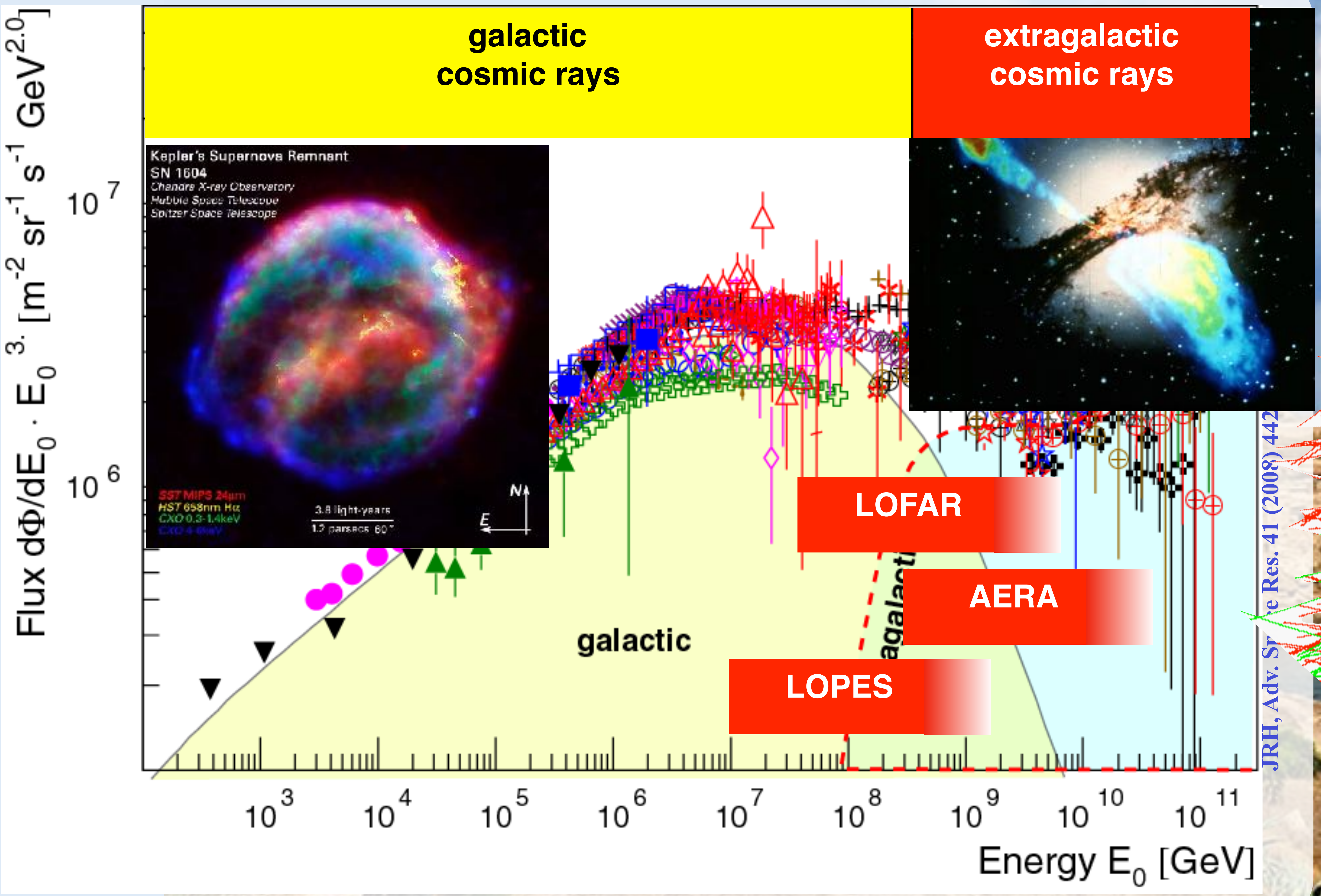
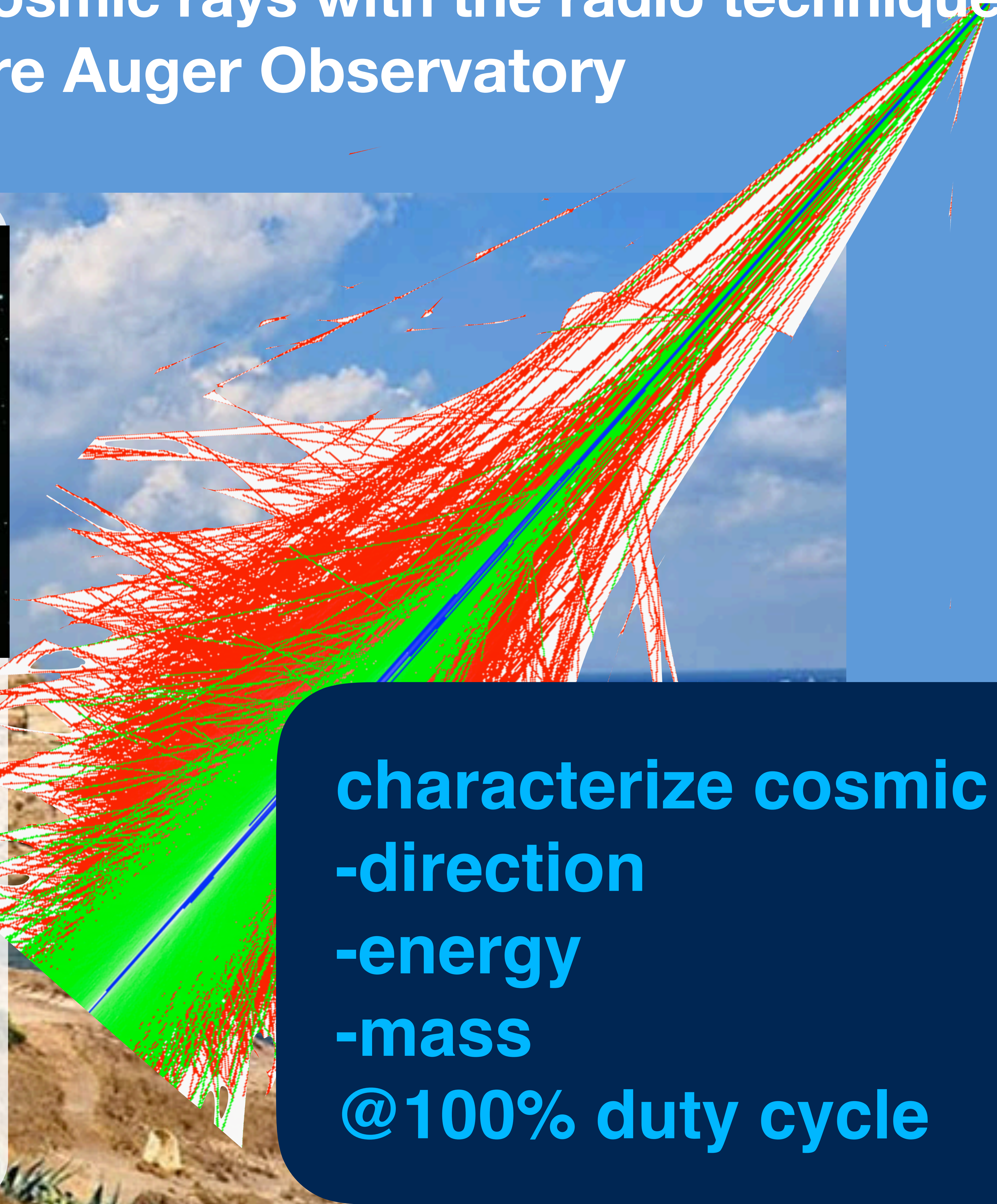
Radio Detection of Extensive Air Showers

Measurements of the properties of cosmic rays with the radio technique at LOFAR and the Pierre Auger Observatory





characterize cosmic rays:

- direction
- energy
- mass

@100% duty cycle

taskleader radio at Pierre Auger Observatory

PI LOFAR key science project Cosmic Rays

Jörg R. Hörandel

Radboud University Nijmegen, Nikhef

http://particle.astro.ru.nl

1.E.5
8.A.1

Nuclear Physics B21 (1970) 135-157. North-Holland Publishing Company

HIGH-ENERGY SCATTERING OF PROTONS BY NUCLEI

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Received 19 February 1970

Abstract: The theory of high-energy hadron-nucleus collisions is discussed by means of the multiple-diffraction theory. Effects of the Coulomb field are accounted for in elastic scattering by light and heavy nuclei. Inelastic scattering is treated by means of the shadowed single collision approximation at small momentum transfer and the corresponding multiple collision expansion at large momentum transfers. The theory is compared with the measurements of Bellettini et al. on proton-nucleus scattering at 20 GeV/c by finding density distributions for the nuclei which provide least-squares fits to the data. The nucleon densities found are closely comparable in dimensions to the known charge densities. The predicted sums of the angular distributions of elastic and inelastic scattering reproduce the experimental angular distributions fairly closely.

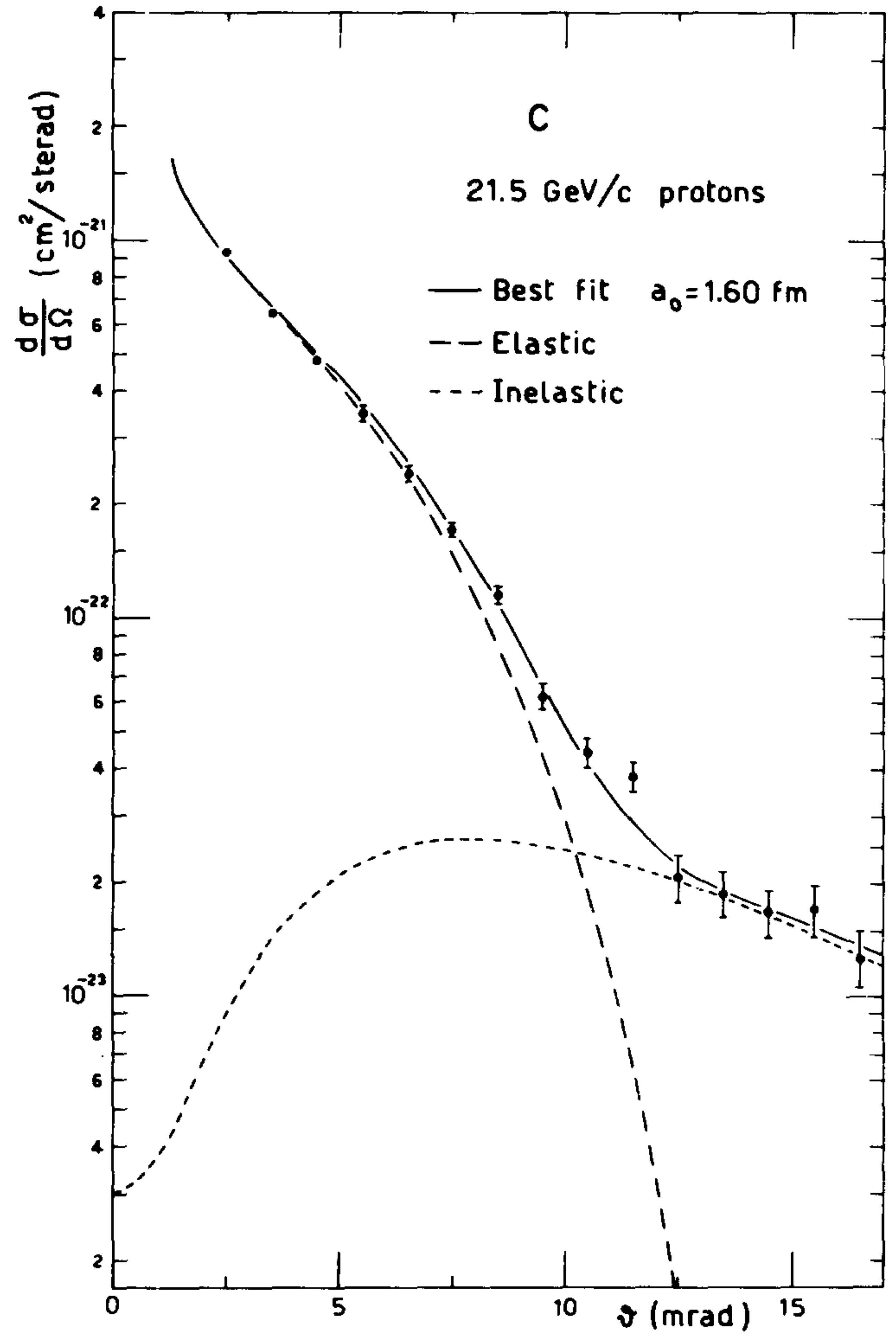


Fig. 4. The experimental data of ref. [4] on the scattering of 21.5 GeV/c protons by C are shown together with the result of the best fit. Elastic and inelastic contributions are shown separately.

Radio Emission in Air Showers

- **Mainly: Charge separation in geomagnetic field**

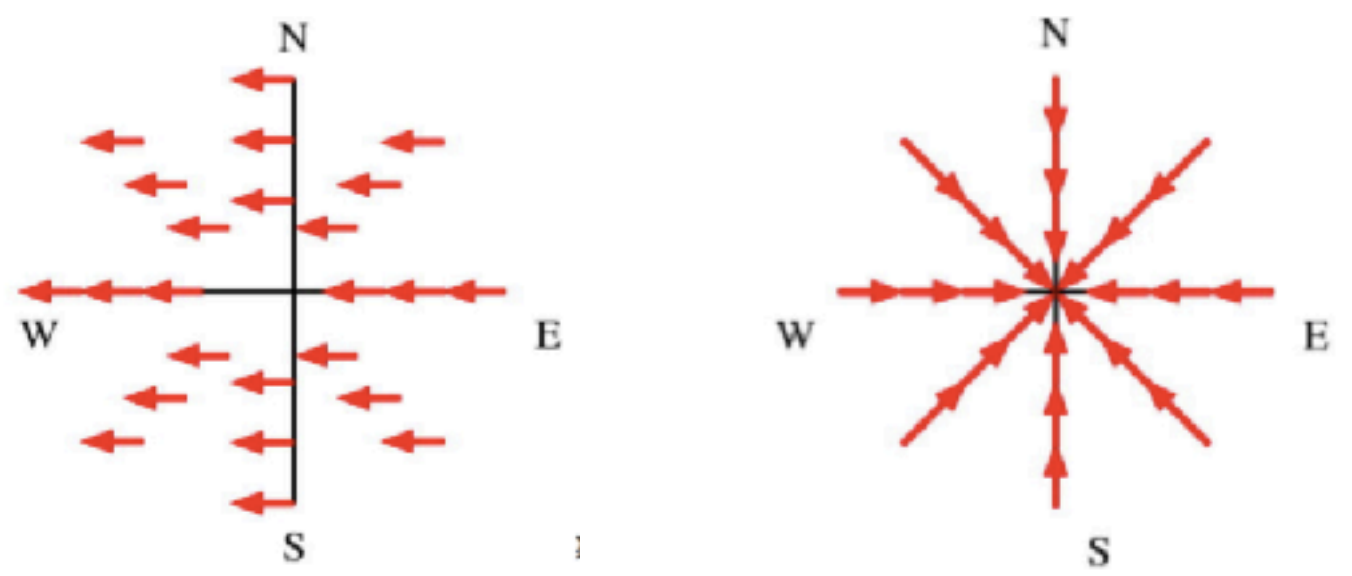
$$\vec{E} \propto \vec{v} \times \vec{B}$$

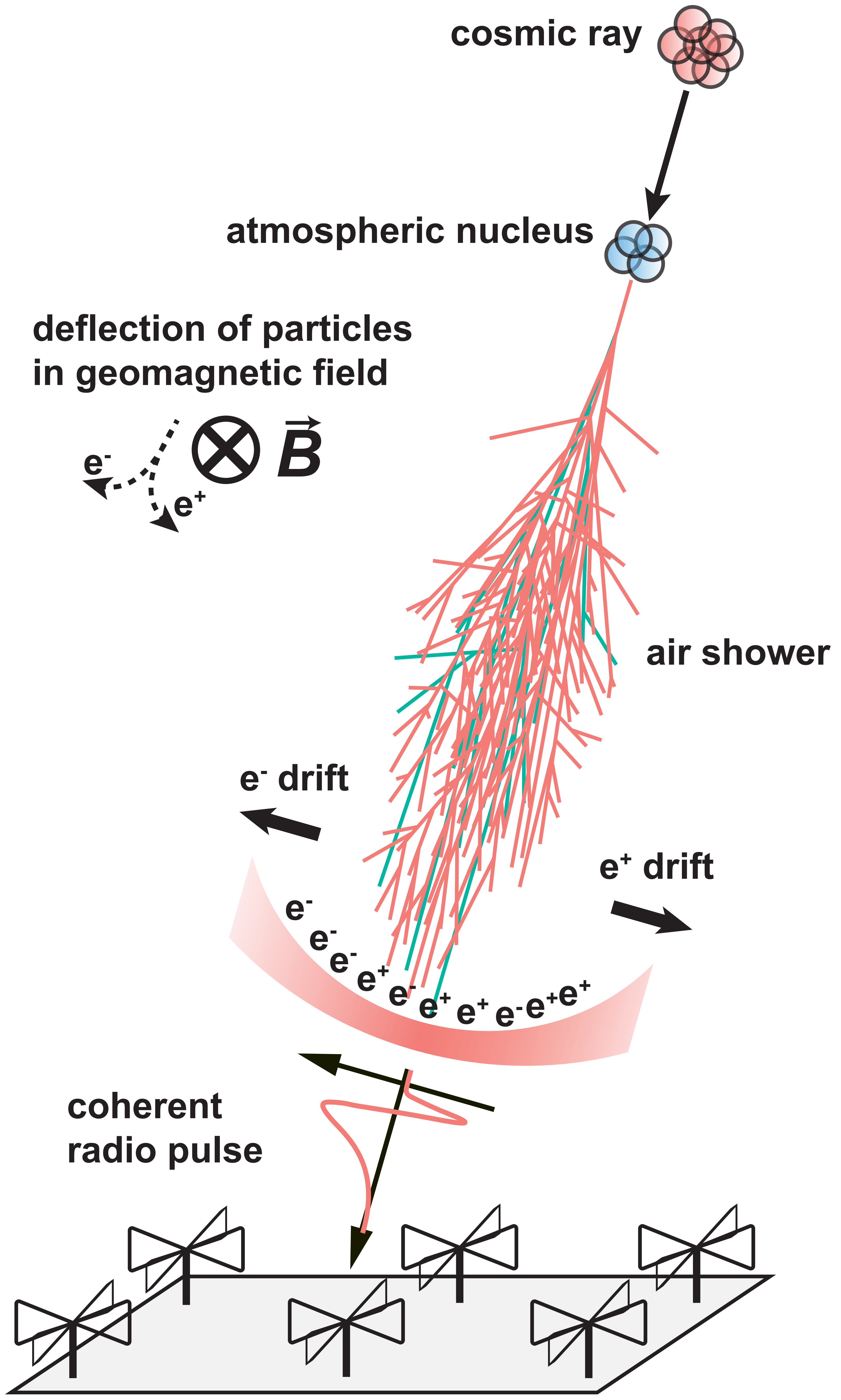
Theory predicts additional mechanisms:

- **excess of electrons in shower: charge excess**
- **superposition of emission due to Cherenkov effects in atmosphere**

