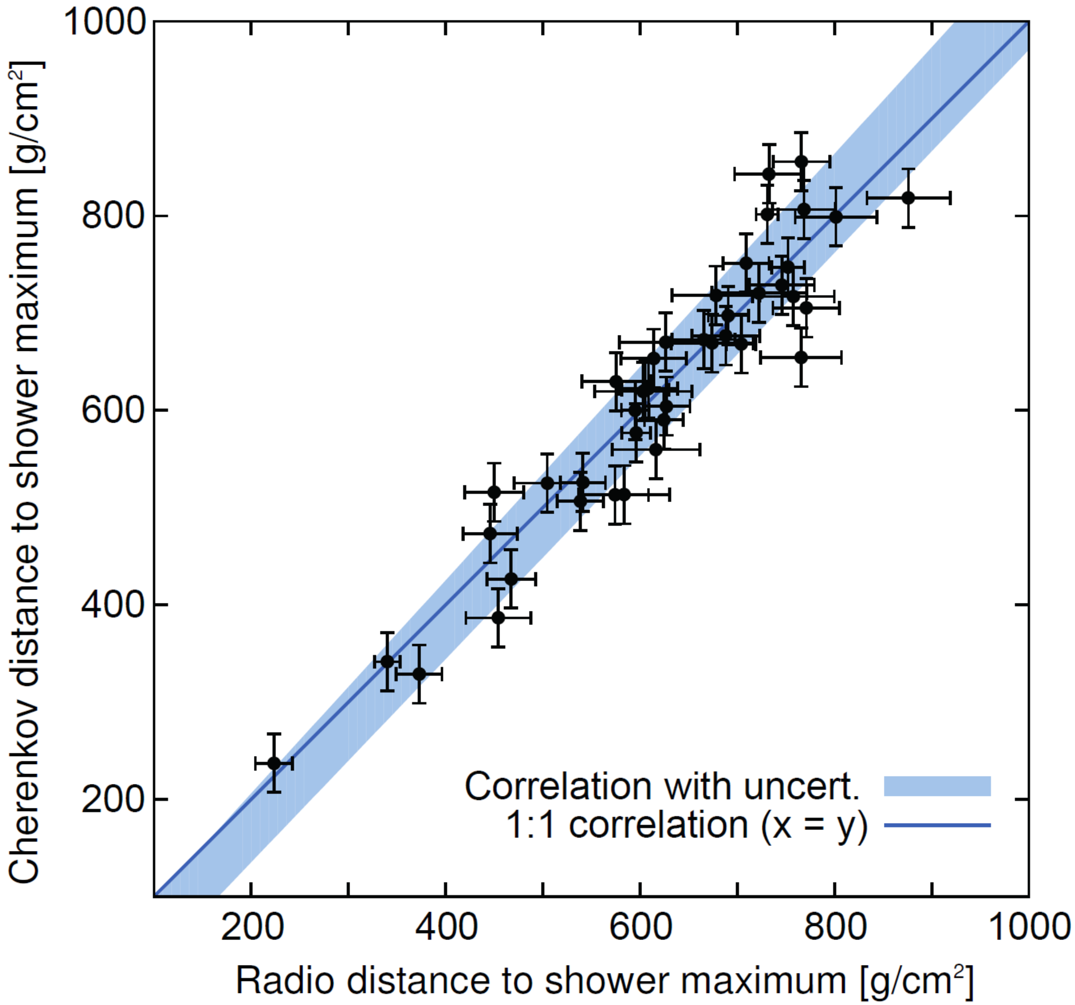
vertical proton shower
at LOPES frequencies
simulated with CoREAS