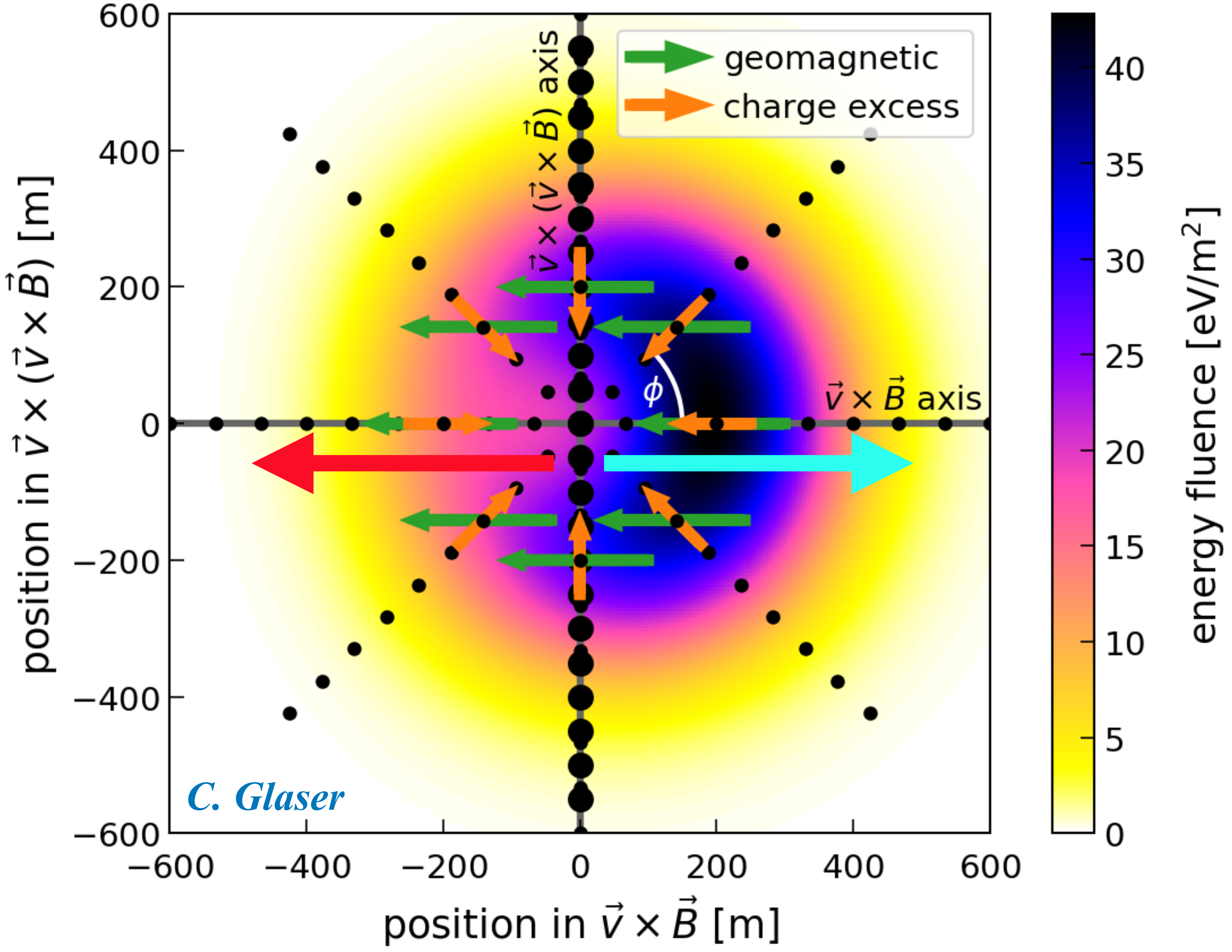
polarization of radio signal

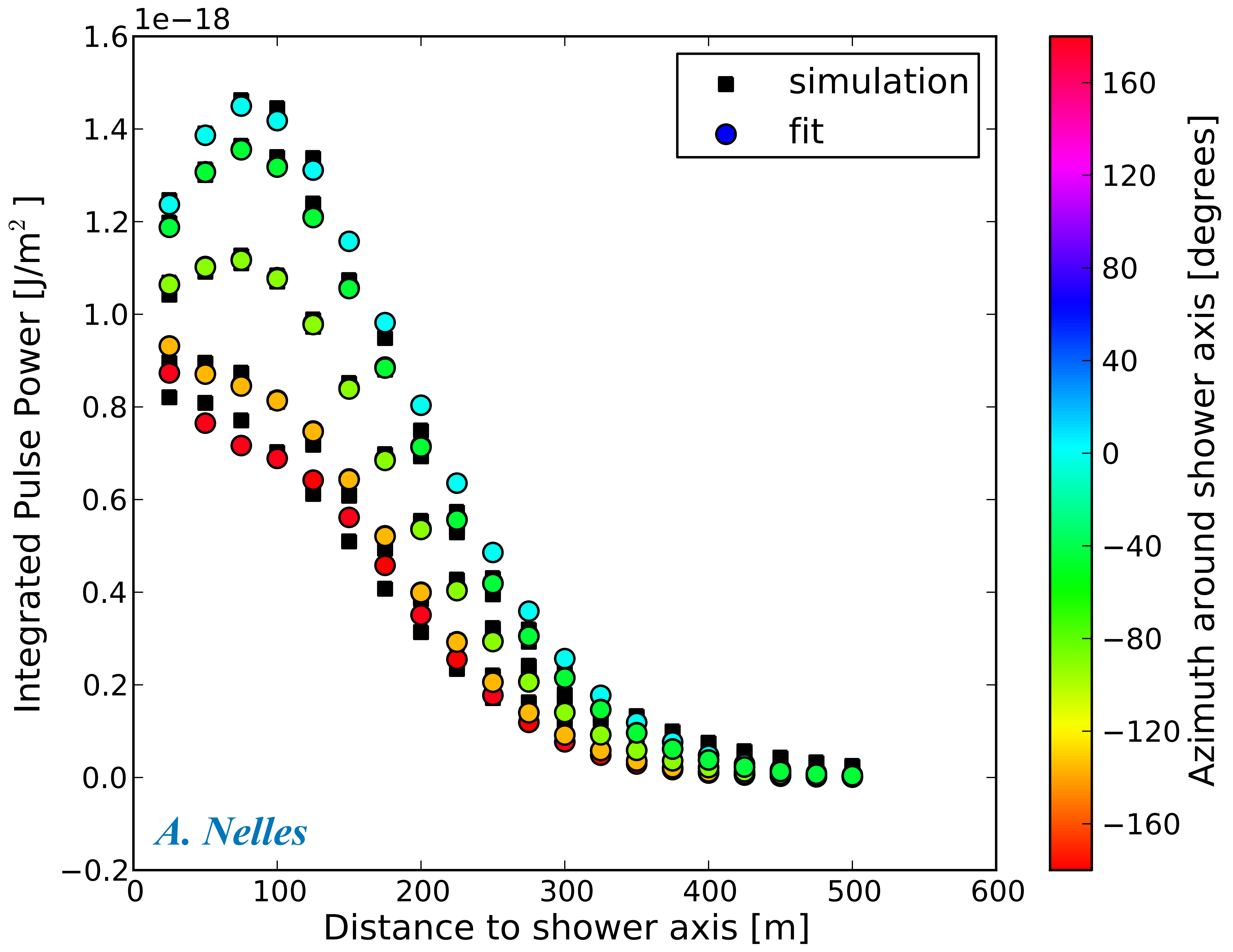
geomagnetic **Askaryan**

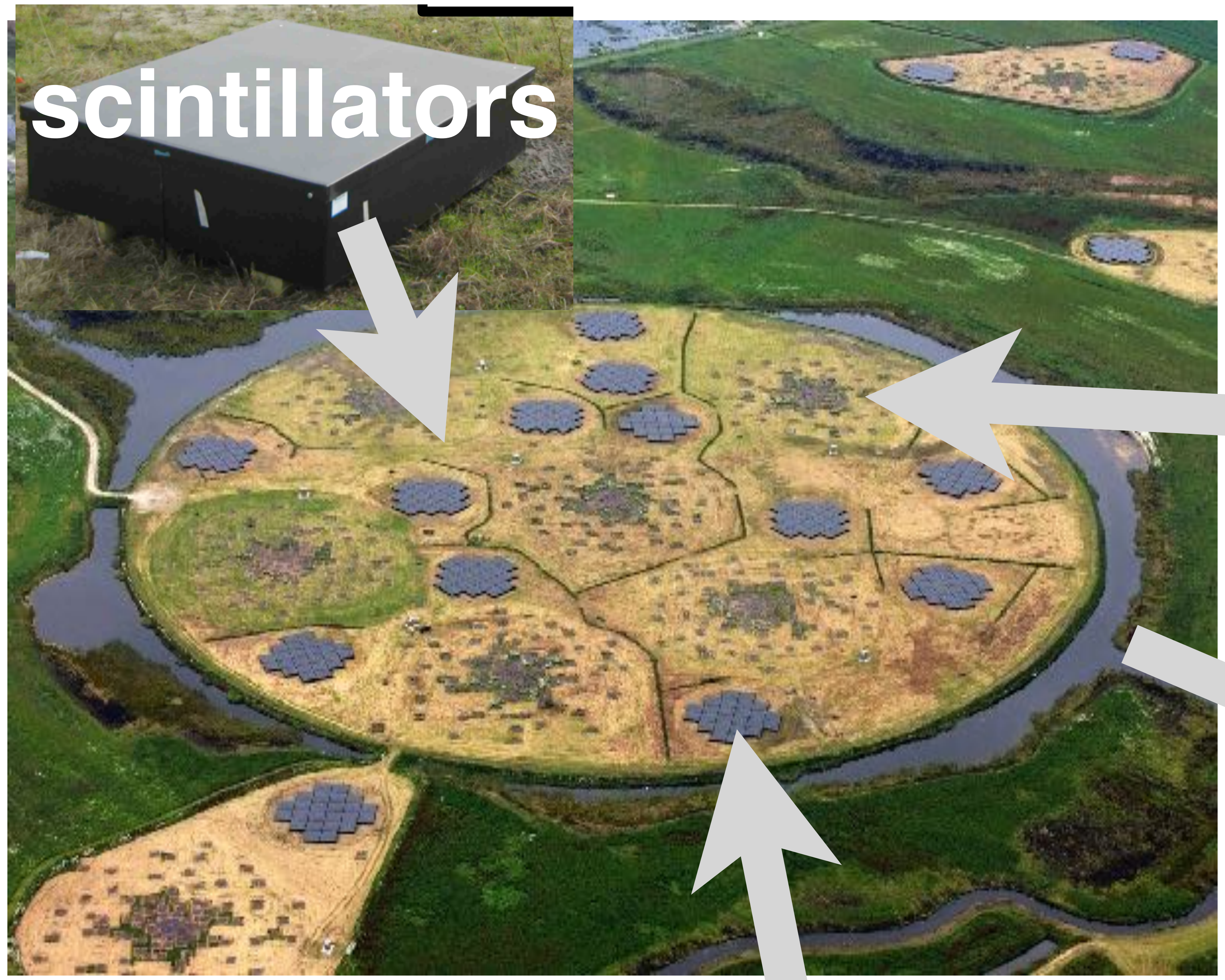


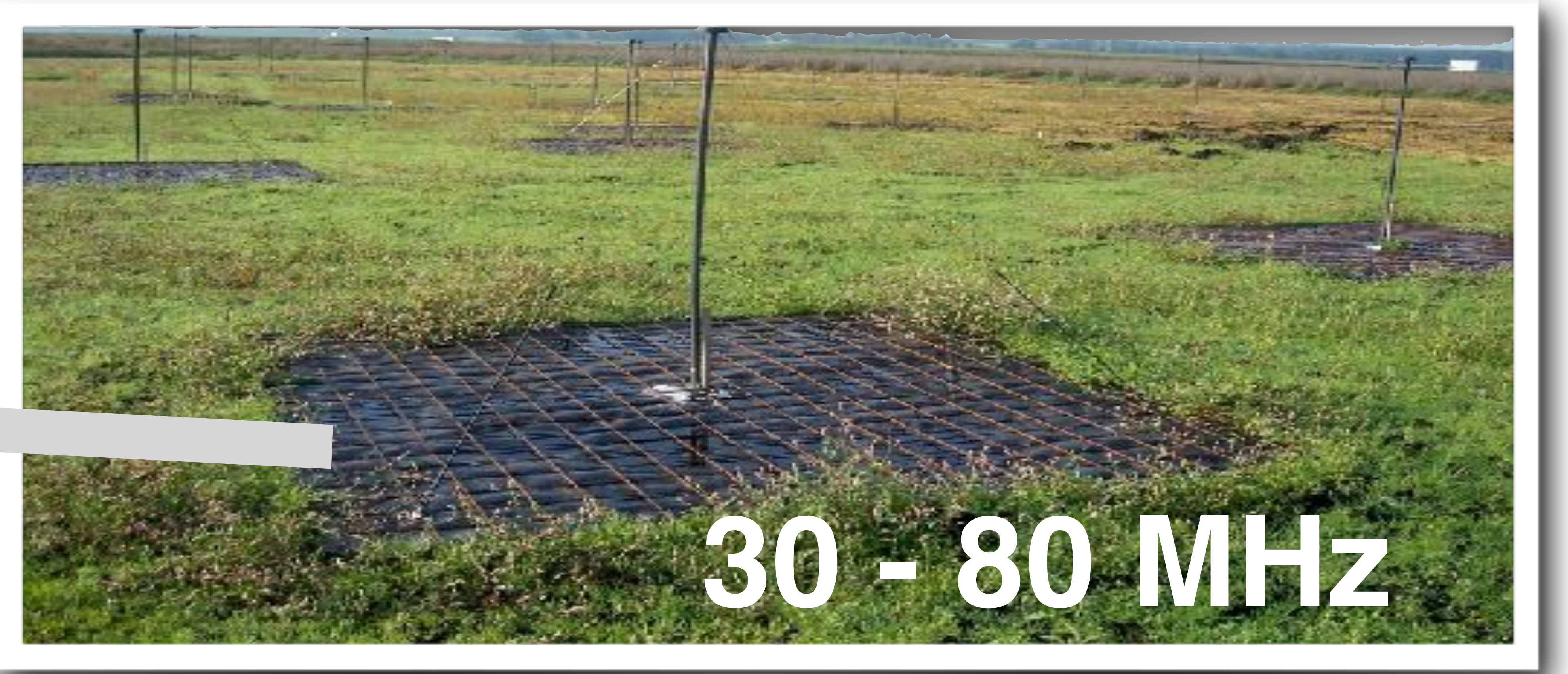


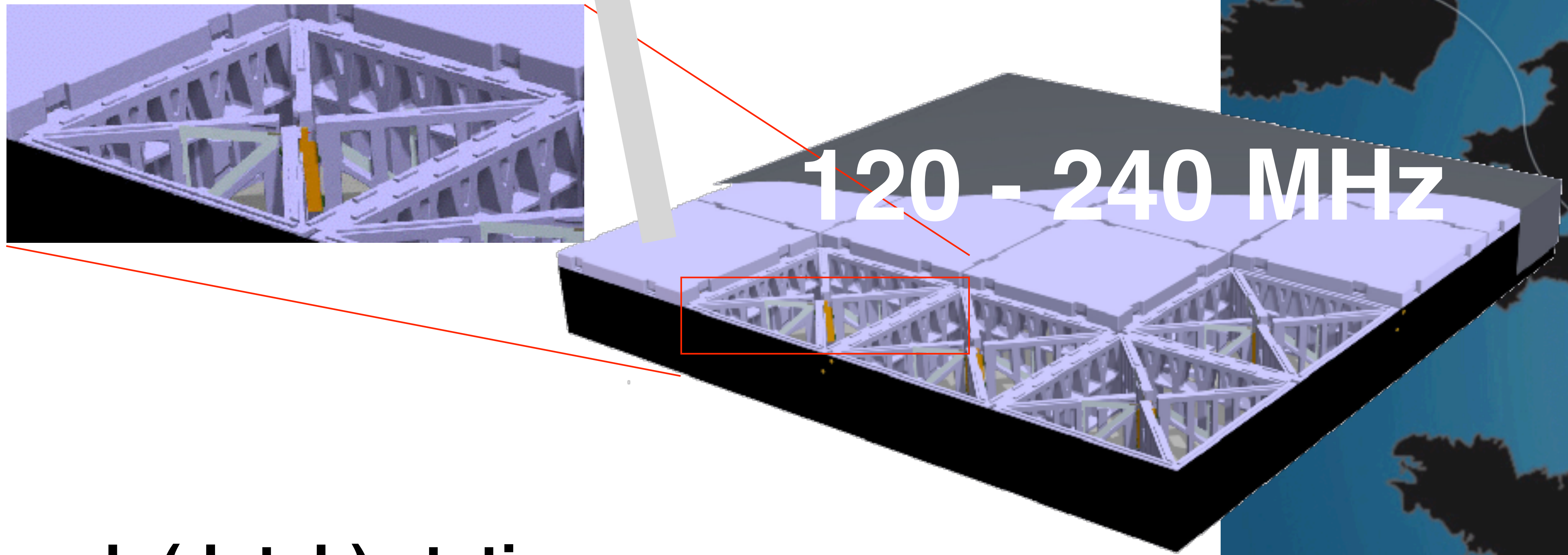
Footprint of radio emission on the ground

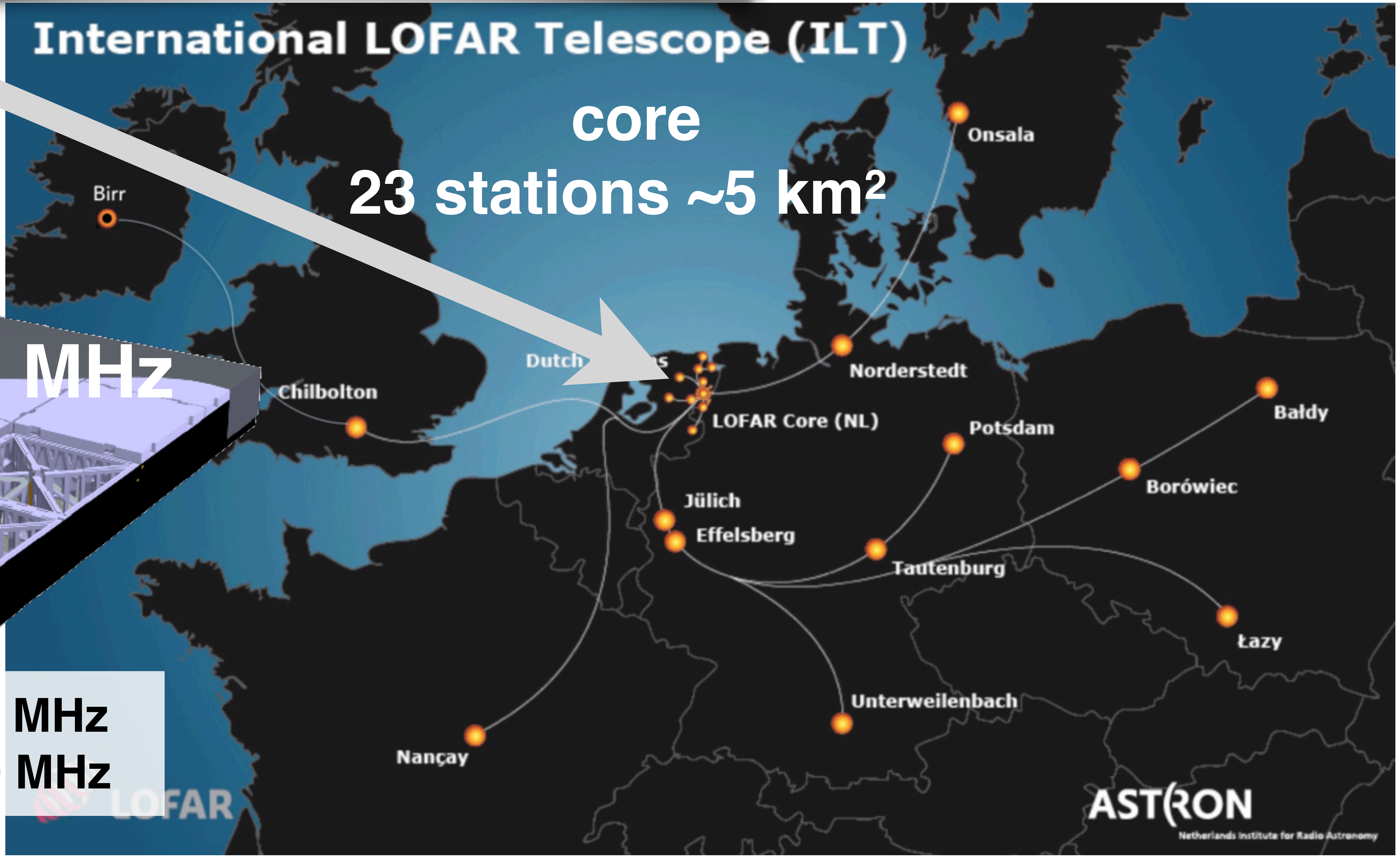












each (dutch) station:

96 low-band antennas 30- 80 MHz

high-band antennas (2x24 tiles) 120-240 MHz

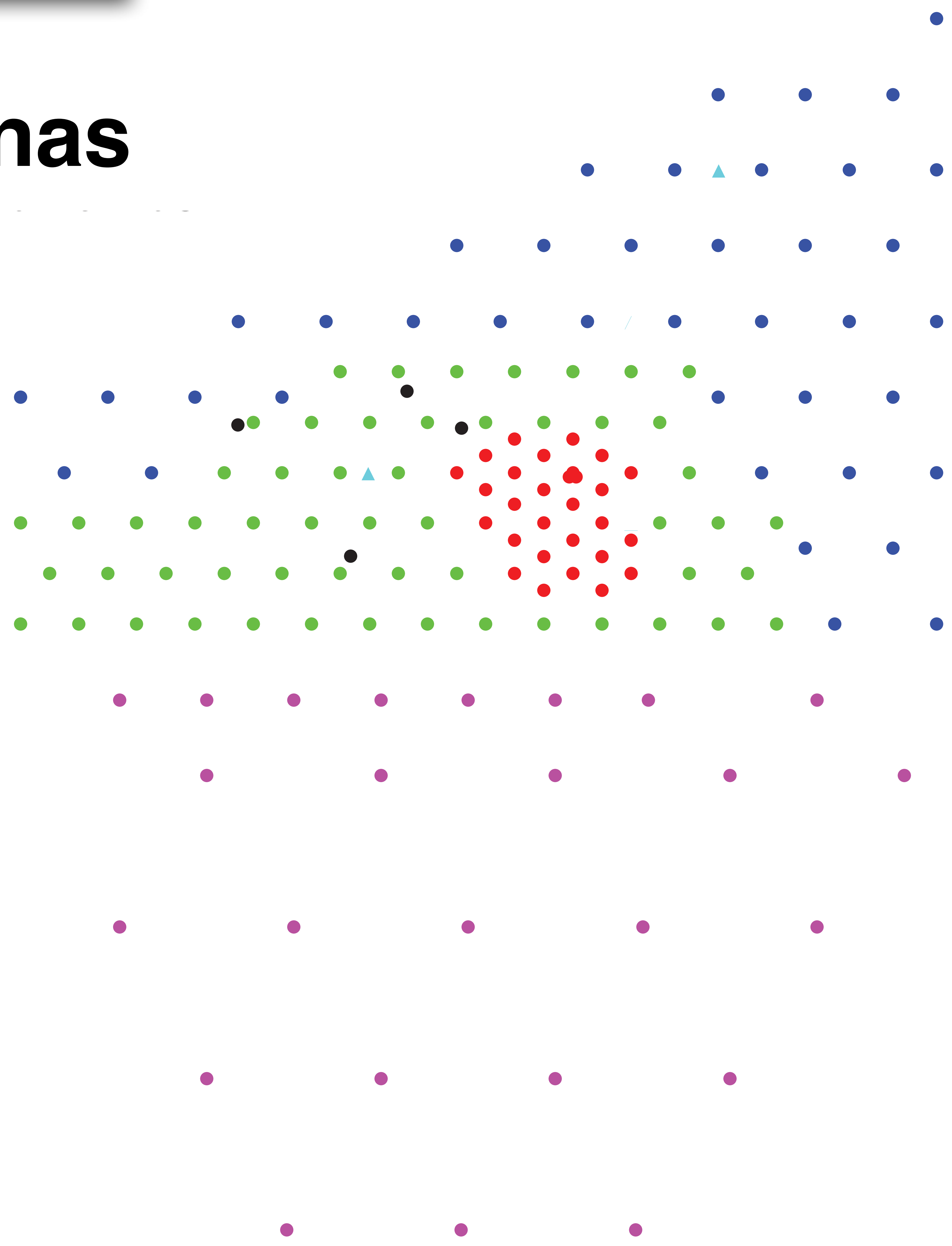
M. van Haarlem et al., A&A 556 (2013) A2

S. Thoudam et al., Nucl. Instr. Meth. A 767 (2014) 339

AERA
Auger Engineering Radio Array

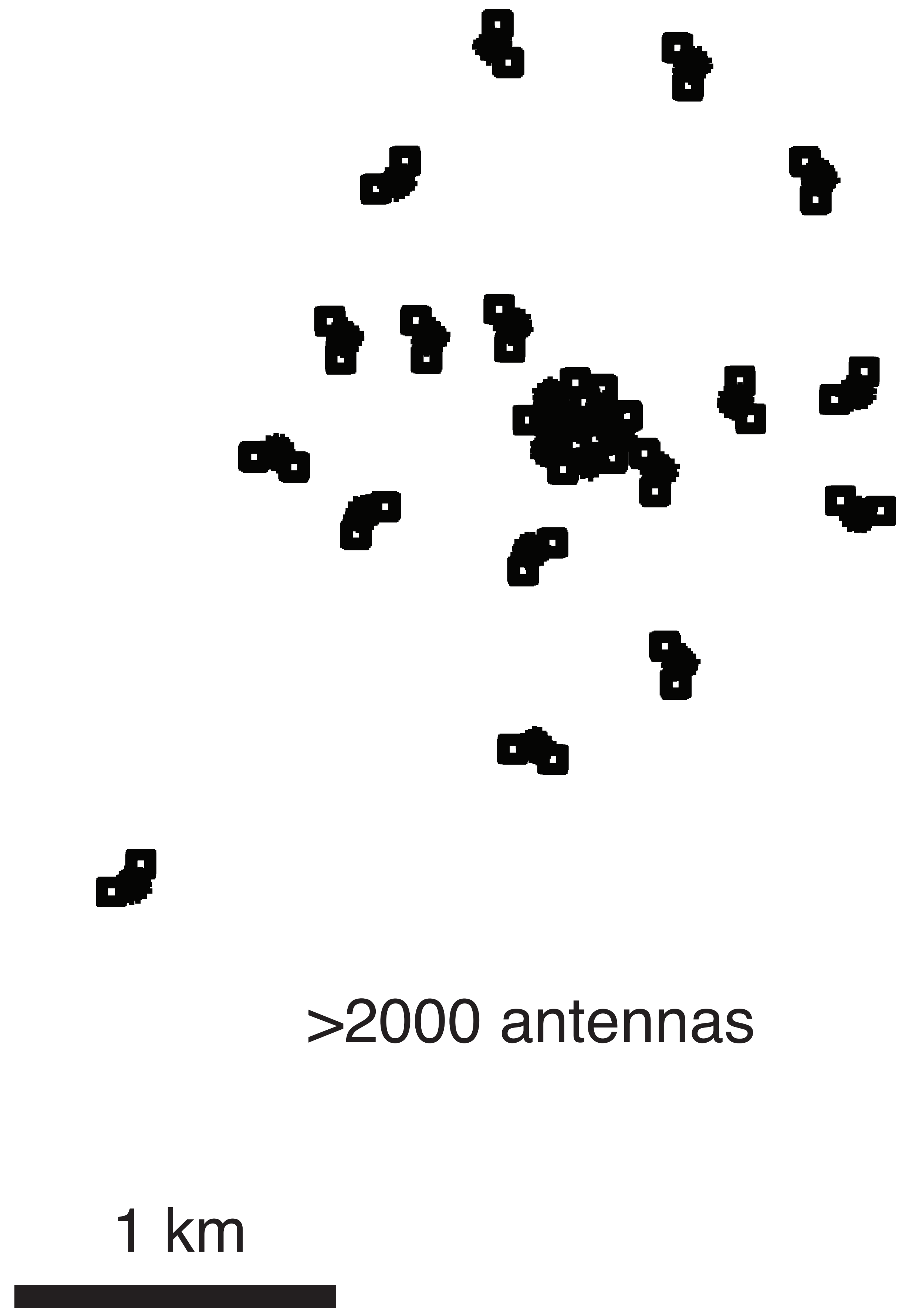
PIERRE AUGER OBSERVATORY

~150 antennas
~17 km²
30-80 MHz



LOFAR core

23 stations ~5 km²



PIERRE AUGER OBSERVATORY

AERA
Auger Engineering Radio Array

~150 antennas
~17 km^2
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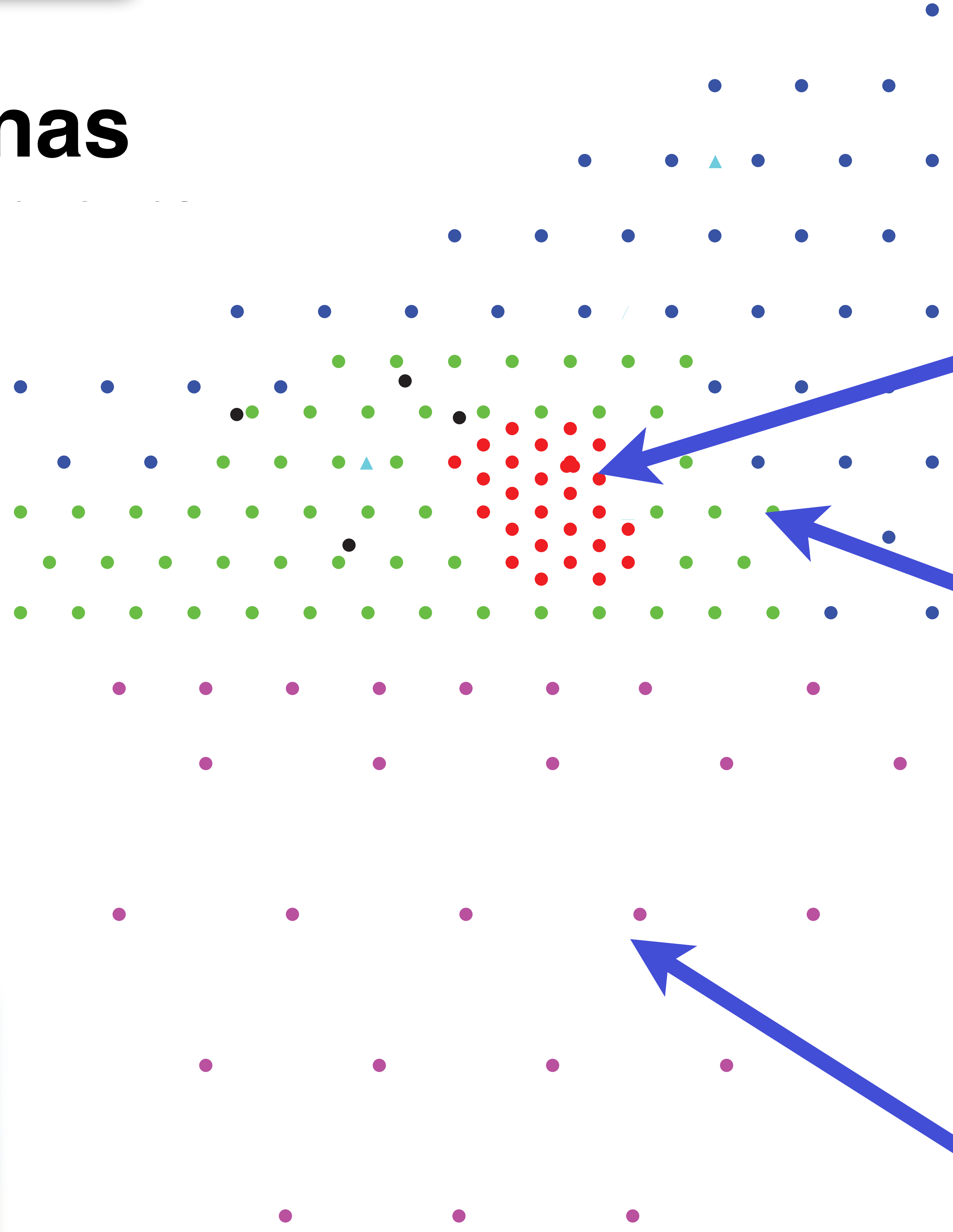
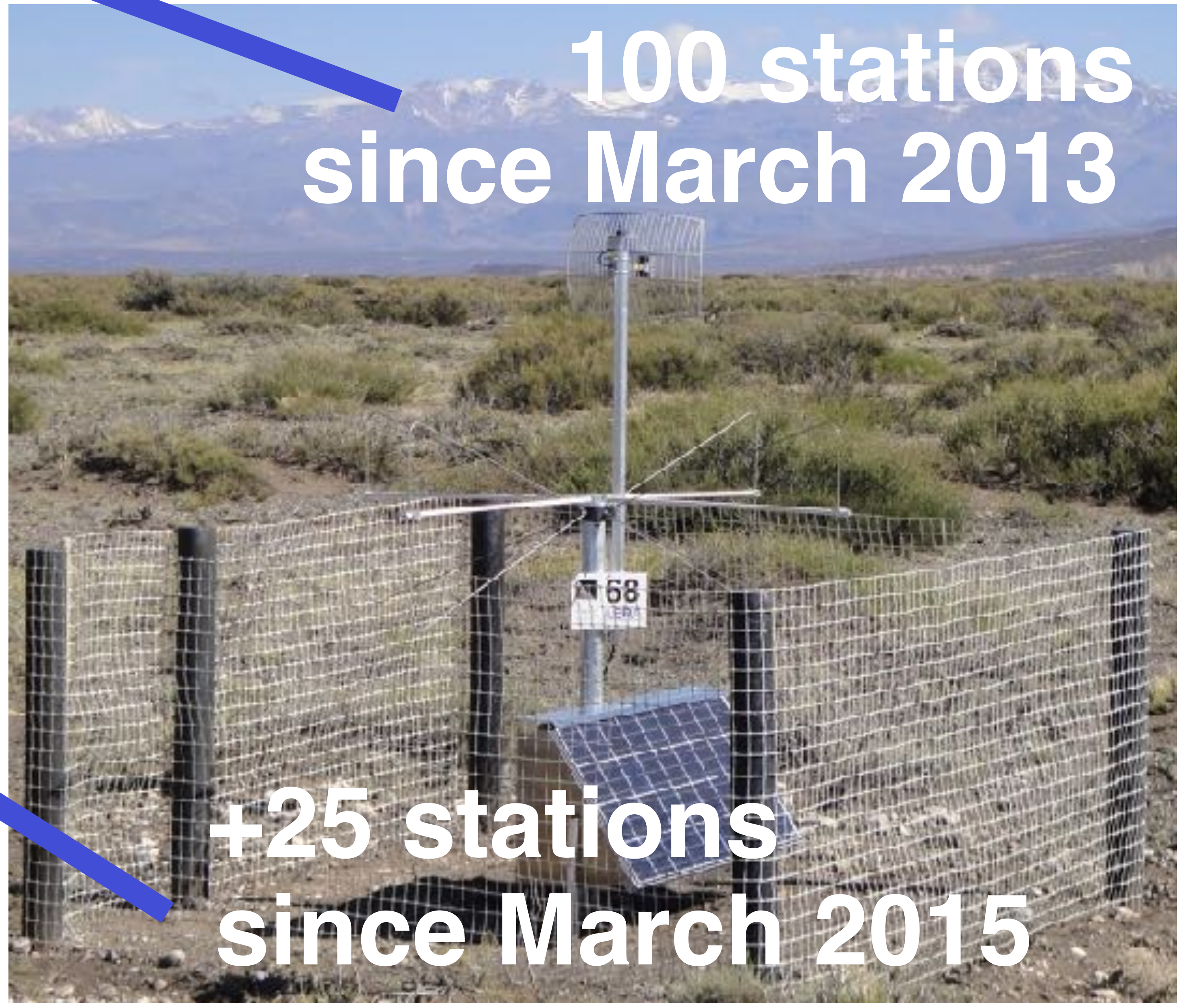
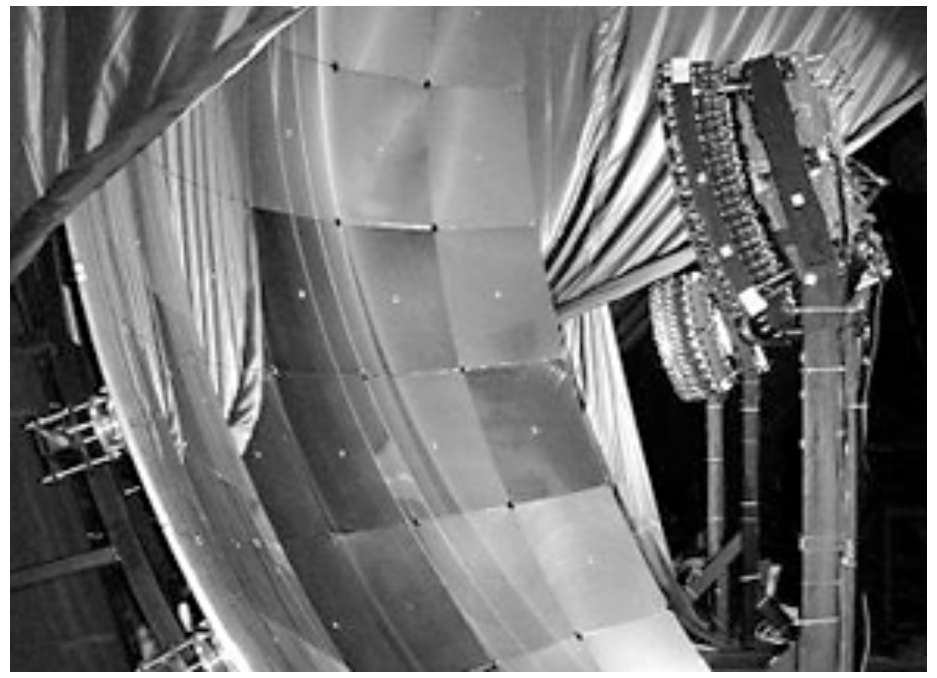