vertical iron shower
at LOPES frequencies
simulated with CoREAS

T. Huege

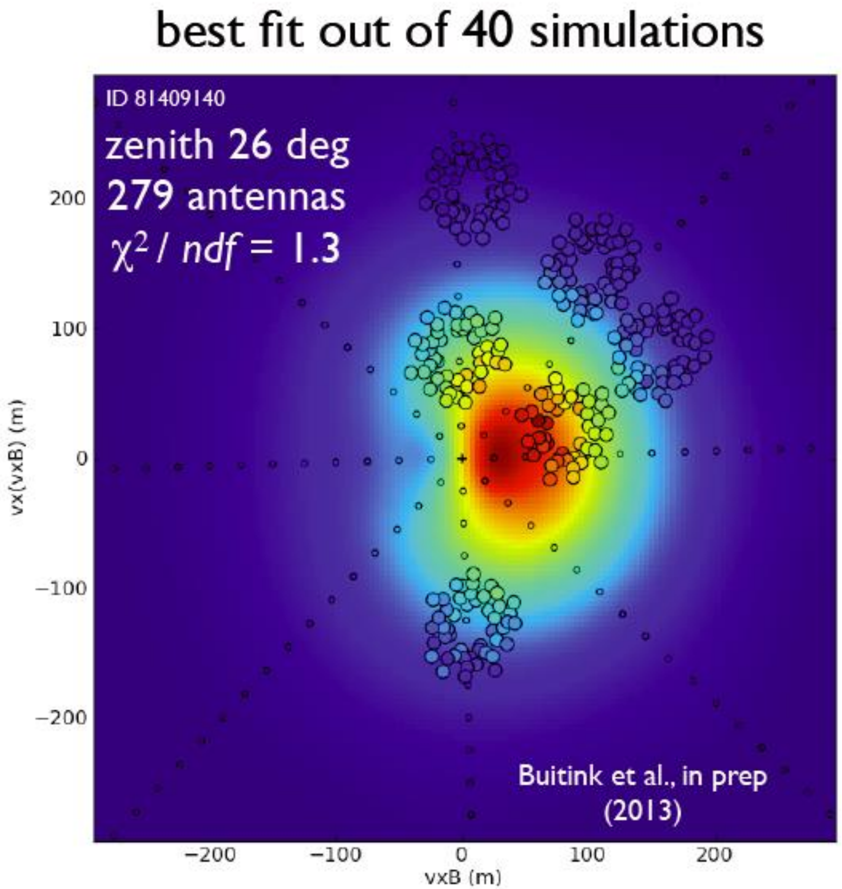
Experimental Xmax validation by Tunka-Rex

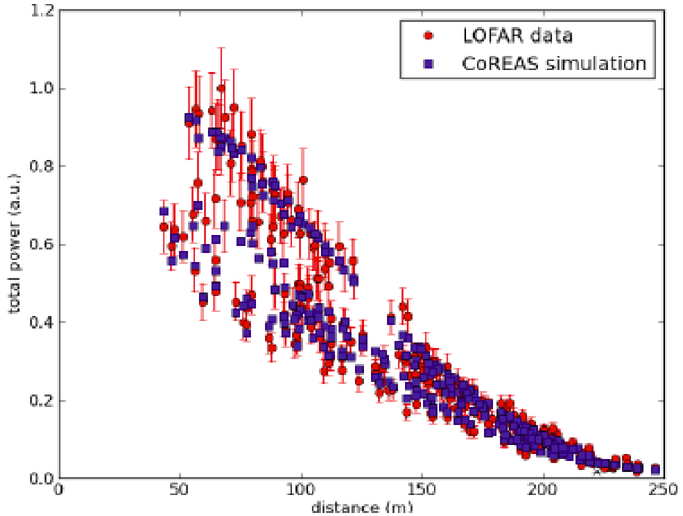


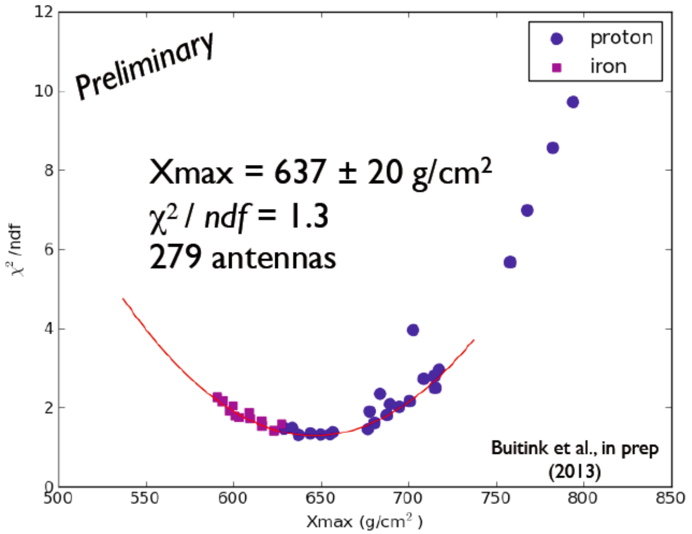
- **slope of radio-LDF as Xmax estimator**
- **Xmax from optical Cherenkov detectors and radio antennas agrees very well**
- **combined Xmax resolution ~50 g/cm^2, Tunka alone ~28 g/cm^2**