Properties of incoming cosmic ray

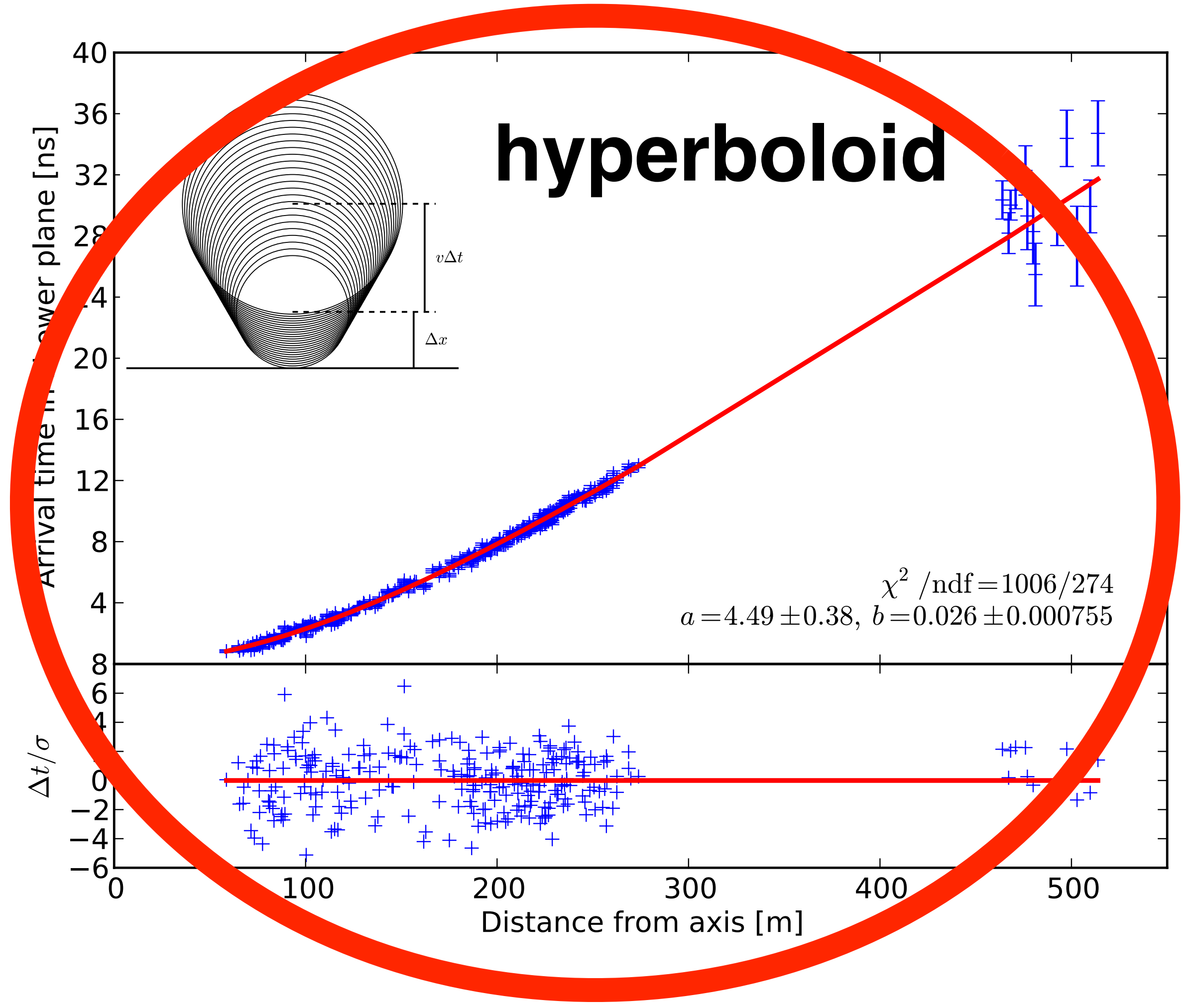
- direction
- energy
- type

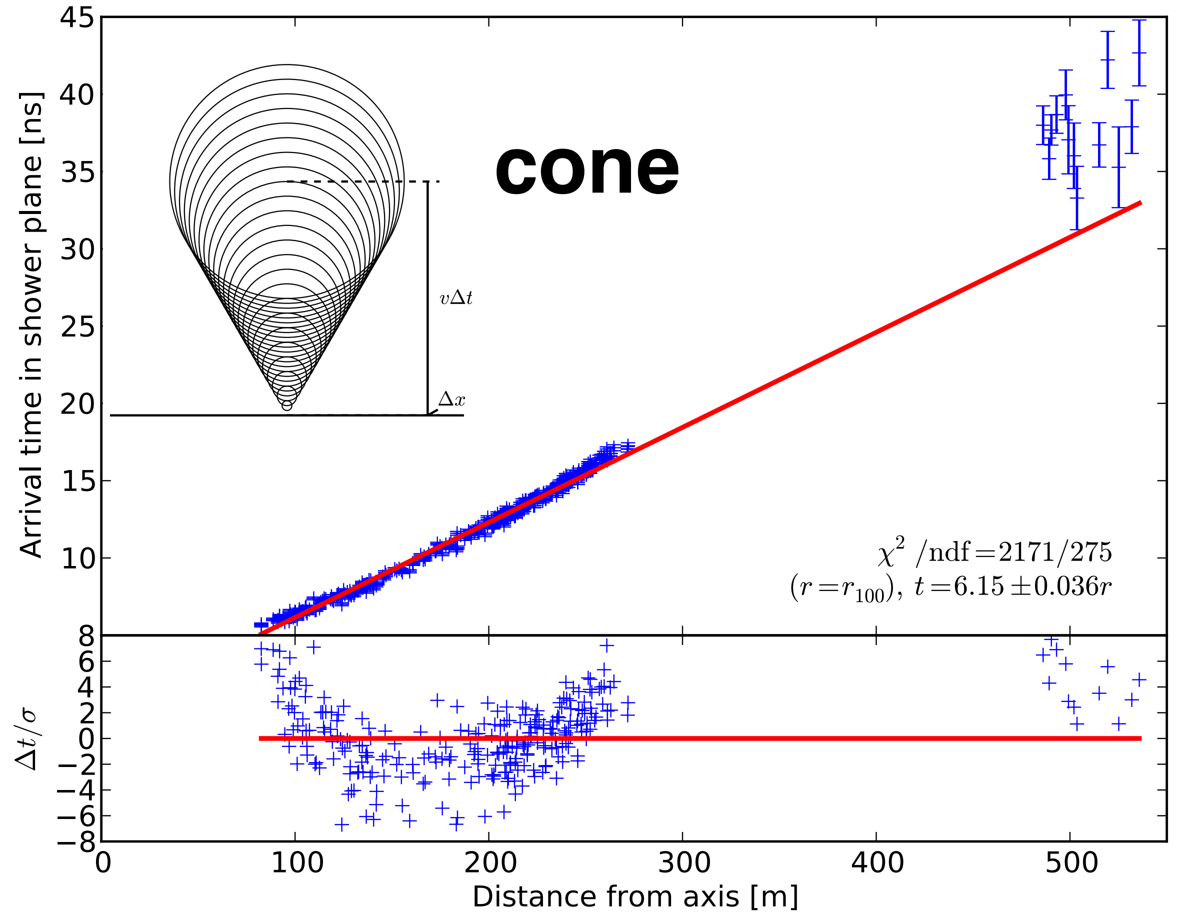
Direction

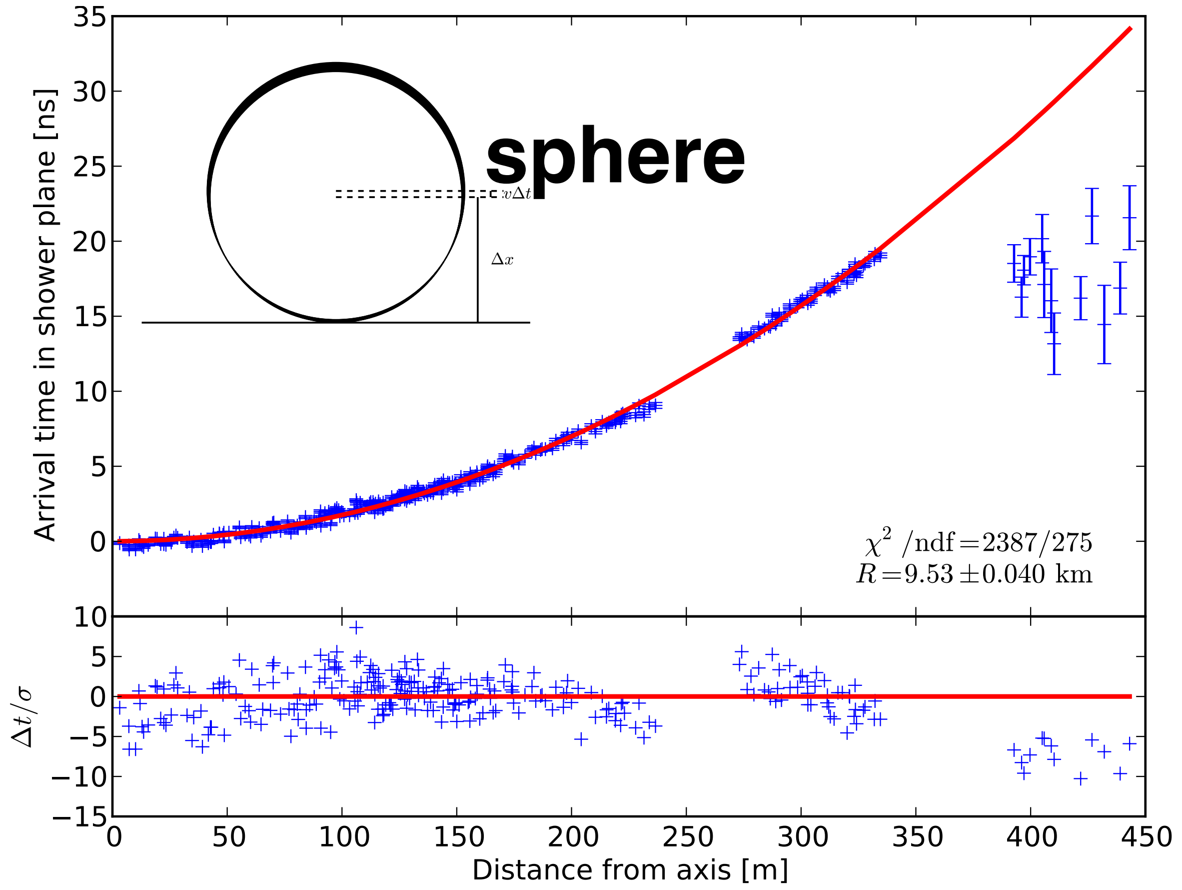
Shape of Shower Front

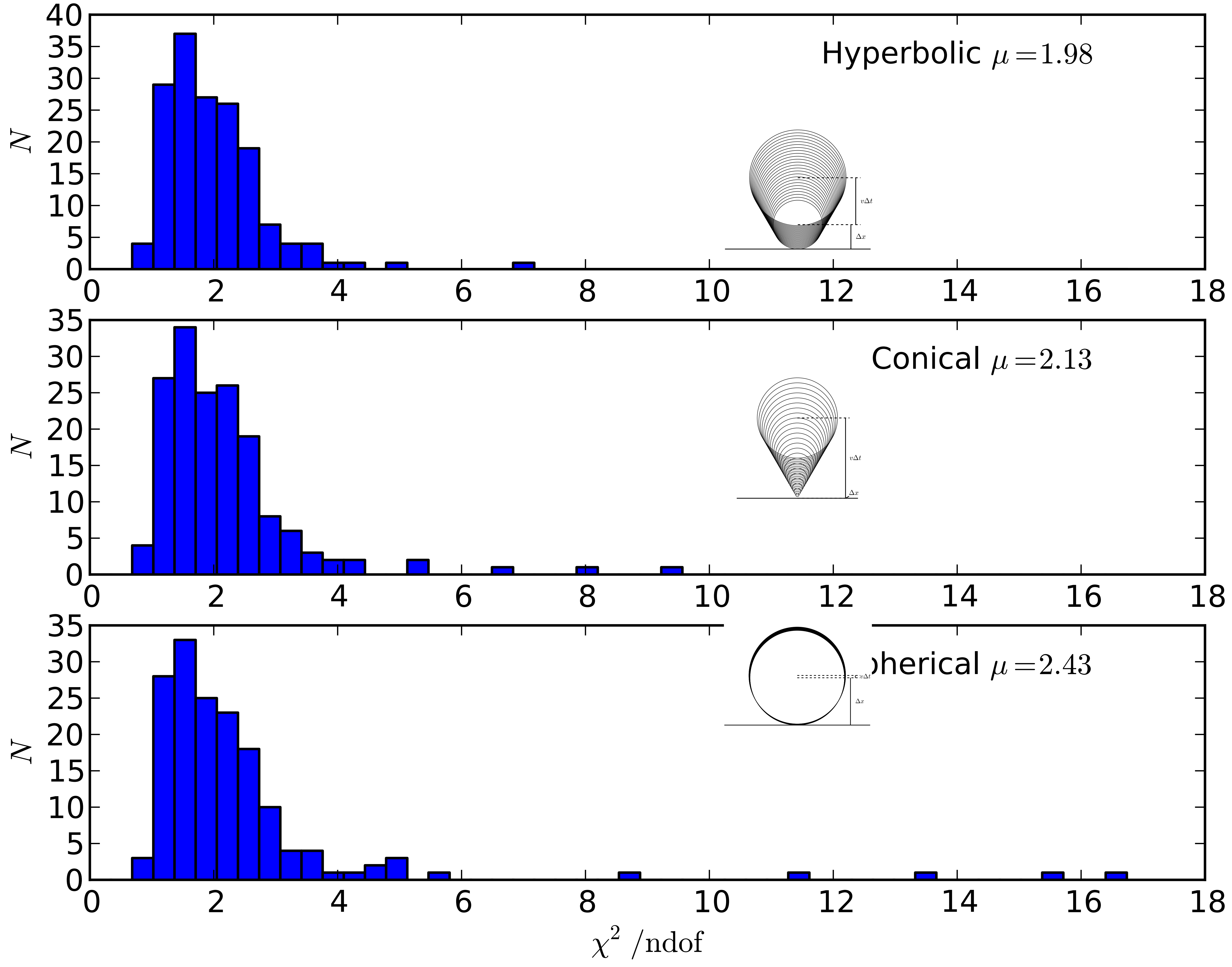
LOFAR

fit quality









A. Corstanje et al., Astropart. Phys. 61 (2015) 22

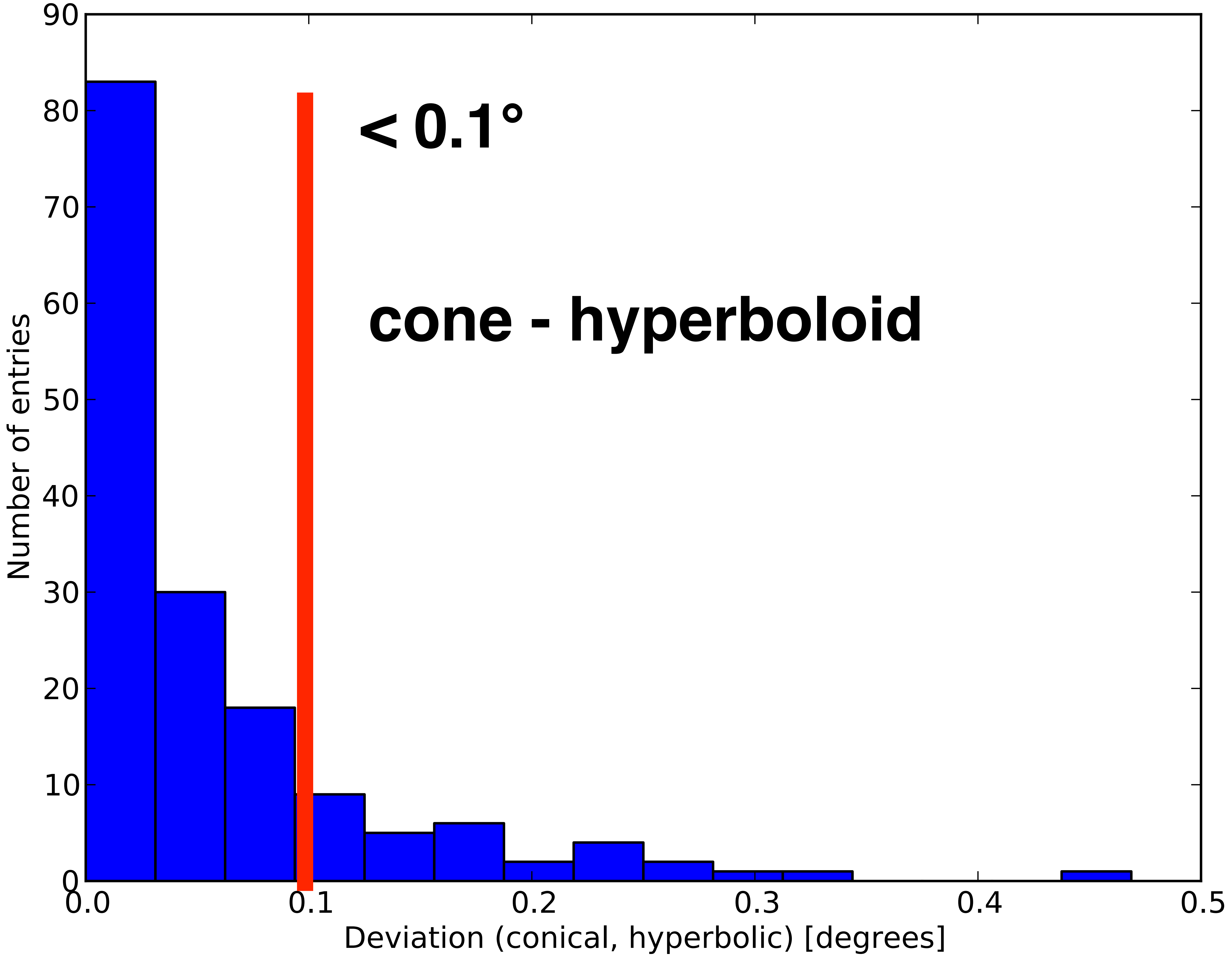
Shape of Shower Front

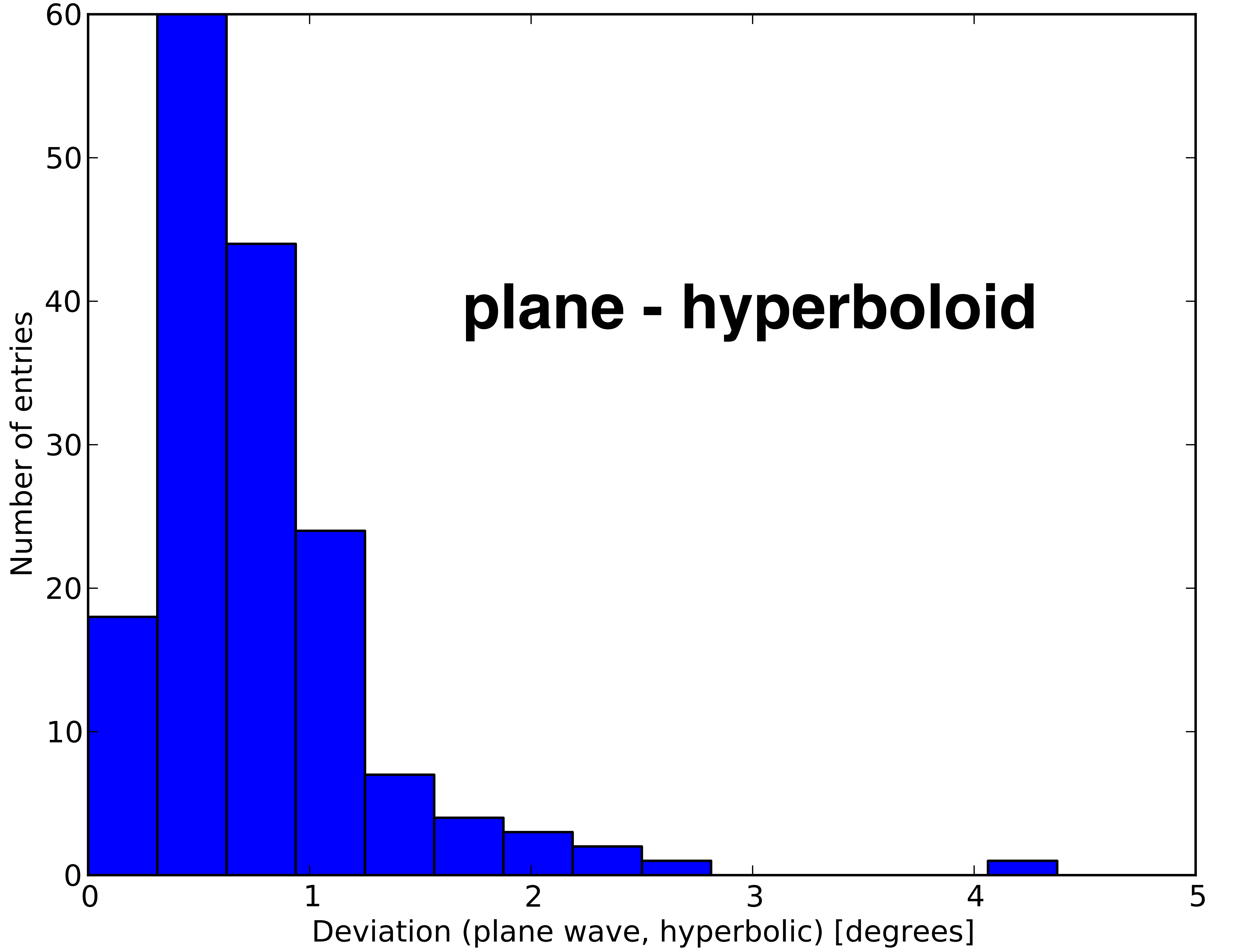
W.D. Apel et al., JCAP 1409 (2014) no.09, 025

A. Corstanje et al., Astropart. Phys. 61 (2015) 22

Accuracy of Shower Direction

angular difference between..