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

Global fit of particle and radio LDF with LOFAR





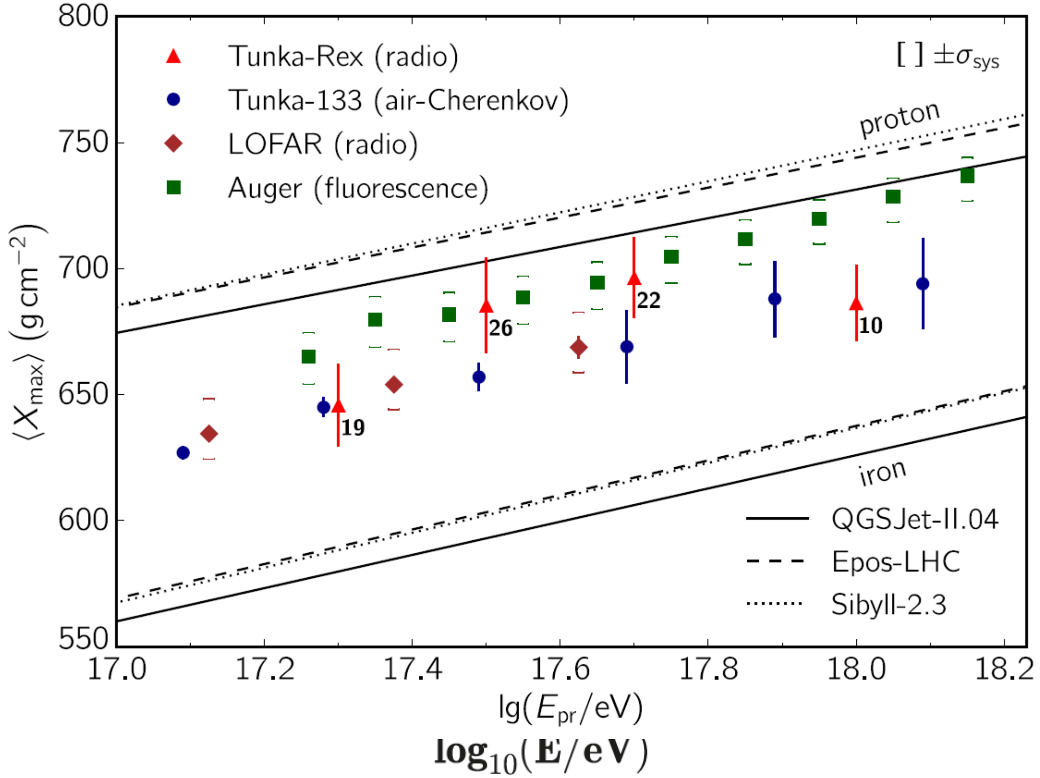


- **global fit to CoREAS simulations gives Xmax to ~17 g/cm^2**

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

Xmax / Composition by Radio

A lot of (promising) progress in Xmax determination by radio Experiments



- **published already by**

LOPES
PhysRevD 90(2014)062001
Tunka-Rex
PRD 97, 122004 (2018)
LOFAR
Nature 531(2016)70

- **Auger/AERA promising**

- **Higher energy**
- **More accurate EAS**
- **Calibration**
- **Various methods**

➔ **Interpretation debatable:** "Unless, contrary to current expectations, the extragalactic component of cosmic rays contributes substantially to the total flux below $10^{17.5}$ eV, our measurements indicate the existence of an additional galactic component to account for the light composition we measured….." (LOFAR@Nature)

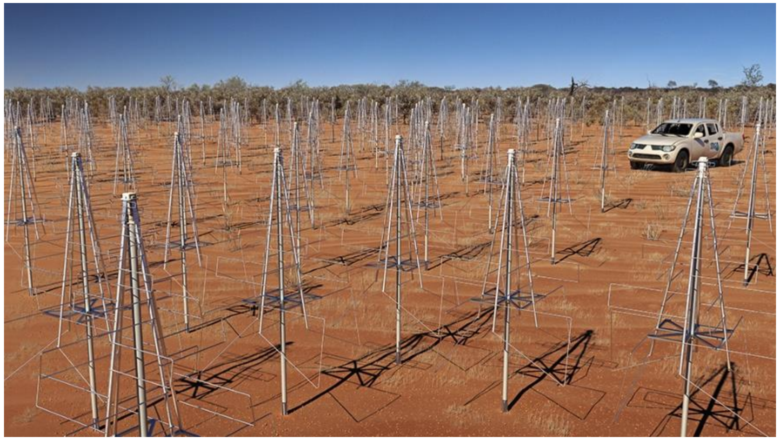
Strengths and limitations of radio detection

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

Slide by Tim Huege

Prospects for future radio experiments

- **Future radio arrays for air-showers (plans and ideas)**
  - **Auger Radio Upgrade**
  - **GRAND**
  - **SKA**
  - **Radio array at the South Pole**

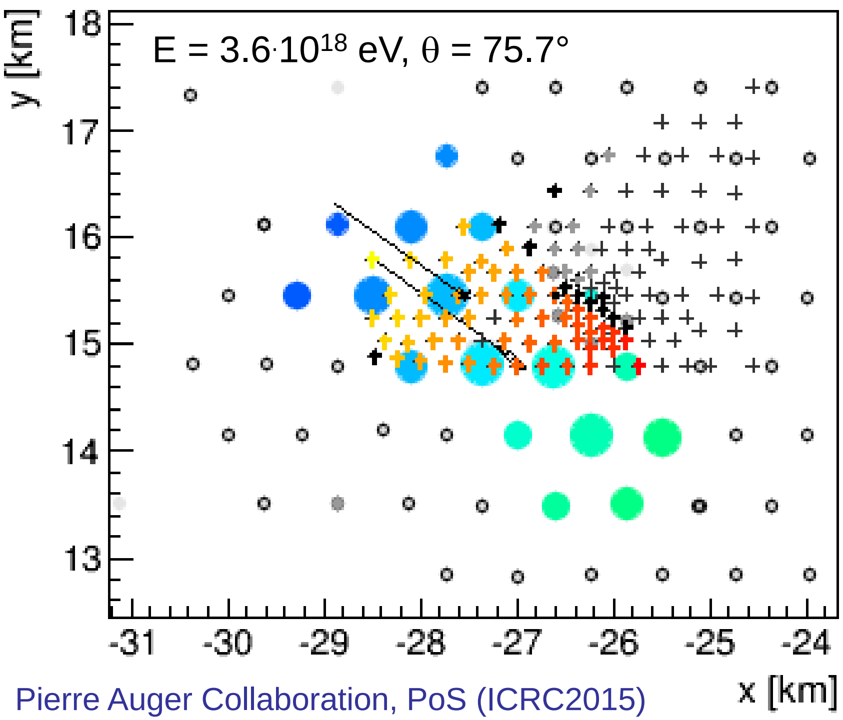


Huge footprint for inclined showers

- air showers up to 83° zenith angle measured
- footprints with radii up to 2 km in shower plane
- detection with 1.5 km antenna grid would be sufficient

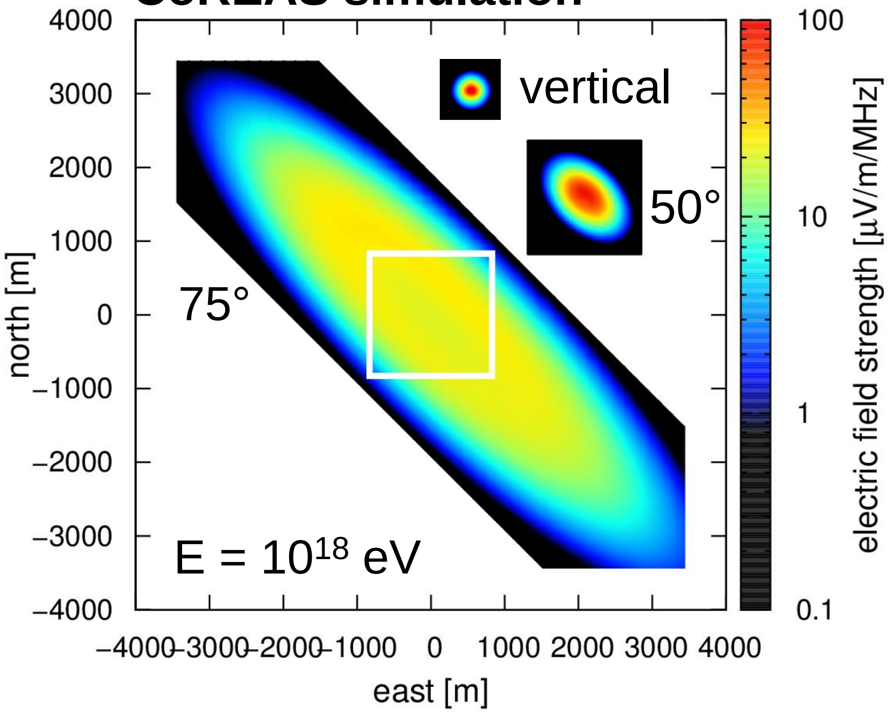
Enables sparse antenna arrays for highest energies at reasonable costs