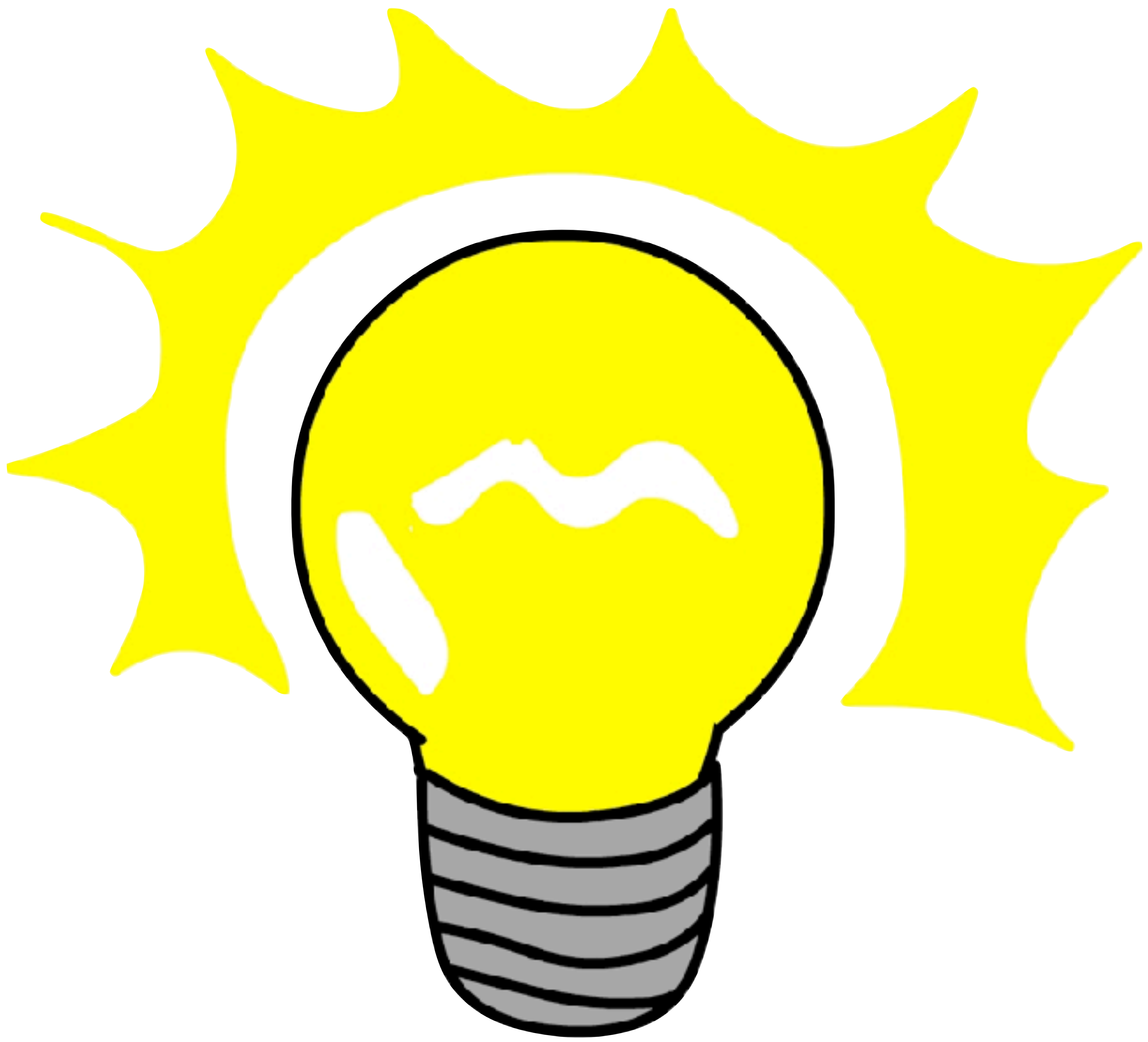




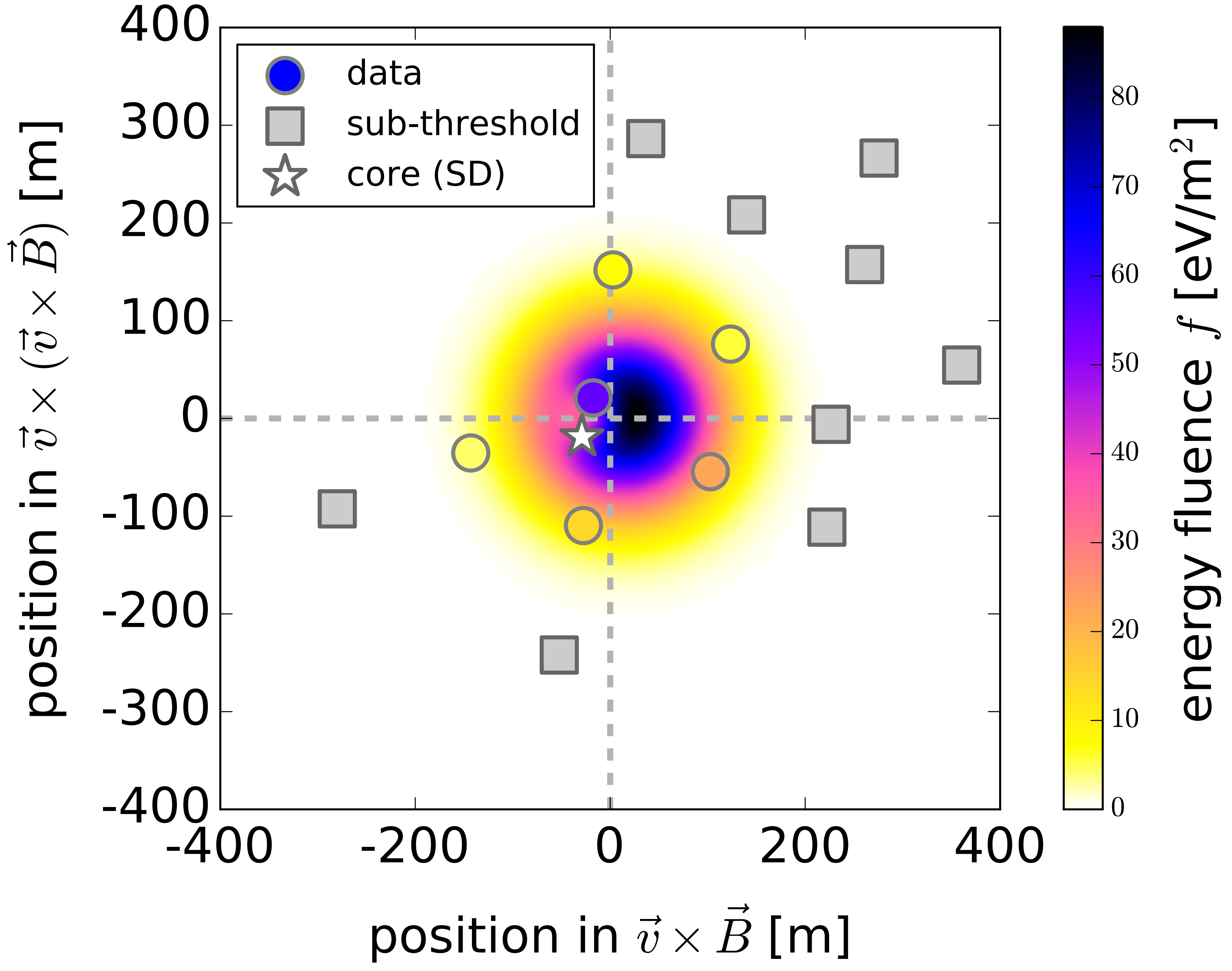
A. Corstanje et al., Astropart. Phys. 61 (2015) 22

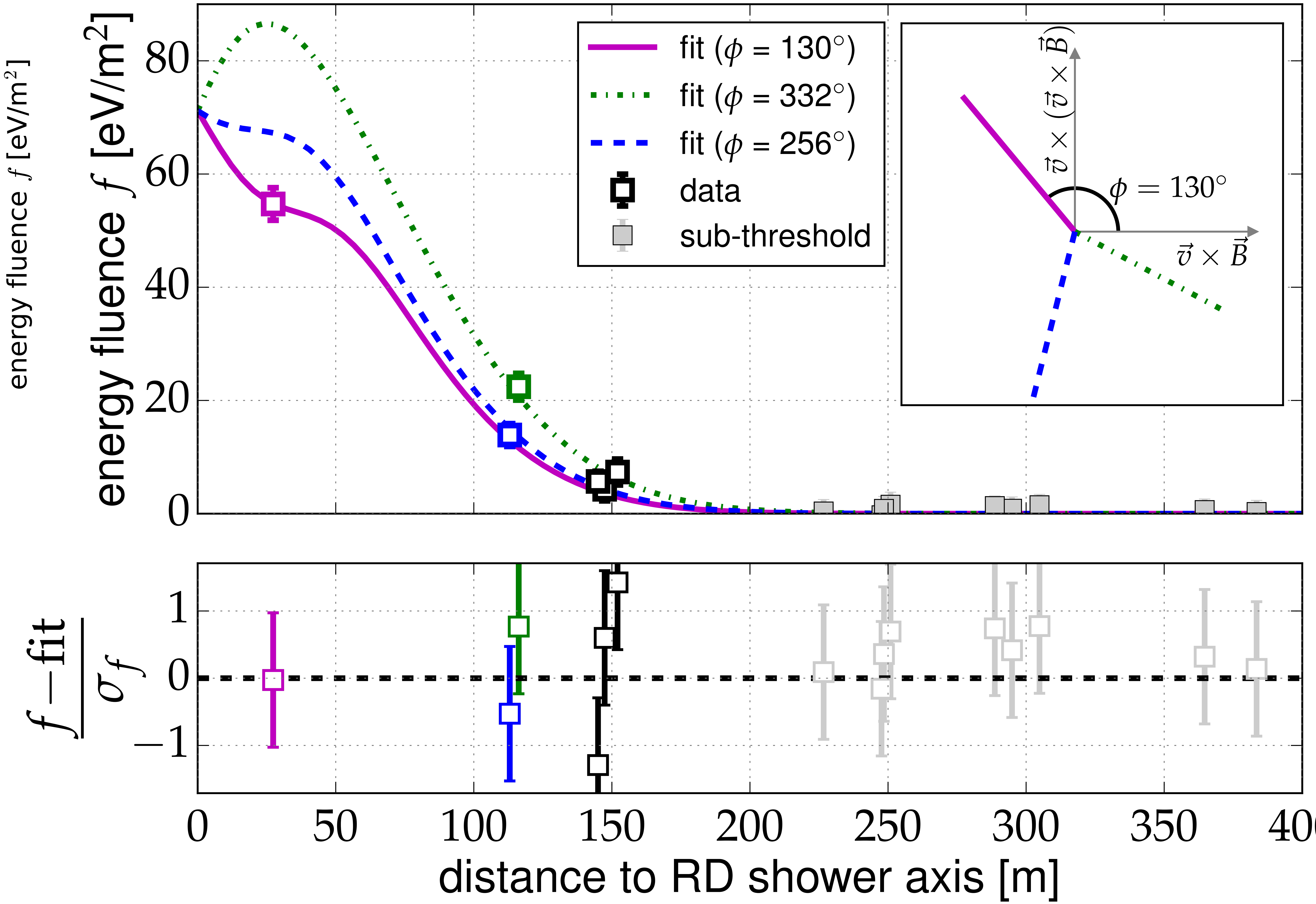
LOFAR

Energy



Measurement of the Radiation Energy in the Radio Signal of Extensive Air Showers as a Universal Estimator of Cosmic-Ray Energy



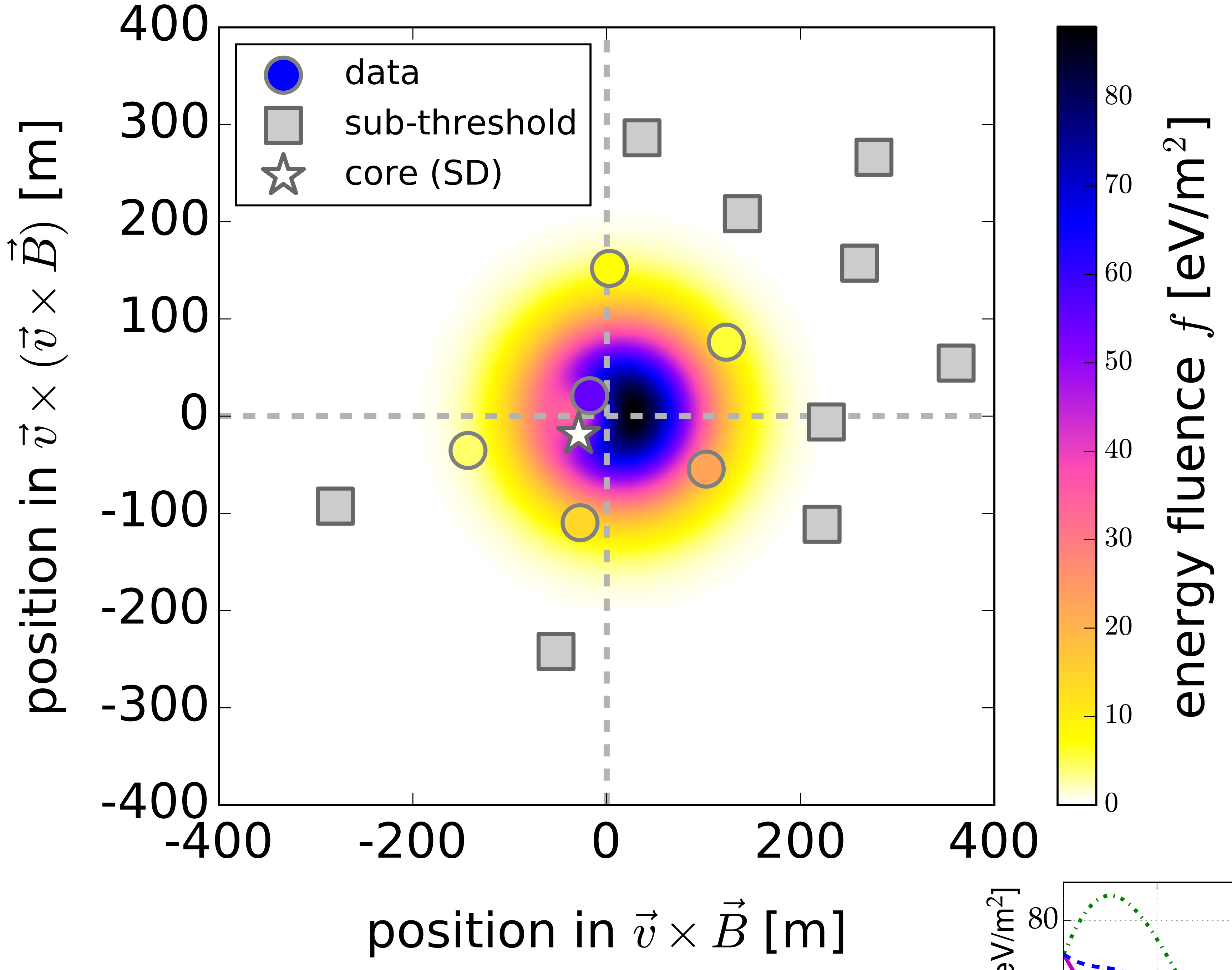


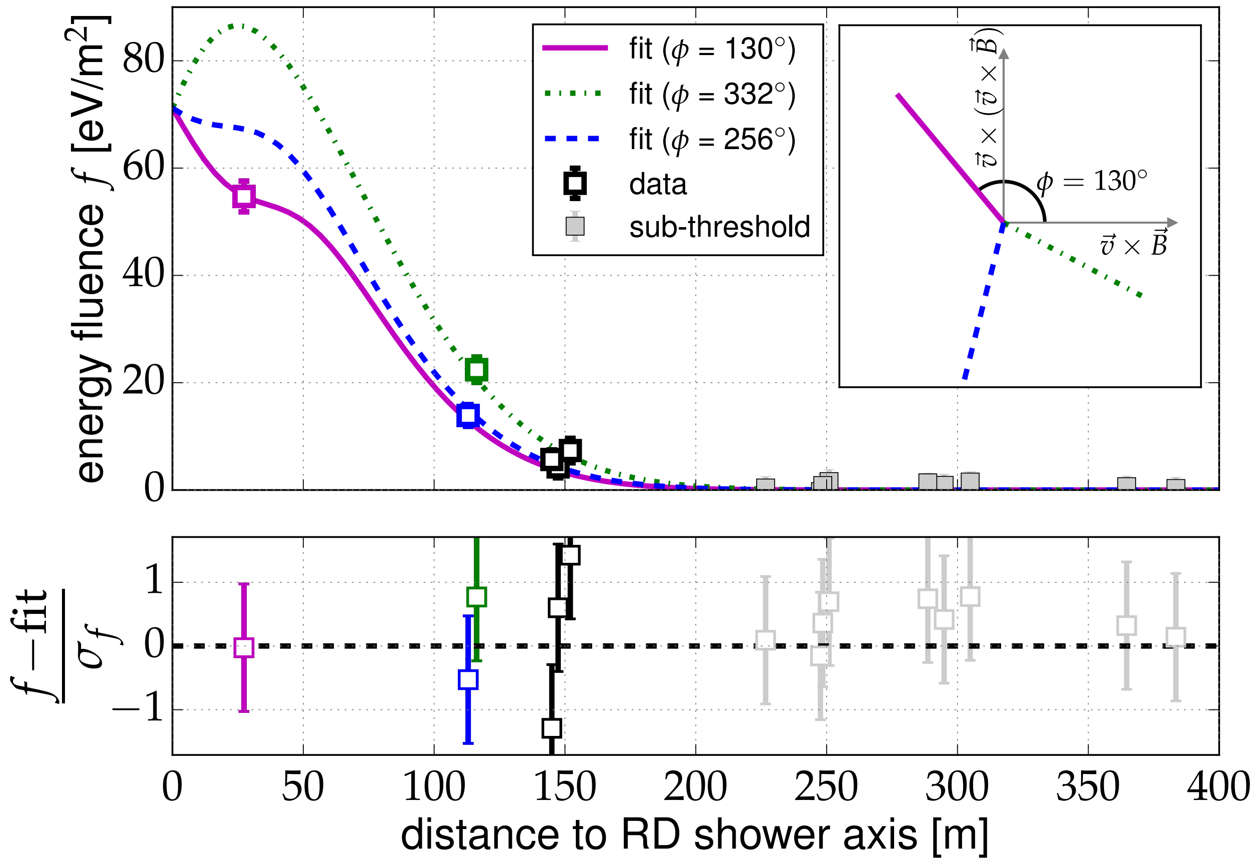
PIERRE AUGER OBSERVATORY

AERA Auger Engineering Radio Array

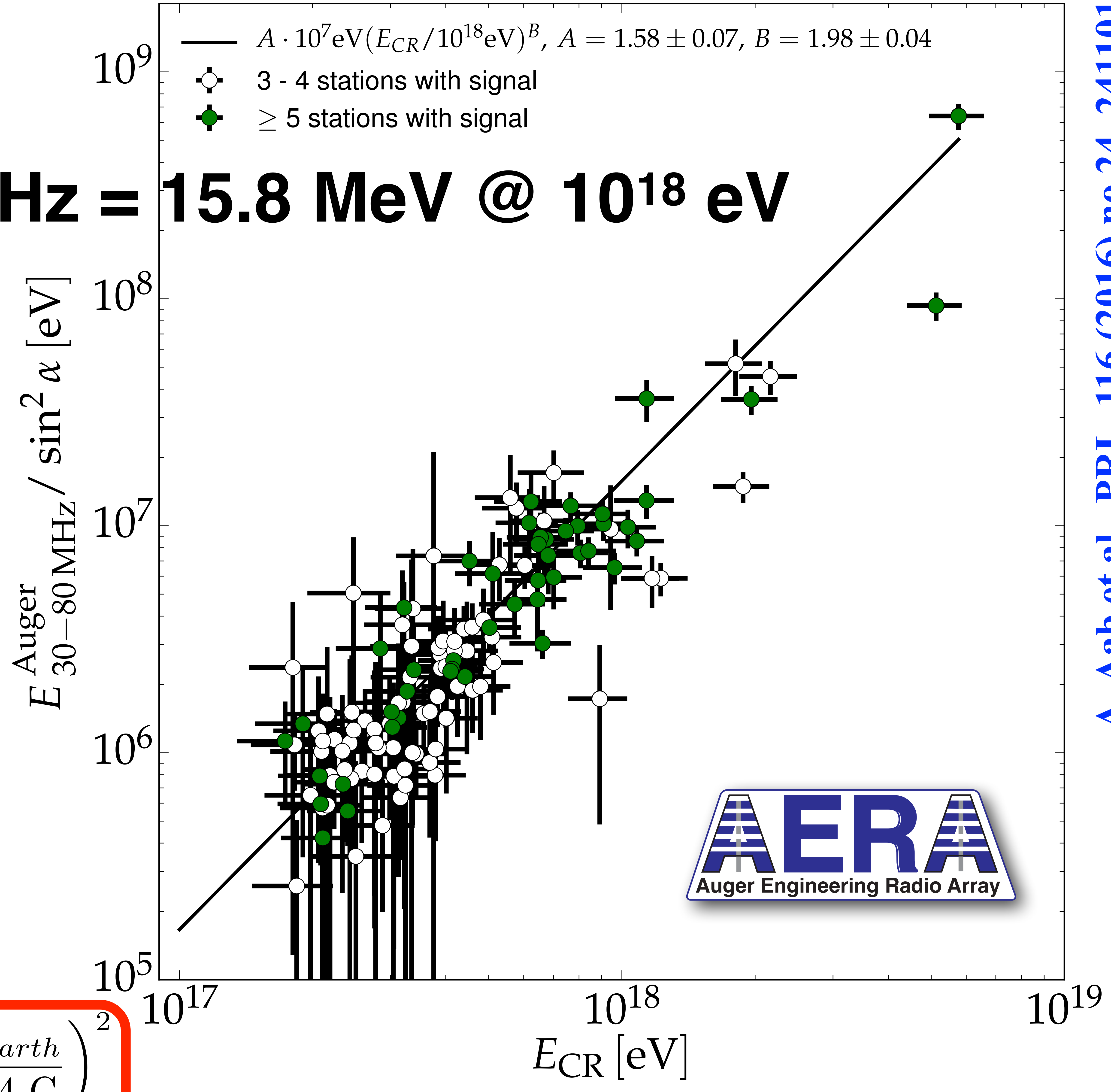
A. Aab et al., PRL 116 (2016) no.24, 241101

Measurement of the Radiation Energy in the Radio Signal of Extensive Air Showers as a Universal Estimator of Cosmic-Ray Energy