Auger measurement



Pierre Auger Collaboration, PoS (ICRC2015) 615

CoREAS simulation

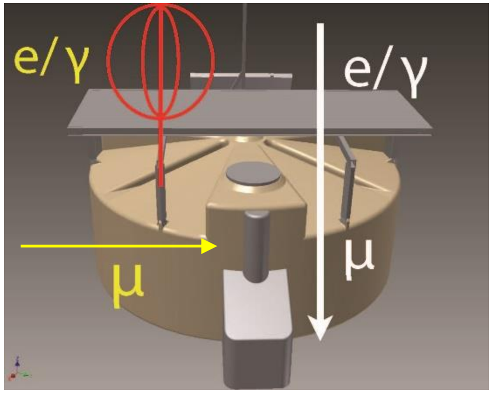


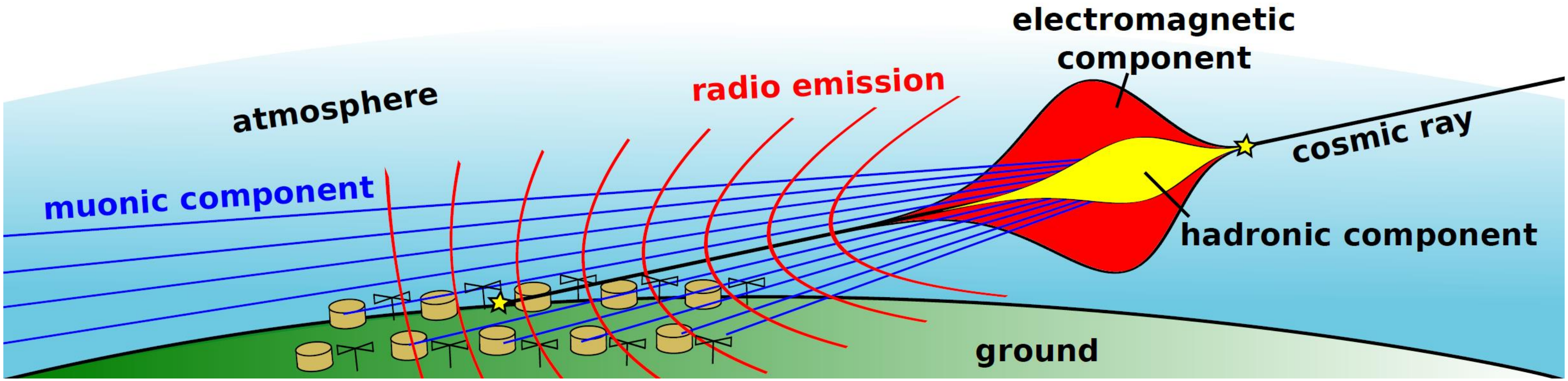
O. Kambeitz for the Pierre Auger Collaboration, ARENA2016 conference, arXiv:1609.05456

Radio upgrade of the Pierre Auger Observatory

Add one antenna to each upgraded surface detector

- Enhanced mass-sensitivity for inclined showers
- Mass-sensitive anisotropy studies with increased sky coverage
- Search for neutrinos + photons



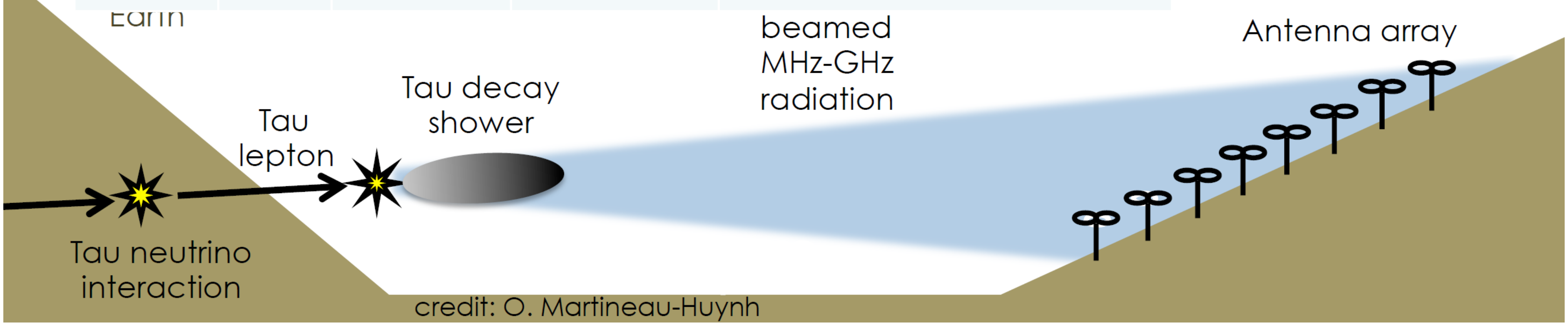


Auger Coll.

Giant Radio Array for Neutrino Detection (GRAND)

- Huge array in China for cosmic rays and neutrinos above 10^{17} eV

GRAND	Start	Antennas	Size	Main Goal
Phase 1	2018	35	2 km²	technical prototype
Phase 2	2020	300	ca. 200 km²	galactic cosmic rays
Phase 3	2025	10.000	10.000 km²	extragalactic CR + neutrinos
Phase 4	2030‘s	200.000	200.000 km²	cosmogenic neutrinos



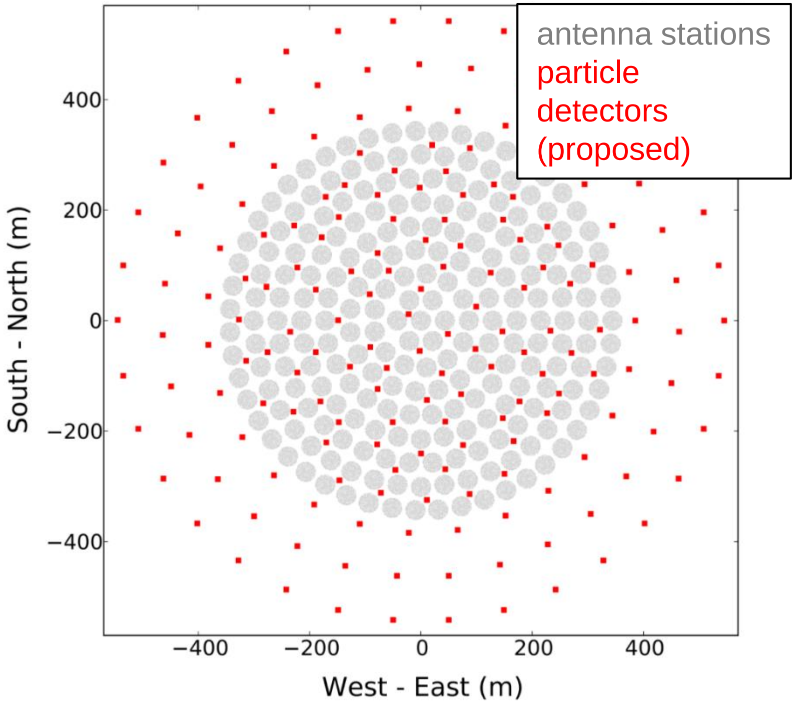
The Square Kilometer Array: ultra high precision

- Air-showers detection in parallel to astronomy (50-350 MHz)
- X_{max} resolution of < 10 g/cm²
- Might enable detailed shower physics with radio

https://www.icrar.org/wa-government-invests-26m-astronomy-square-kilometre-array/