$E_{30\text{-}80}$ MHz = 15.8 MeV @ 10^{18} eV



A. Aab et al., PRL 116 (2016) no.24, 241101

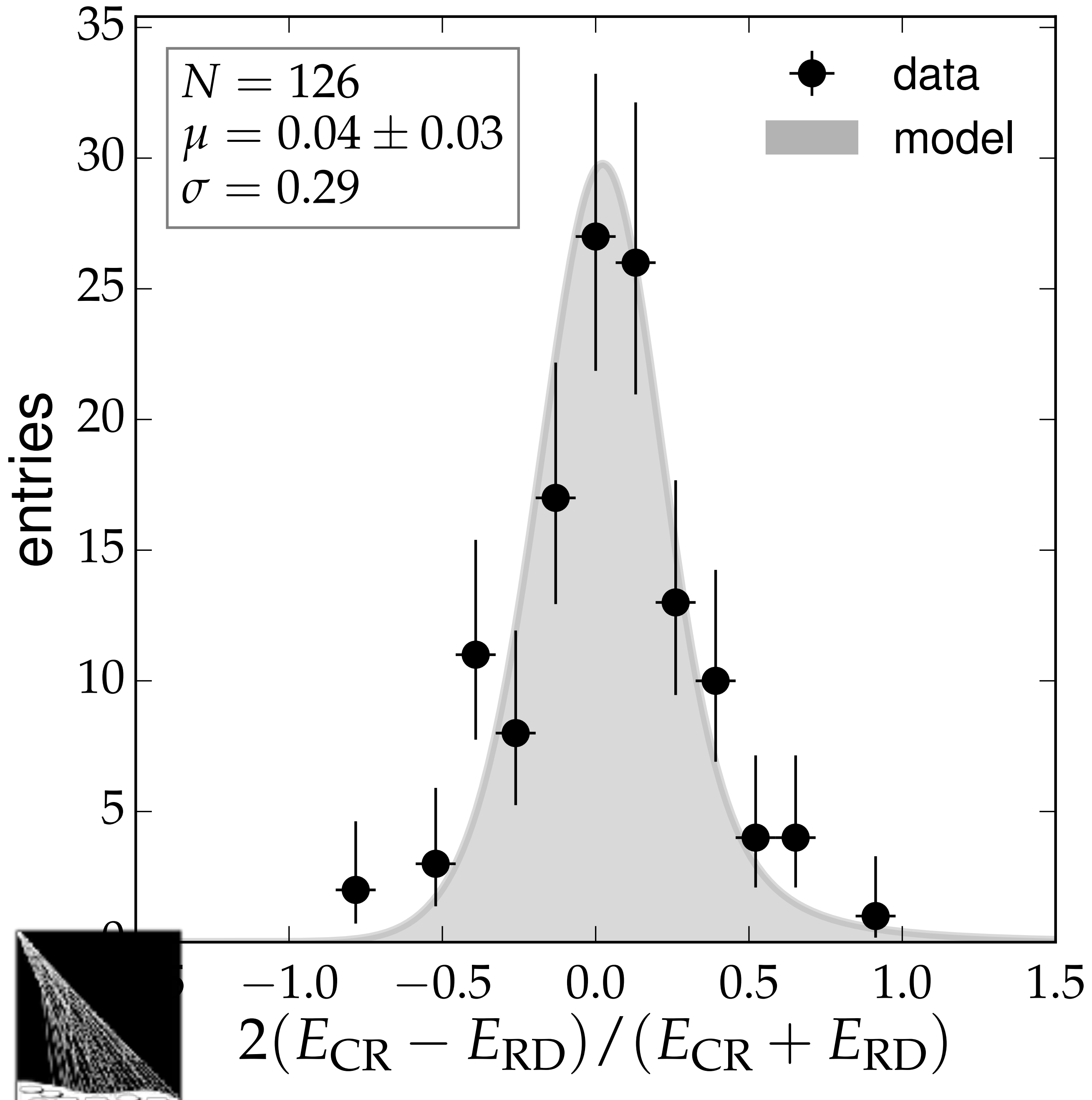
PIERRE AUGER OBSERVATORY

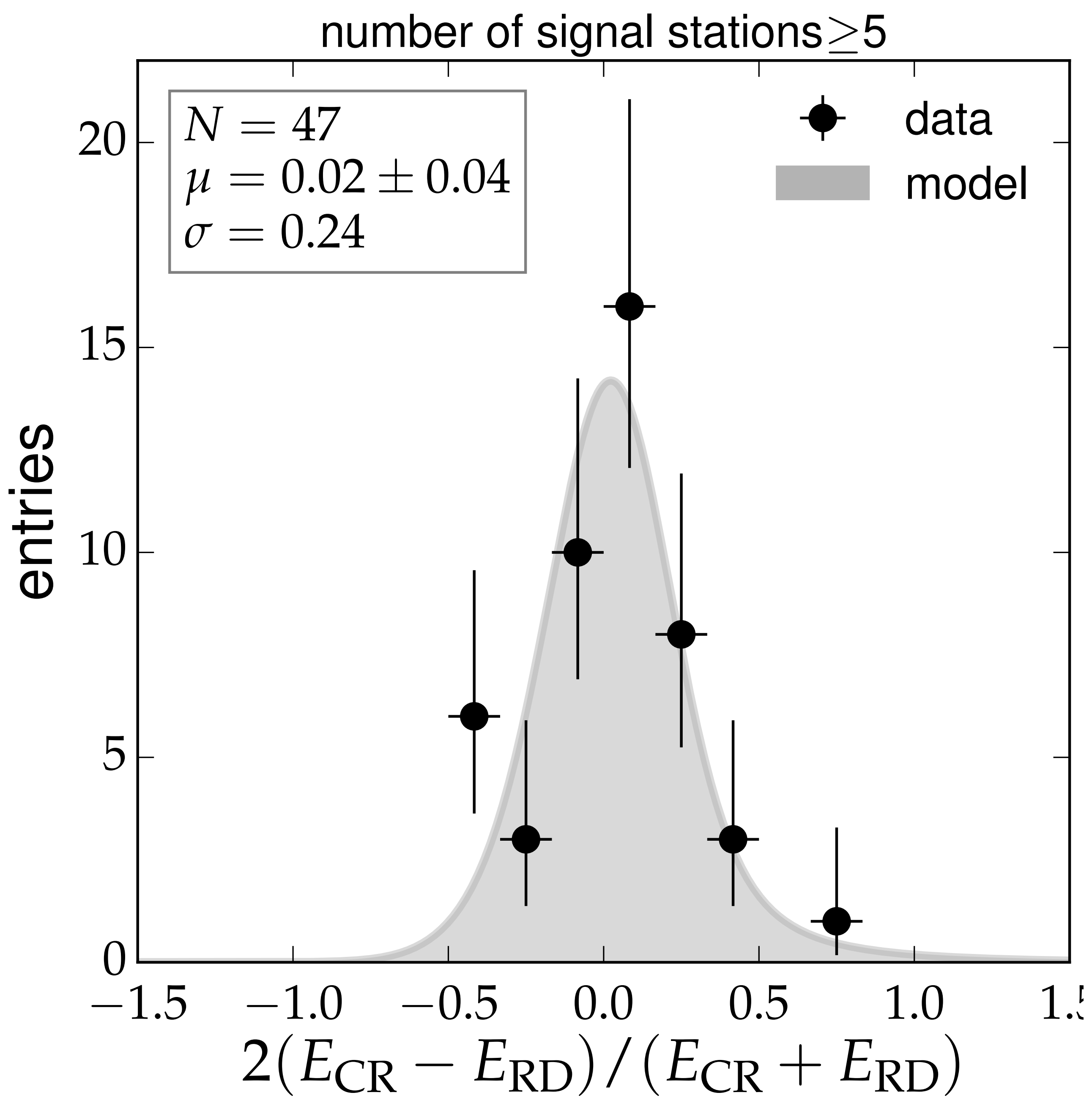
AERA Auger Engineering Radio Array

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

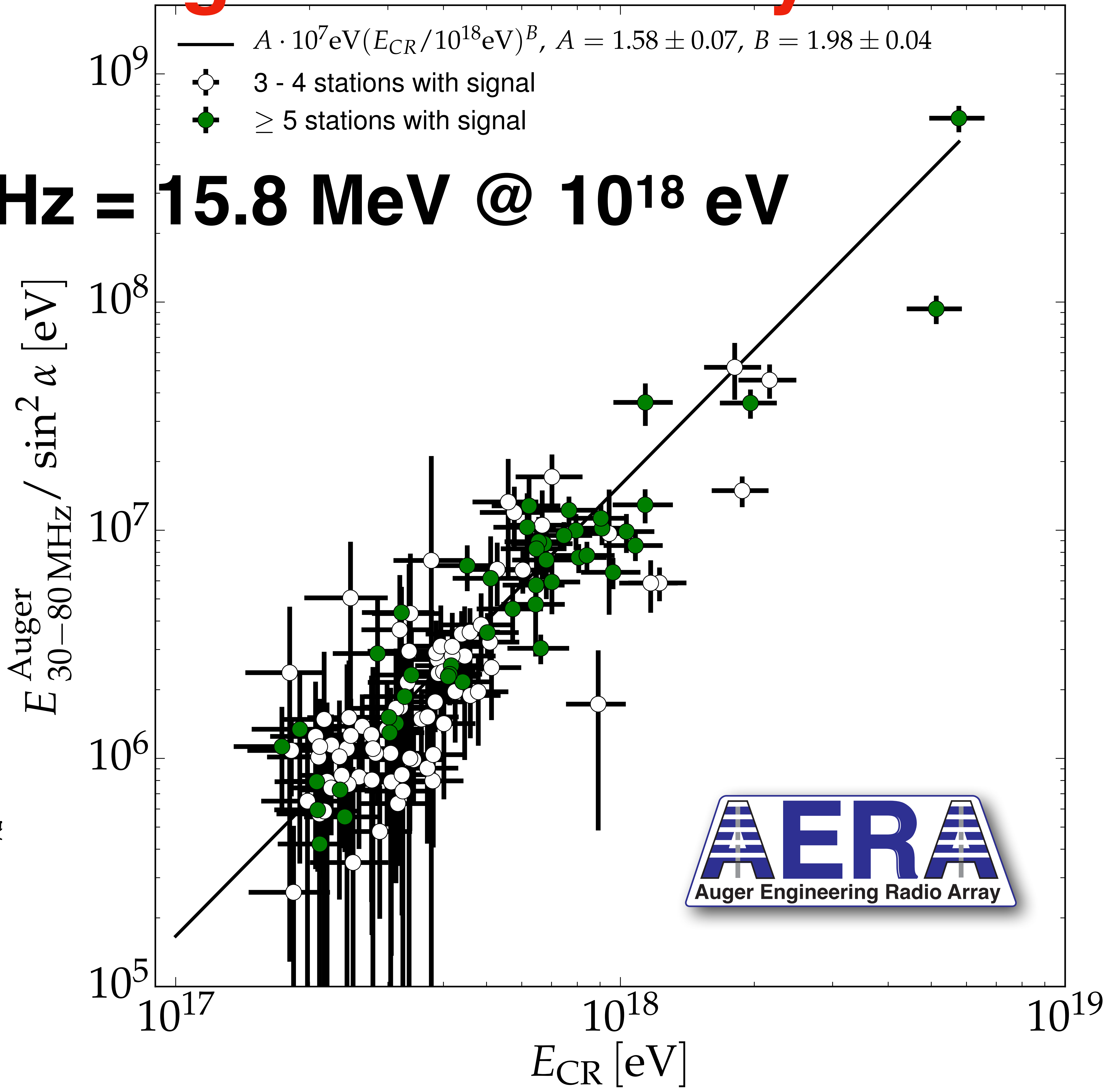
Energy Estimation of Cosmic Rays with the Engineering Radio Array of the Pierre Auger Observatory

$E_{30\text{-}80}$ **MHz = 15.8 MeV @ 10^{18} eV**





$$\sigma \approx 24\%$$

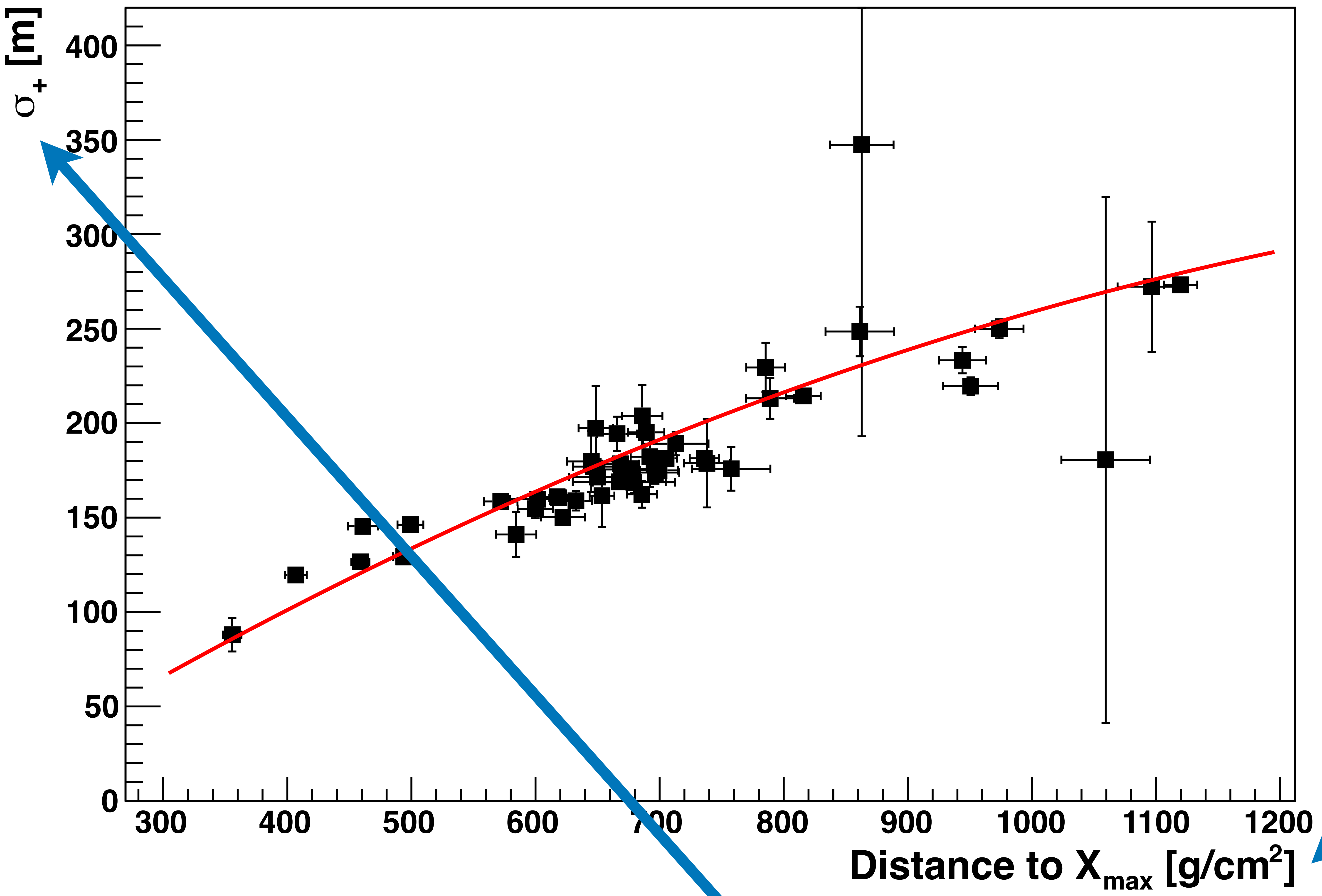


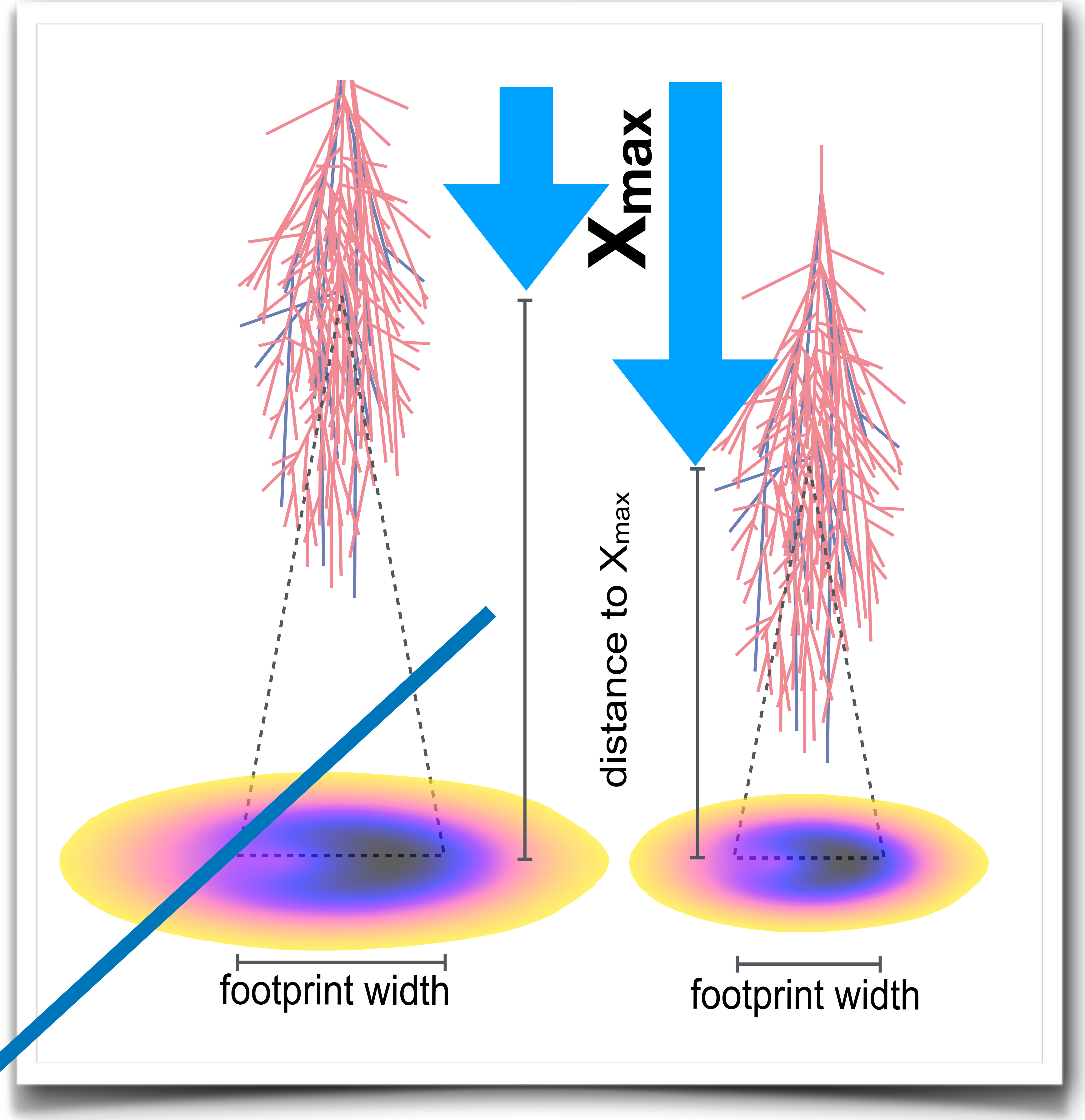
A. Aab et al., PRL 116 (2016) no.24, 241101

A. Aab et al., PRD 93 (2016) no.12, 122005

Particle type
Mass

Distance to Xmax





$$P(x', y') = A_{+} \cdot \exp\left(\frac{-[(x' - X_{+})^2 + (y' - Y_{+})^2]}{\sigma_{+}^2}\right) - A_{-} \cdot \exp\left(\frac{-[(x' - X_{-})^2 + (y' - Y_{-})^2]}{\sigma_{-}^2}\right) + O$$

A. Nelles et al., JCAP 05 (2015) 018

Measurement of particle mass

$\sigma_E \approx 32\%$

$\sigma_{X_{max}} \approx 17\ \mathrm{g/cm^2}$

S. Buitink et al., PRD 90 (2014) 082003

Depth of the shower maximum

LETTER nature

doi:10.1038/nature16976

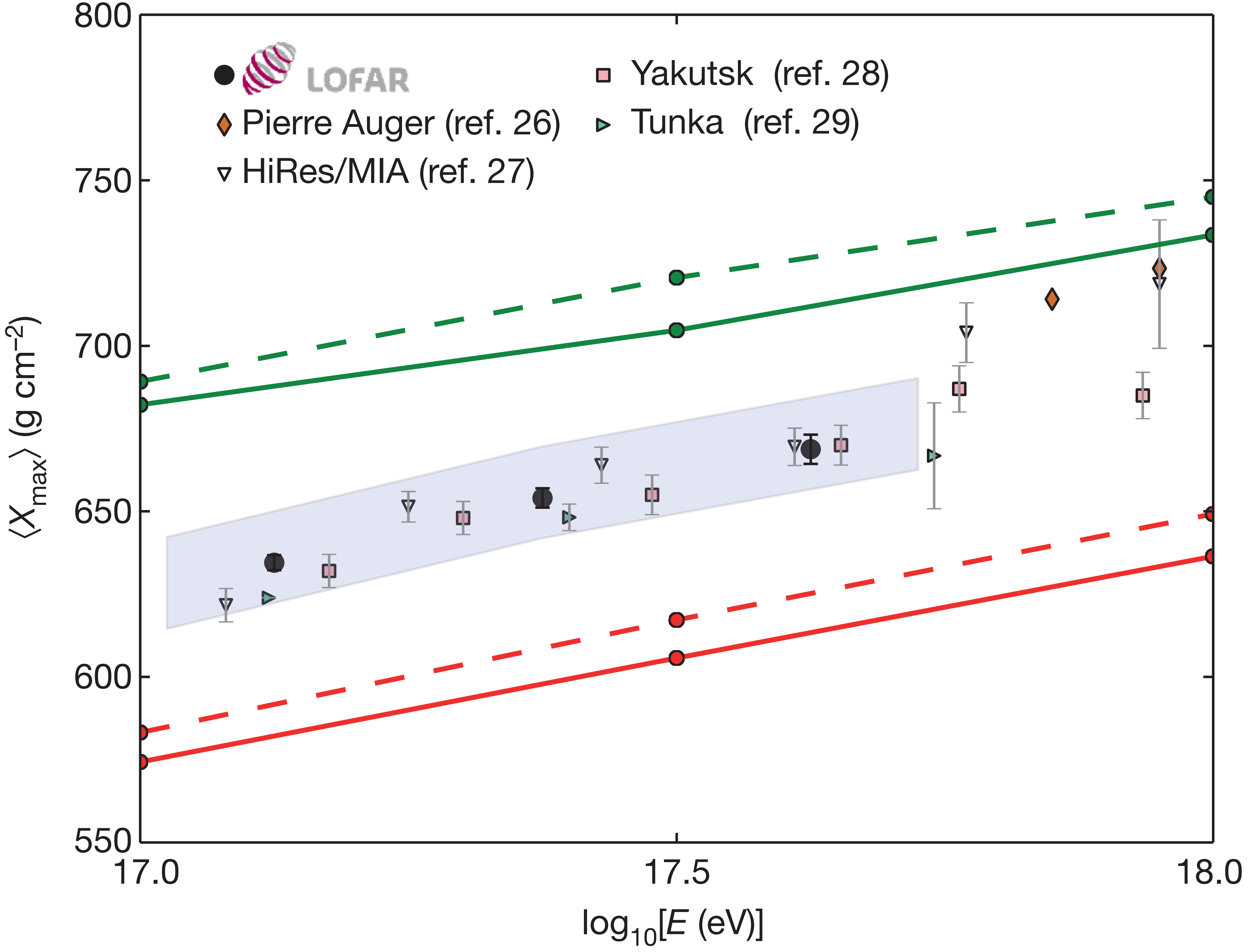
A large light-mass component of cosmic rays at 10^{17}–$10^{17.5}$ electronvolts from radio observations

S. Buitink[1,2], A. Corstanje[2], H. Falcke[2,3,4,5], J. R. Hörandel[2,4], T. Huege[6], A. Nelles[2,7], J. P. Rachen[2], L. Rossetto[2], P. Schellart[2], O. Scholten[8,9], S. ter Veen[3], S. Thoudam[2], T. N. G. Trinh[8], J. Anderson[10], A. Asgekar[3,11], I. M. Avruch[12,13], M. E. Bell[14], M. J. Bentum[3,15], G. Bernardi[16,17], P. Best[18], A. Bonafede[19], F. Breitling[20], J. W. Broderick[21], W. N. Brouw[3,13], M. Brüggen[19], H. R. Butcher[22], D. Carbone[23], B. Ciardi[24], J. E. Conway[25], F. de Gasperin[19], E. de Geus[3,26], A. Deller[3], R.-J. Dettmar[27], G. van Diepen[3], S. Duscha[3], J. Eislöffel[28], D. Engels[29], J. E. Enriquez[3], R. A. Fallows[3], R. Fender[30], C. Ferrari[31], W. Frieswijk[3], M. A. Garrett[3,32], J. M. Grießmeier[33,34], A. W. Gunst[3], M. P. van Haarlem[3], T. E. Hassall[21], G. Heald[3,13], J. W. T. Hessels[3,23], M. Hoeft[28], A. Horneffer[5], M. Iacobelli[3], H. Intema[32,35], E. Juette[27], A. Karastergiou[30], V. I. Kondratiev[3,36], M. Kramer[5,37], M. Kuniyoshi[38], G. Kuper[3], J. van Leeuwen[3,23], G. M. Loose[3], P. Maat[3], G. Mann[20], S. Markoff[23], R. McFadden[3], D. McKay-Bukowski[39,40], J. P. McKean[3,13], M. Mevius[3,13], D. D. Mulcahy[21], H. Munk[3], M. J. Norden[3], E. Orru[3], H. Paas[41], M. Pandey-Pommier[42], V. N. Pandey[3], M. Pietka[30], R. Pizzo[3], A. G. Polatidis[3], W. Reich[5], H. J. A. Röttgering[32], A. M. M. Scaife[21], D. J. Schwarz[43], M. Serylak[30], J. Sluman[3], O. Smirnov[17,44], B. W. Stappers[37], M. Steinmetz[20], A. Stewart[30], J. Swinbank[23,45], M. Tagger[33], Y. Tang[3], C. Tasse[44,46], M. C. Toribio[3,32], R. Vermeulen[3], C. Vocks[20], C. Vogt[3], R. J. van Weeren[16], R. A. M. J. Wijers[23], S. J. Wijnholds[3], M. W. Wise[3,23], O. Wucknitz[5], S. Yatawatta[3], P. Zarka[47] & J. A. Zensus[5]

Cosmic rays are the highest-energy particles found in nature. Measurements of the mass composition of cosmic rays with energies of 10^{17}–10^{18} electronvolts are essential to understanding whether they have galactic or extragalactic sources. It has also been proposed that the astrophysical neutrino signal[1] comes from accelerators capable of producing cosmic rays of these energies[2]. Cosmic rays initiate air showers—cascades of secondary particles in the atmosphere—and their masses can be inferred from measurements of the atmospheric depth of the shower maximum[3] (X_{max}; the depth of the air shower when it contains the most particles) or of the composition of shower particles reaching the ground[4]. Current measurements[5] have either high uncertainty, or a low duty cycle and a high energy threshold. Radio detection of cosmic rays[6–8] is a rapidly developing technique[9] for determining X_{max} (refs 10, 11) with a duty cycle of, in principle, nearly 100 per cent. The radiation is generated by the separation of relativistic electrons and positrons in the geomagnetic field and a negative charge excess in the shower front[6,12]. Here we report radio measurements of X_{max} with a mean uncertainty of 16 grams per square centimetre for air showers initiated by cosmic rays with energies of 10^{17}–$10^{17.5}$ electronvolts. This high resolution in X_{max} enables us to determine the mass spectrum of the cosmic rays: we find a mixed composition, with a light-mass fraction (protons and helium nuclei) of about 80 per cent. Unless, contrary to current expectations, the extragalactic component of cosmic rays contributes substantially to the total flux below $10^{17.5}$ electronvolts, our measurements indicate the existence of an additional galactic component, to account for the light composition that we measured in the 10^{17}–$10^{17.5}$ electronvolt range.

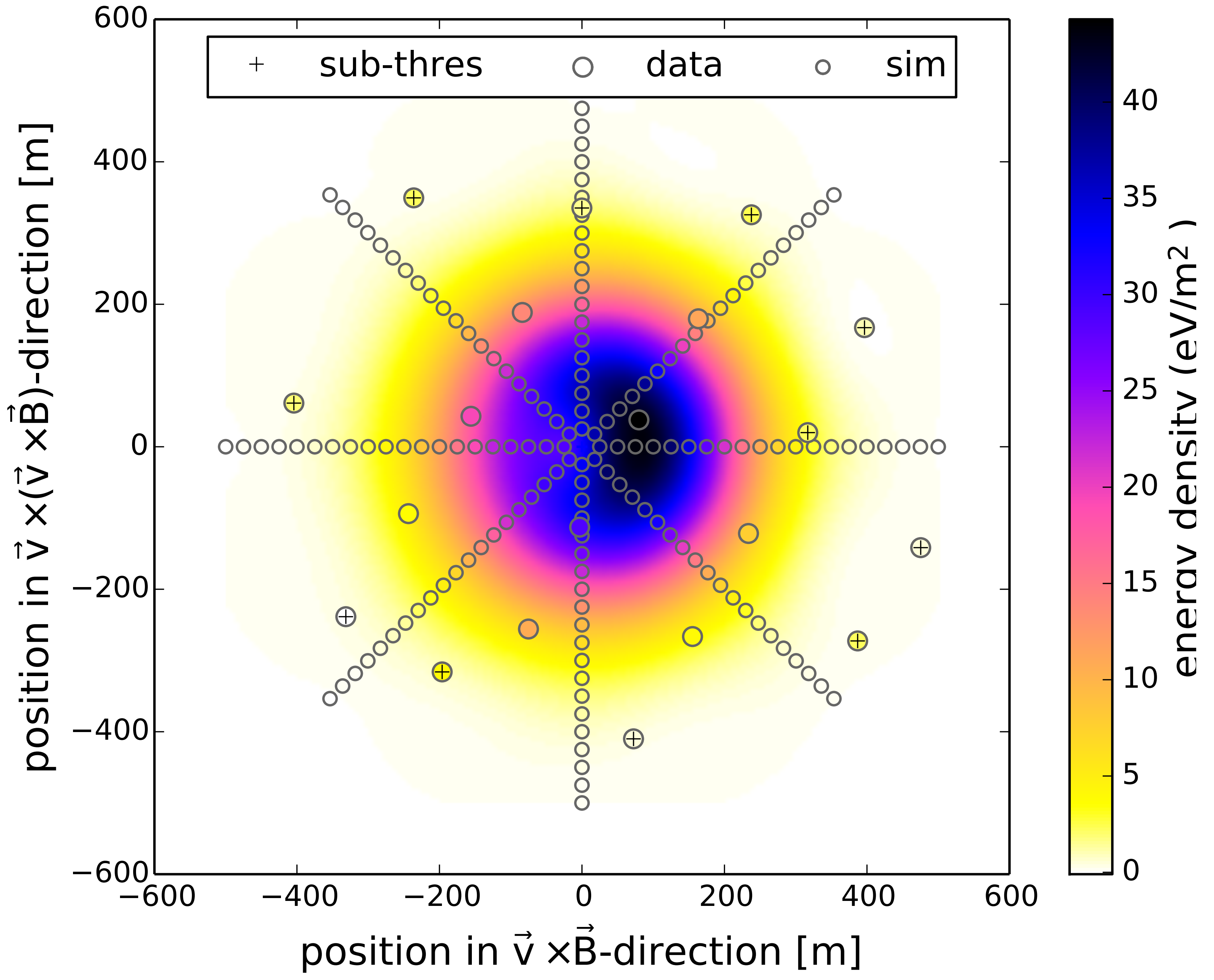
Observations were made with the Low Frequency Array (LOFAR[13]), a radio telescope consisting of thousands of crossed dipoles with built-in air-shower-detection capability[14]. LOFAR continuously records the radio signals from air showers, while simultaneously running astronomical observations. It comprises a scintillator array (LORA) that triggers the read-out of buffers, storing the full waveforms received by all antennas.

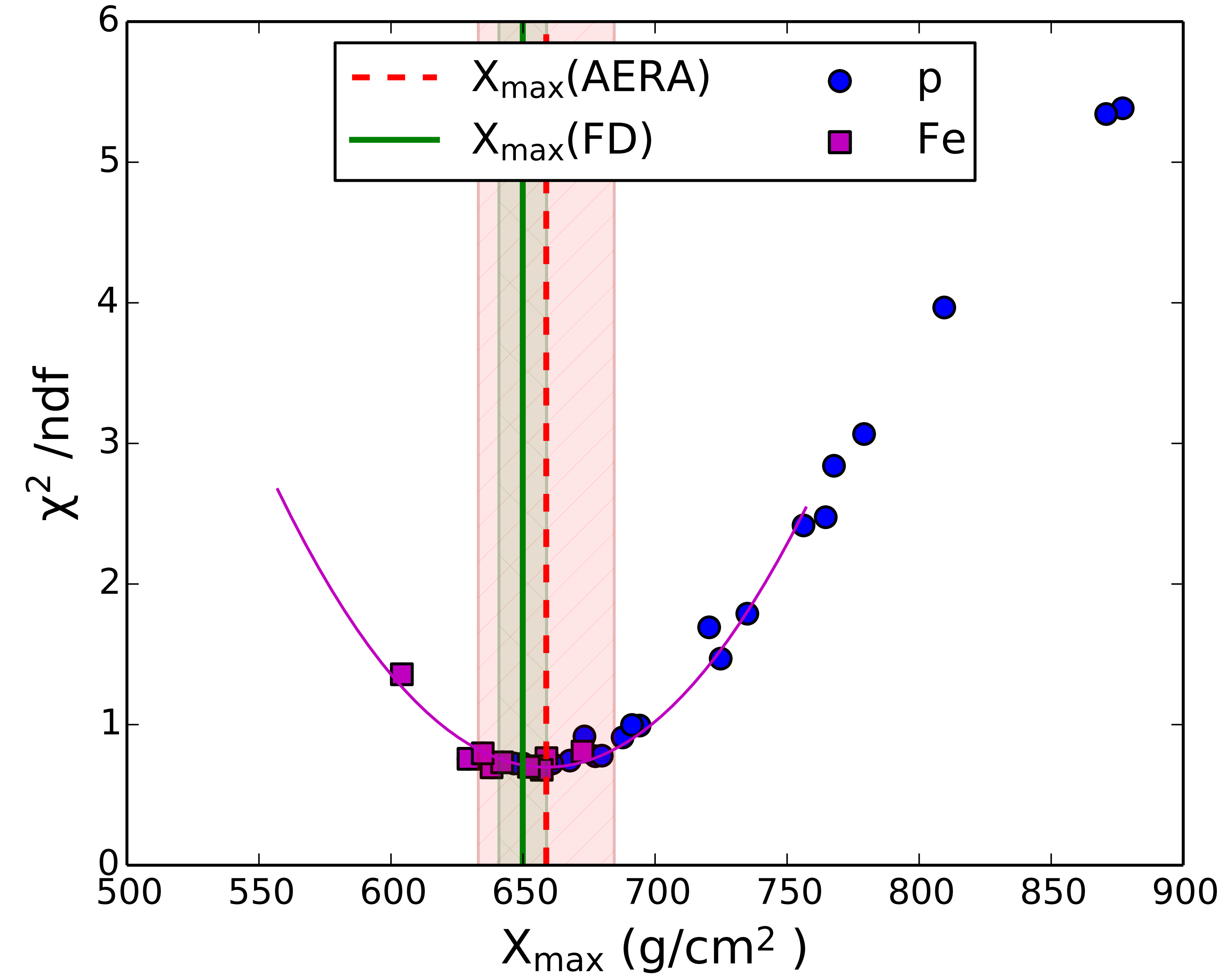
We selected air showers from the period June 2011 to January 2015 with radio pulses detected in at least 192 antennas. The total uptime was about 150 days, limited by construction and commissioning of the

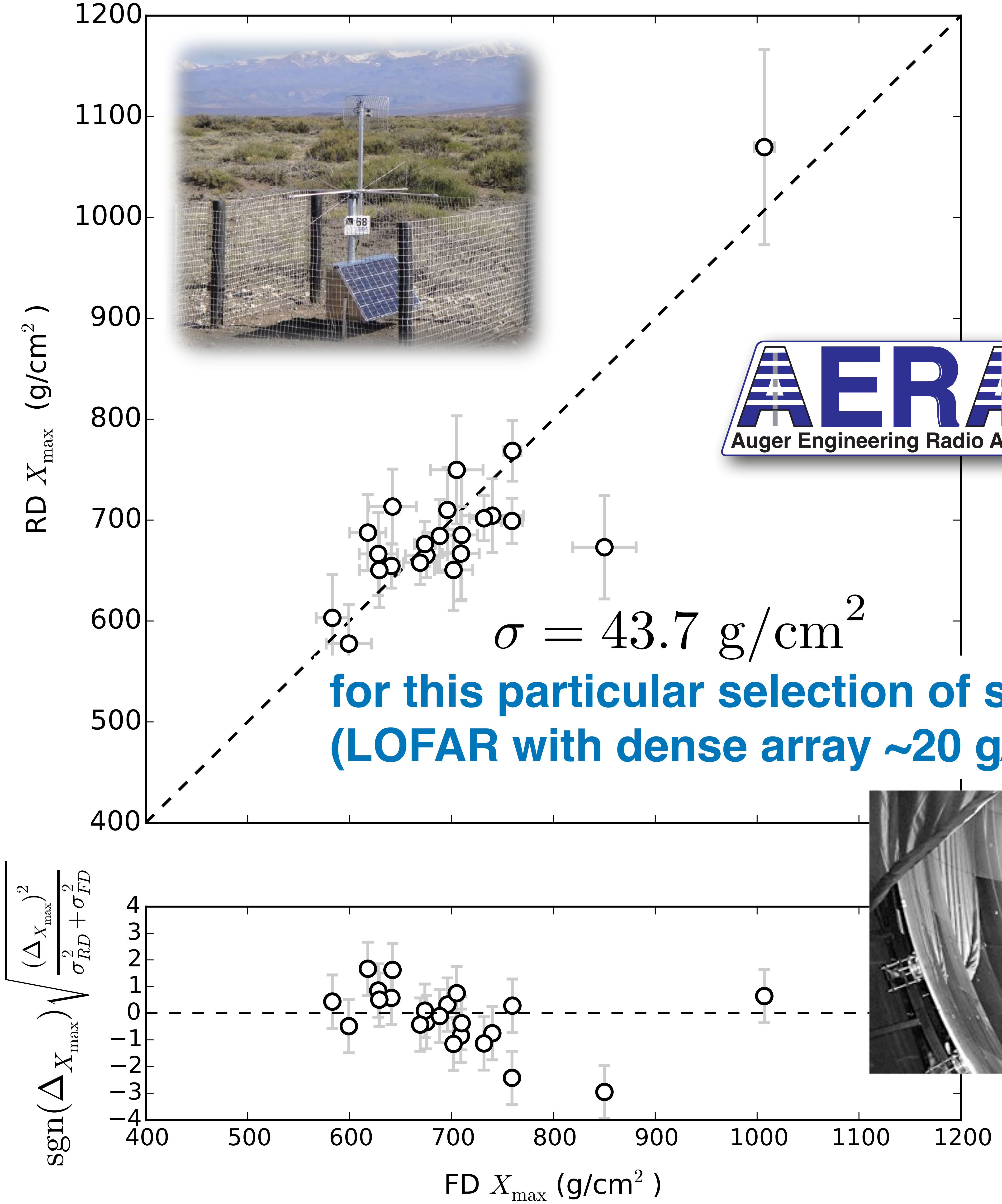


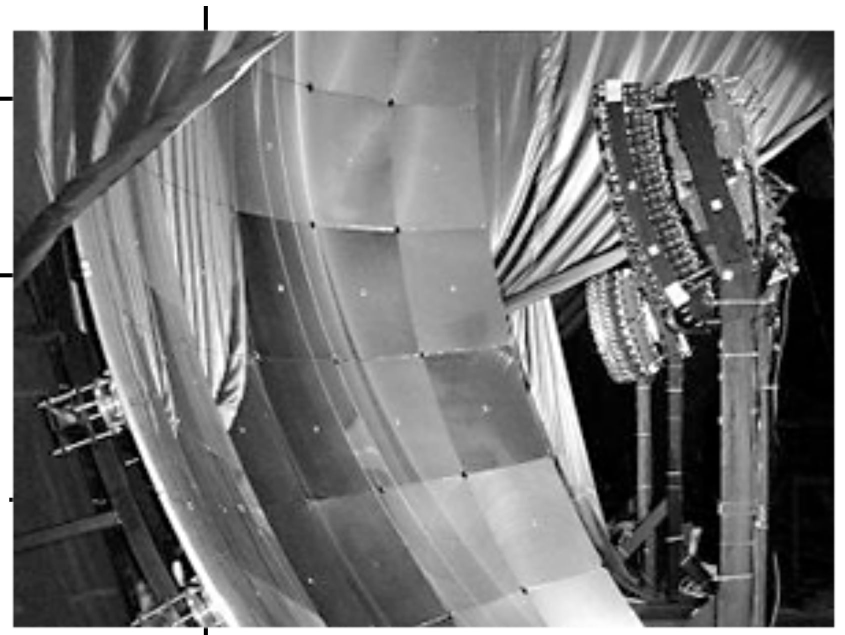
S. Buitink et al., Nature 531 (2016) 70

Xmax radio vs fluorescence









$\sigma = 43.7\ \mathrm{g/cm^2}$

for this particular selection of showers
(LOFAR with dense array ~20 g/cm²)

J. Schulz, PhD thesis RU Nijmegen (2016)

Determine the properties of the incoming particle with the radio technique

- direction ~ 0.1° - 0.5°
- energy ~ 20% - 30%
- type (X_{max}) ~ 20 - 40 g/cm^2

(depending on detector spacing)

—> radio technique is routinely used to measure properties of cosmic rays

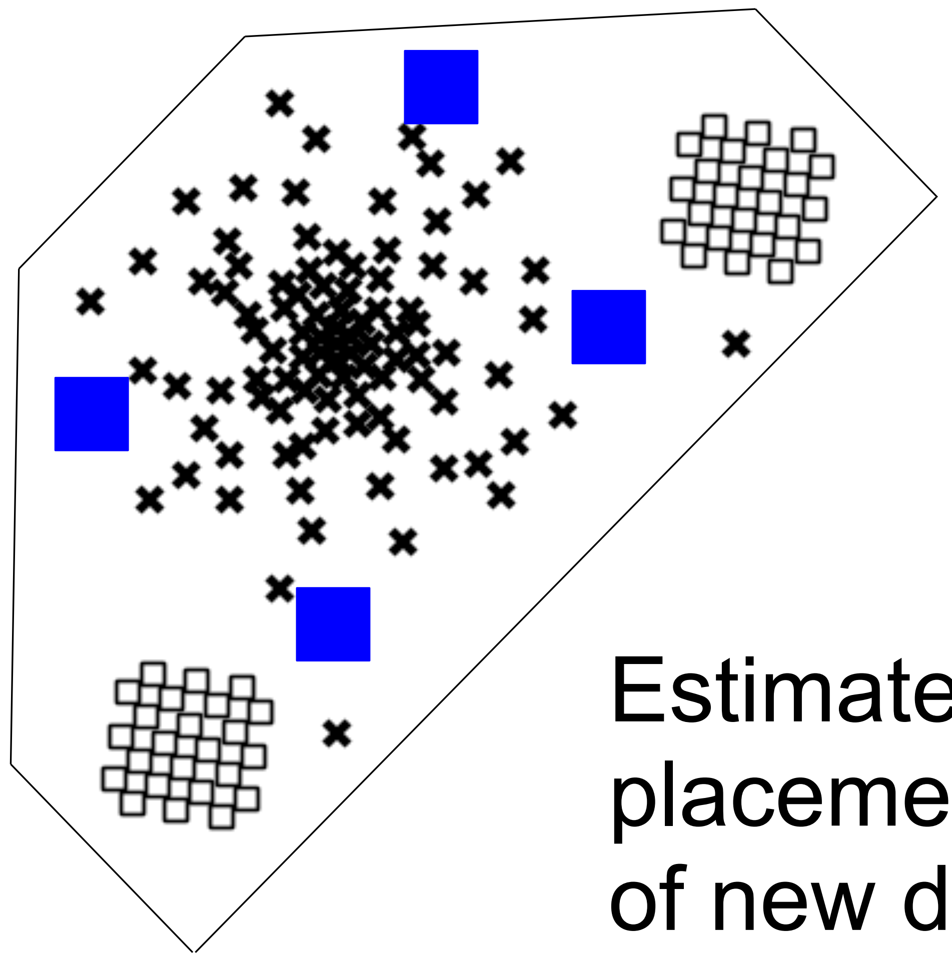
ongoing and future work

Extension of scintillator array (LORA)