Artist impression of SKA-low in Australia

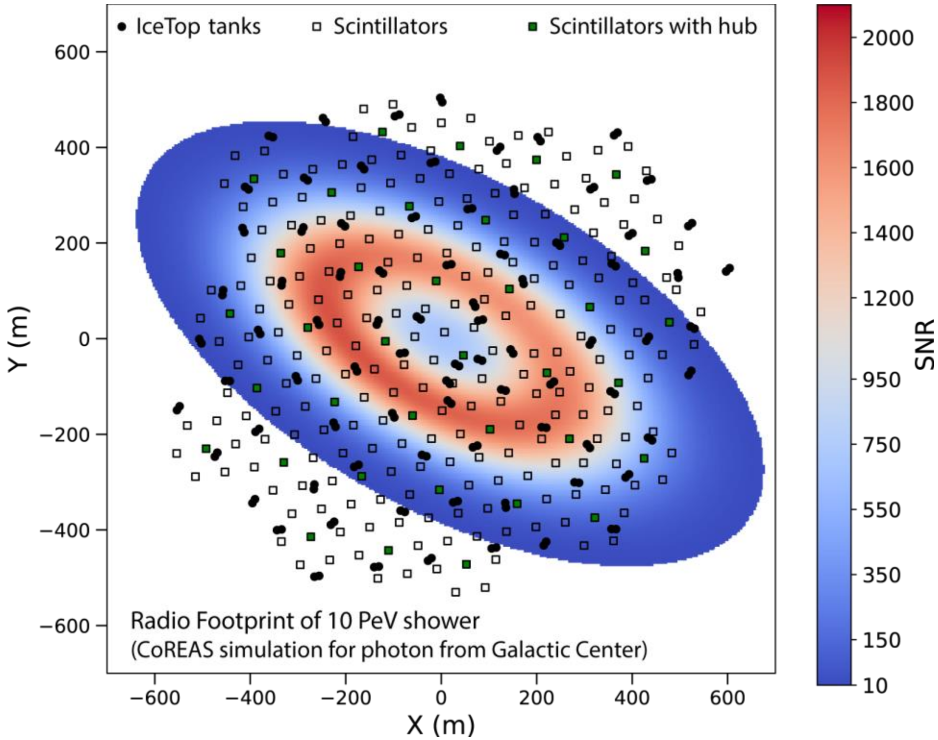
60,000 antennas on ½ km²

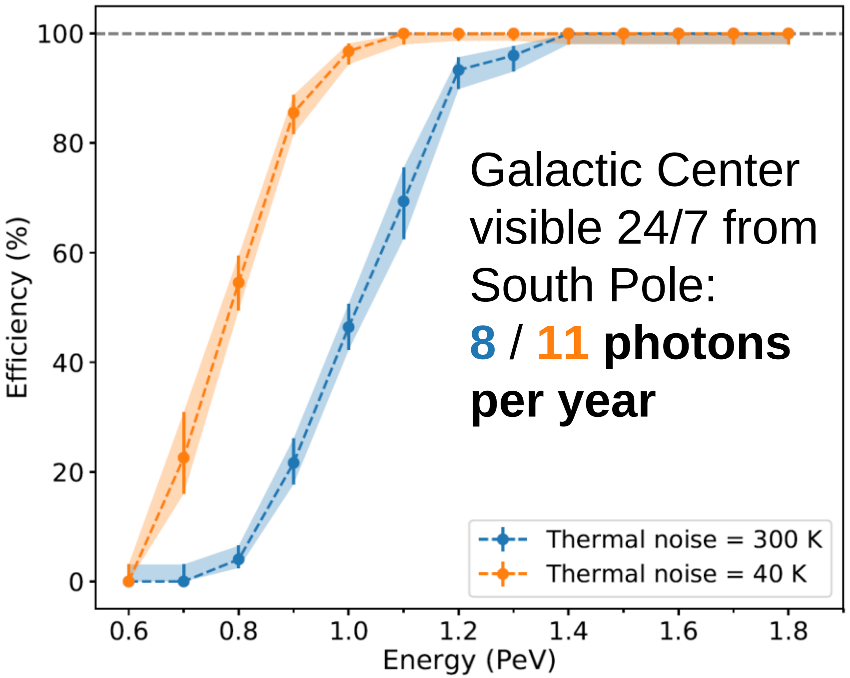


- **to be built in western Australia with first science 2020, planned completion 2023**
- **>60,000 dual-polarized antennas within 750 m diameter; bandwidth 50-350 MHz**
- **can be used for air shower detection with minor additions**
- **precision measurements in energy range of ~$10^{16.5}$ to $10^{18.5}$**

Simulation study on proposed radio array at South Pole

- 1 km² with 125 m spacing between antennas

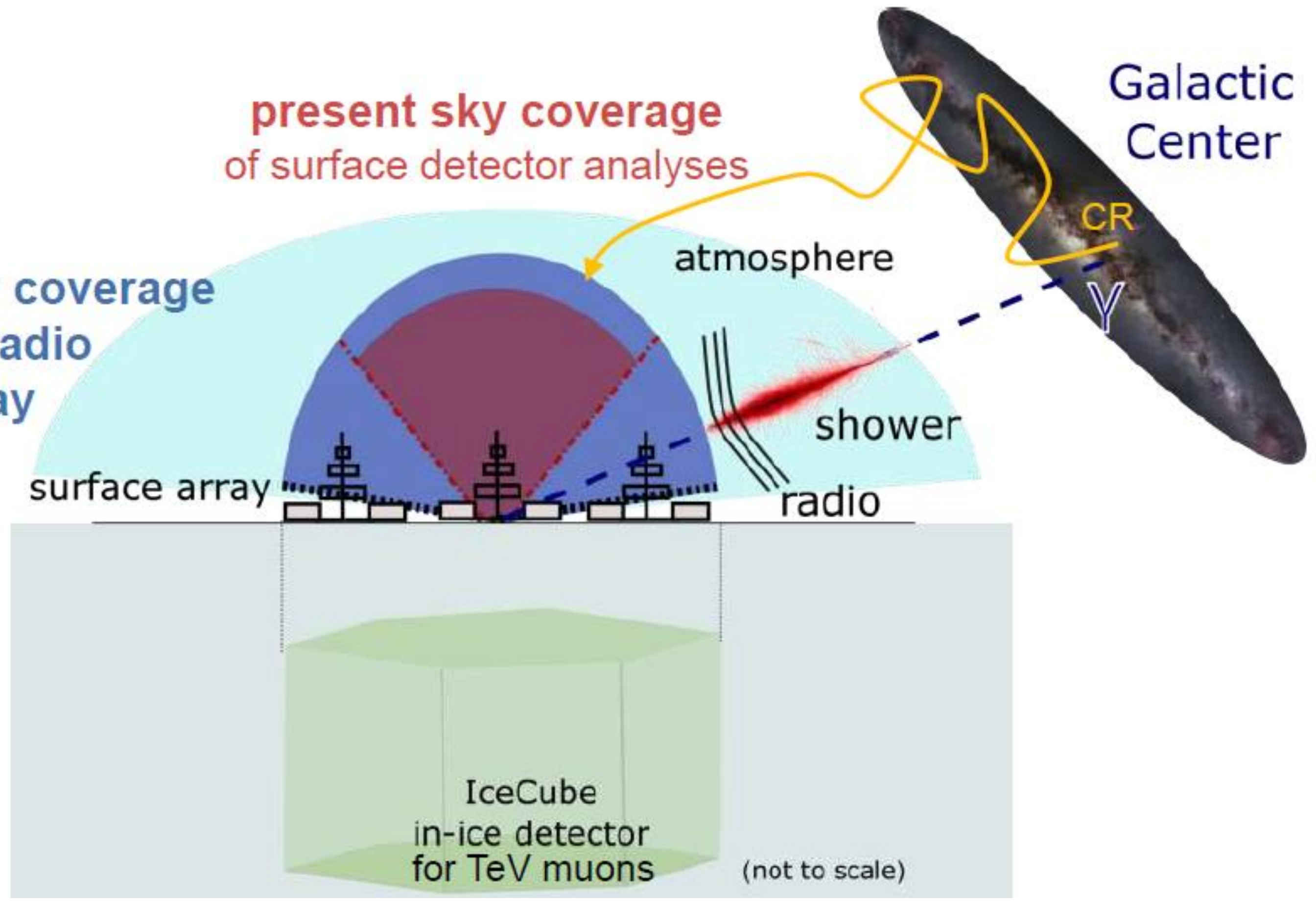




100-190 MHz;
Possible with SKA antenna

Search for PeVatrons at the Galactic Center using a radio air-shower array at the South Pole
A. Balagopal V., A. Haungs, T. Huege, F.G. Schröder,
European Physics Journal C 78 (2018) 111

New Idea: Array with PeV threshold at South Pole



Radio array will make IceTop the most accurate PeV-EeV air-shower detector
PeV photon search from Galactic Center EPJ C 78 (2018) 111

F.Schröder, ARENA2018

Summary and conclusions

- **radio detection of CRs has boomed and matured in the last decade**
- **we have clearly established**
  - ***detailed understanding of complex radio emission physics***
  - **event detection (externally and self-triggered)**
  - **determination of arrival direction (<0.5°)**
  - **determination of air shower energy (<~20%, maybe 10%?)**
  - **radio signal sensitivity to particle mass (via Xmax, <20 g/cm^2)**
- **potential for application**
  - **high-duty-cycle energy & mass reconstruction in hybrid arrays**
  - **cross-calibration of the energy scale of cosmic-ray detectors**
  - **independent calibration of energy scale from first principle calculations**
  - **Air-shower physics via measurement of electromagnetic cascade**
  - **UHE CR & Neutrino measurements**
  - **(Not discussed) in-ice radio EHE Neutrino detection**

Thanks to Frank Schröder (Prog.Part.Nucl.Phys.93-2017-1) and Tim Huege (Phys.Rept.620-2016-1)