2.5 km

Existing station

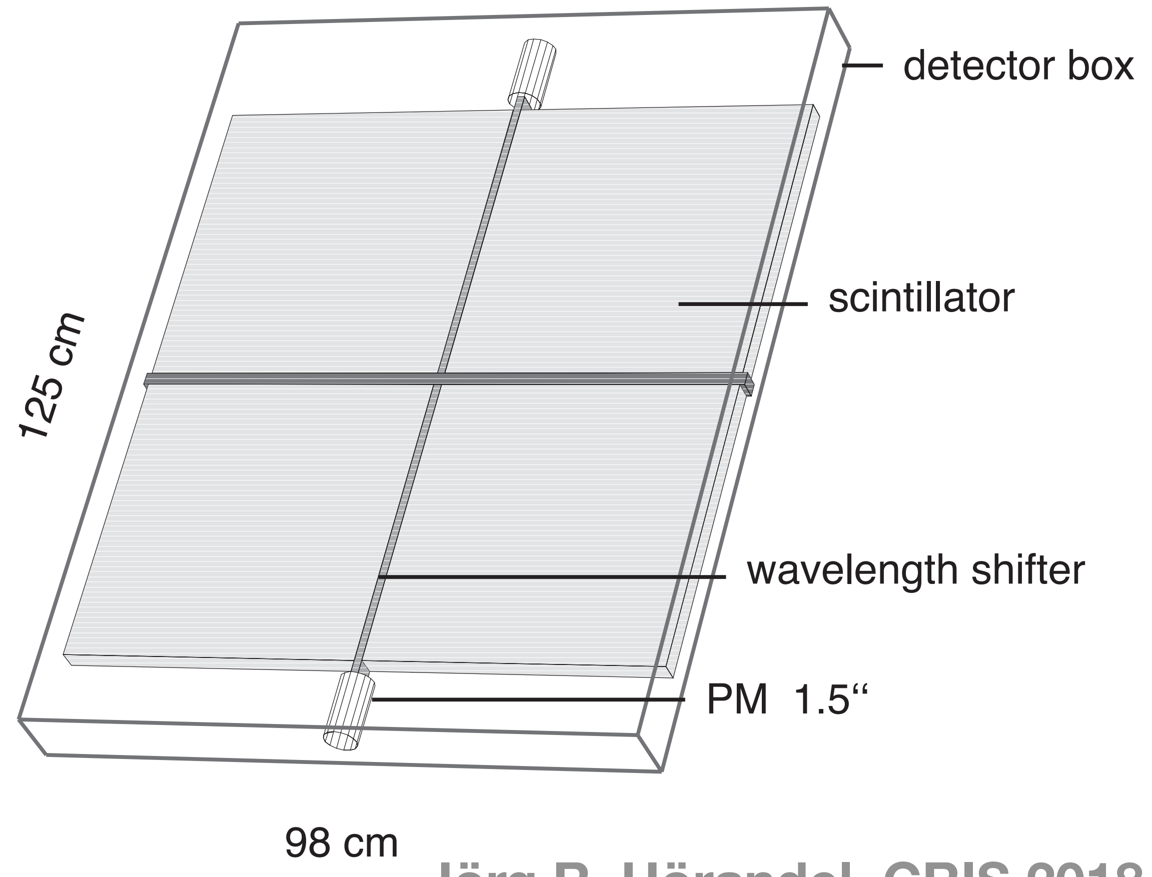
New station

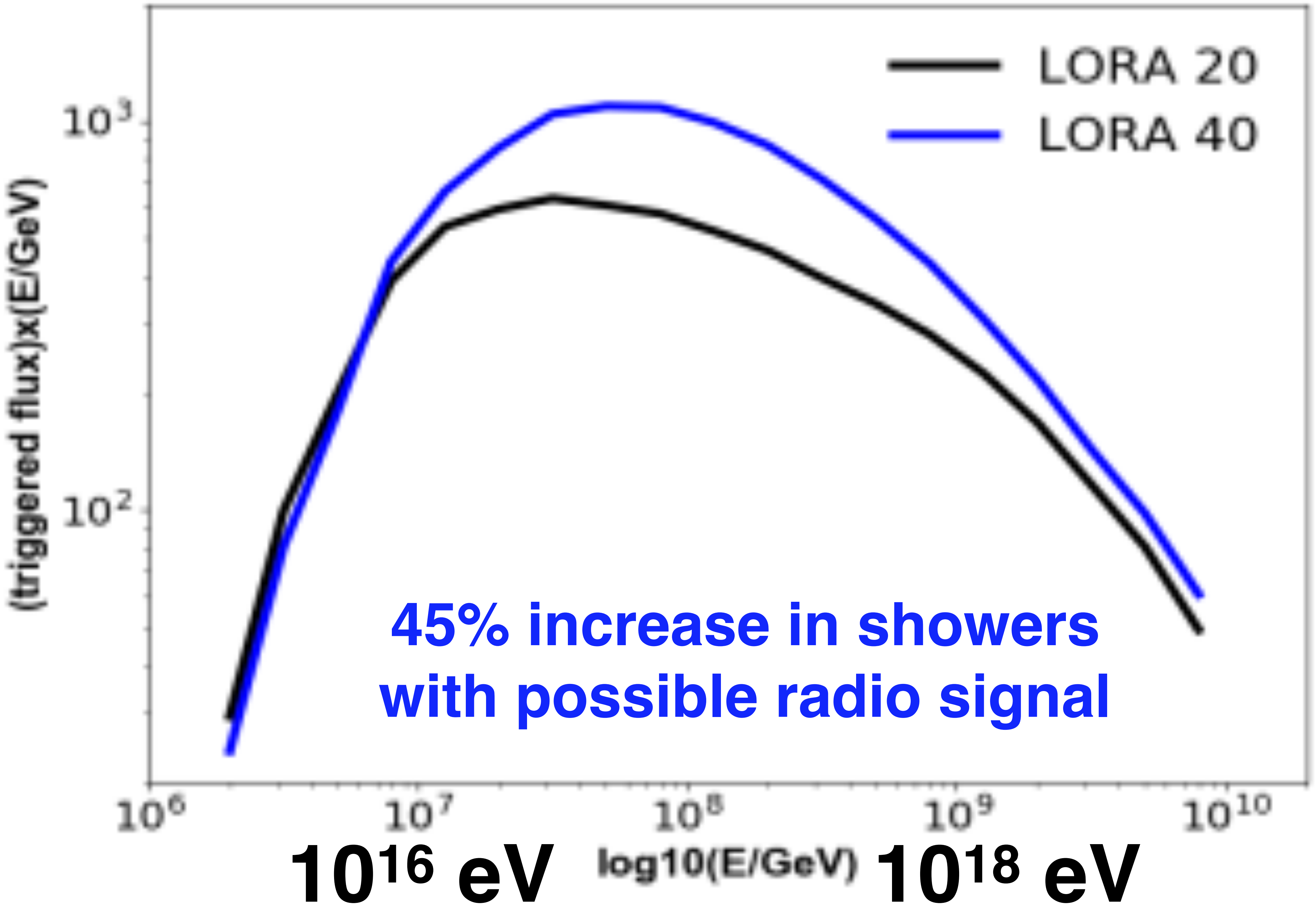


Estimated placement of new detectors

S. Buitink
K. Mulrey

adding 20 scintillator stations in 2018



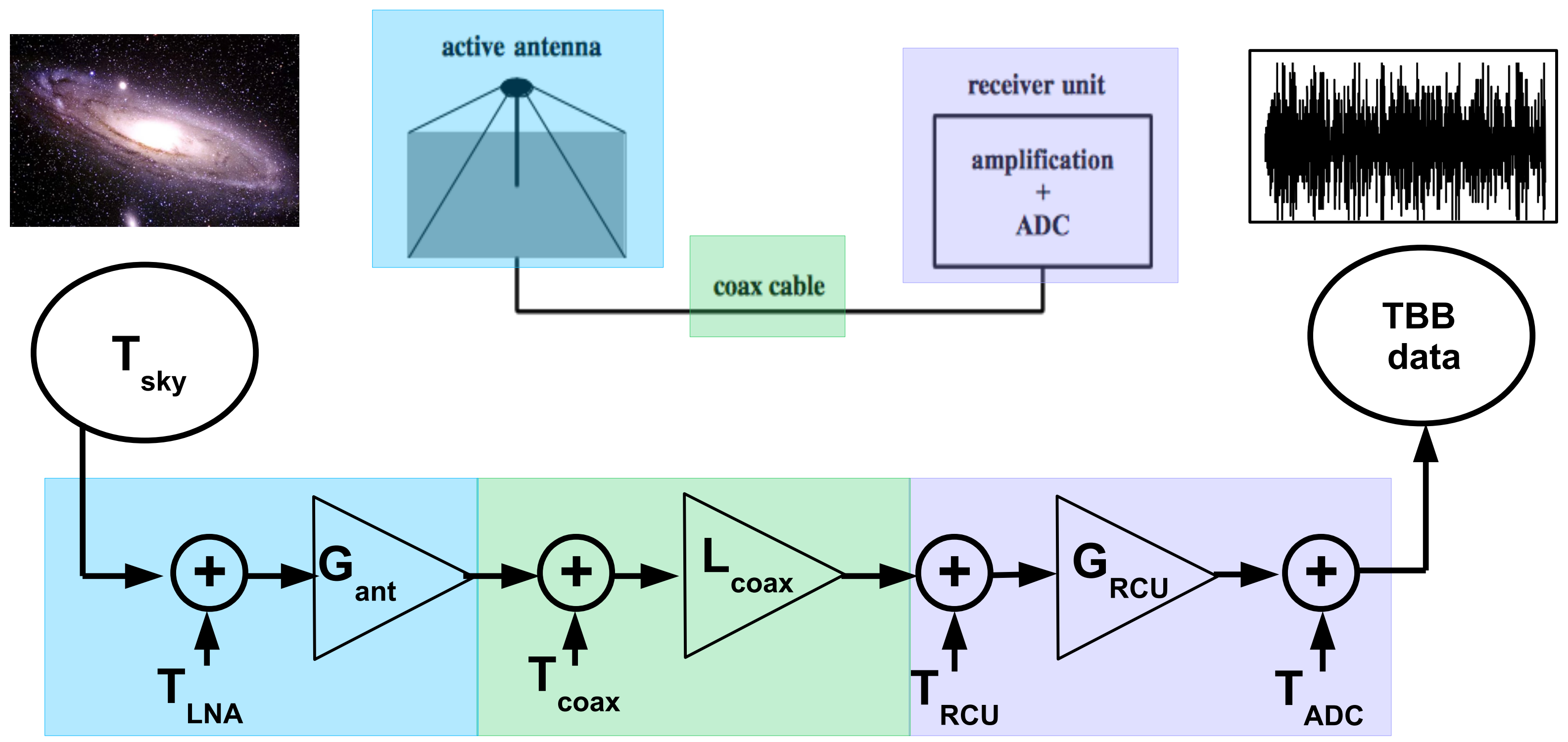


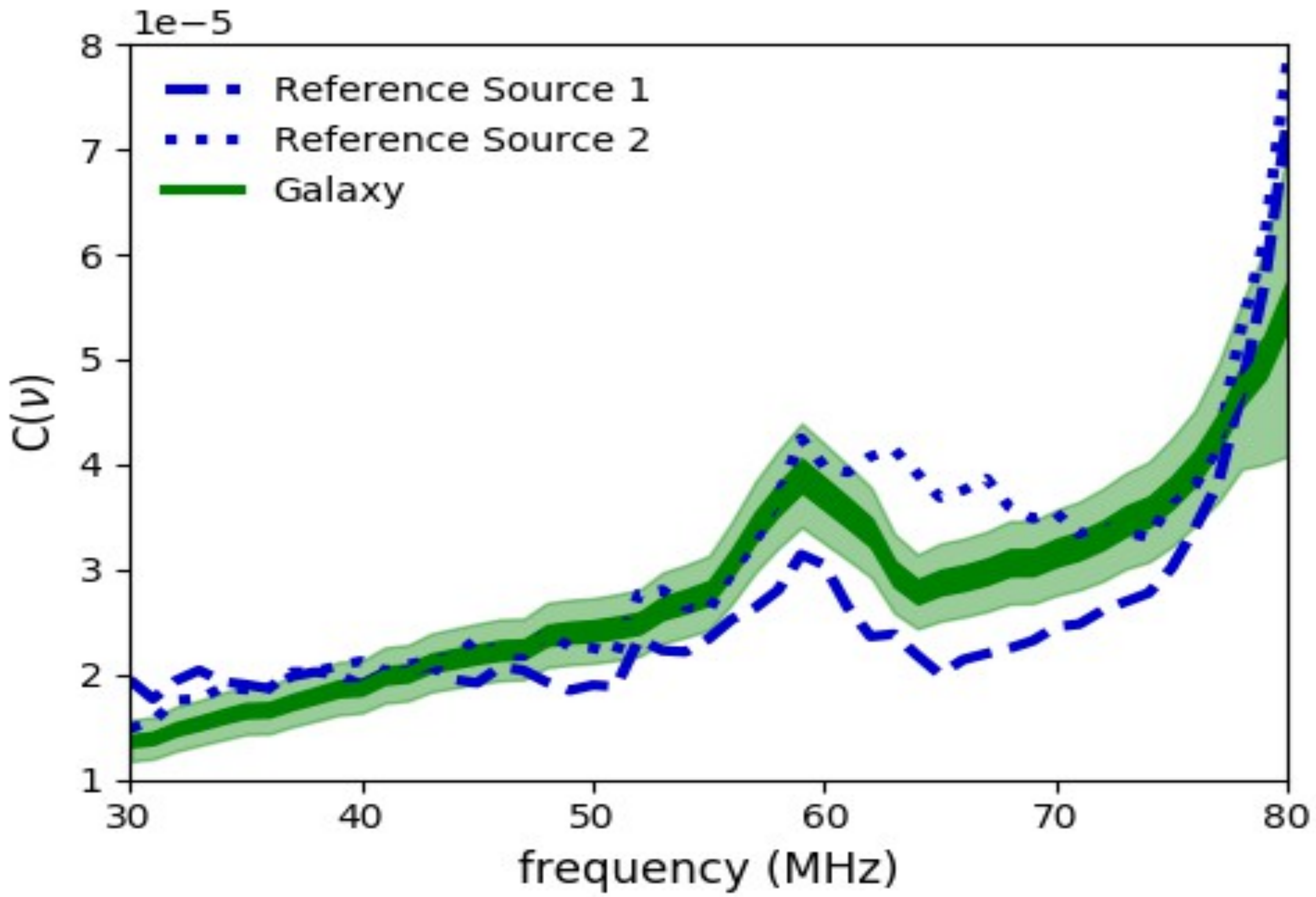
45% increase in showers with possible radio signal

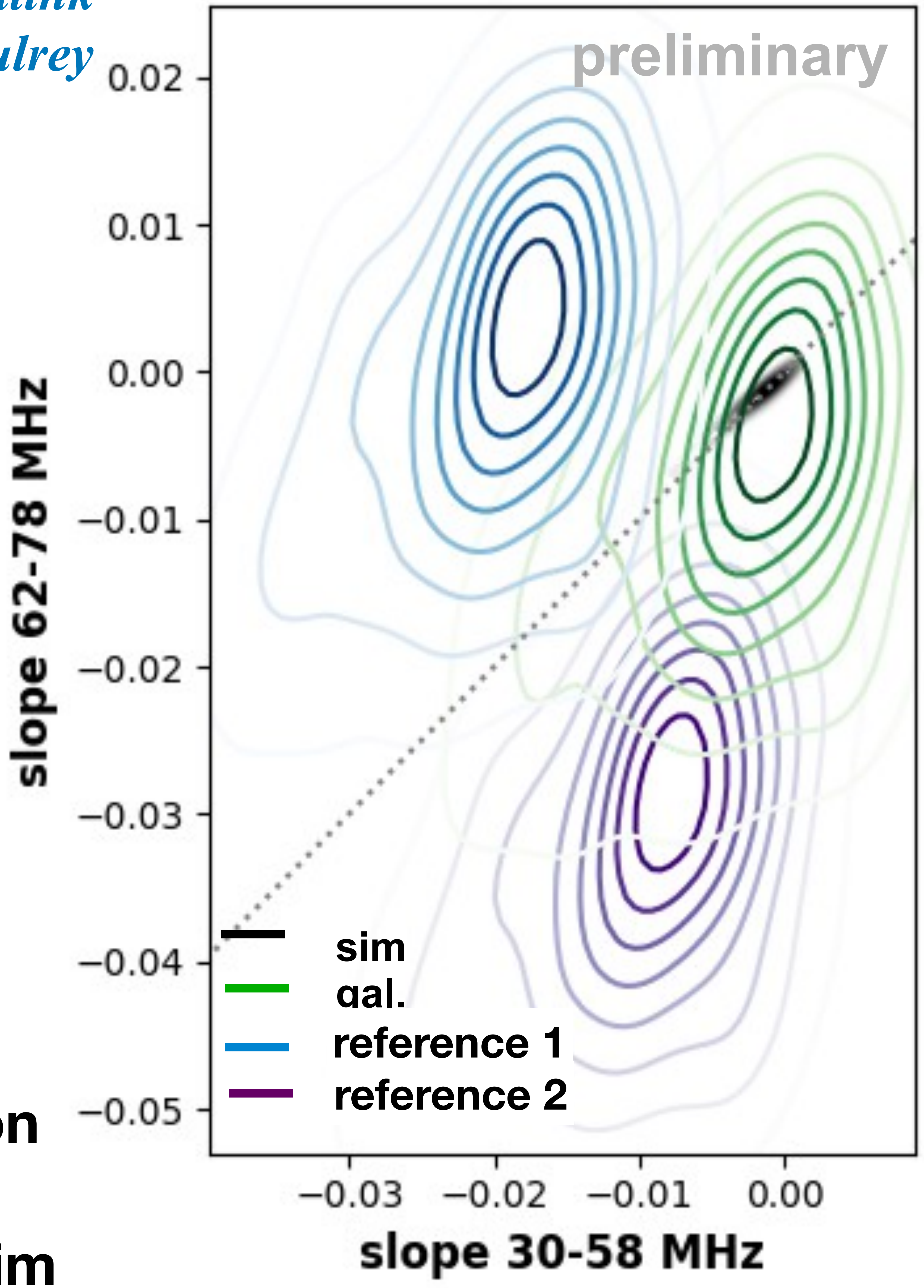
10^{16} eV **10^{18} eV**

Improved calibration

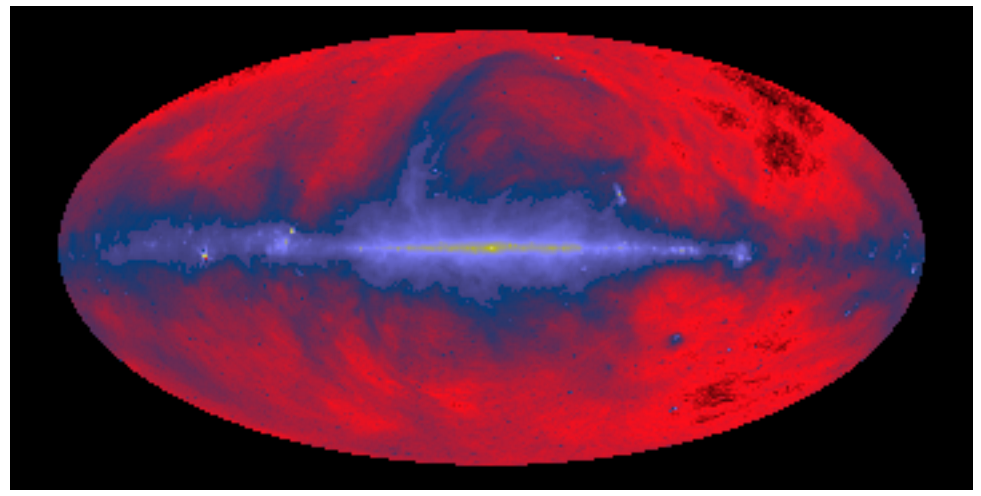
S. Buitink
K. Mulrey







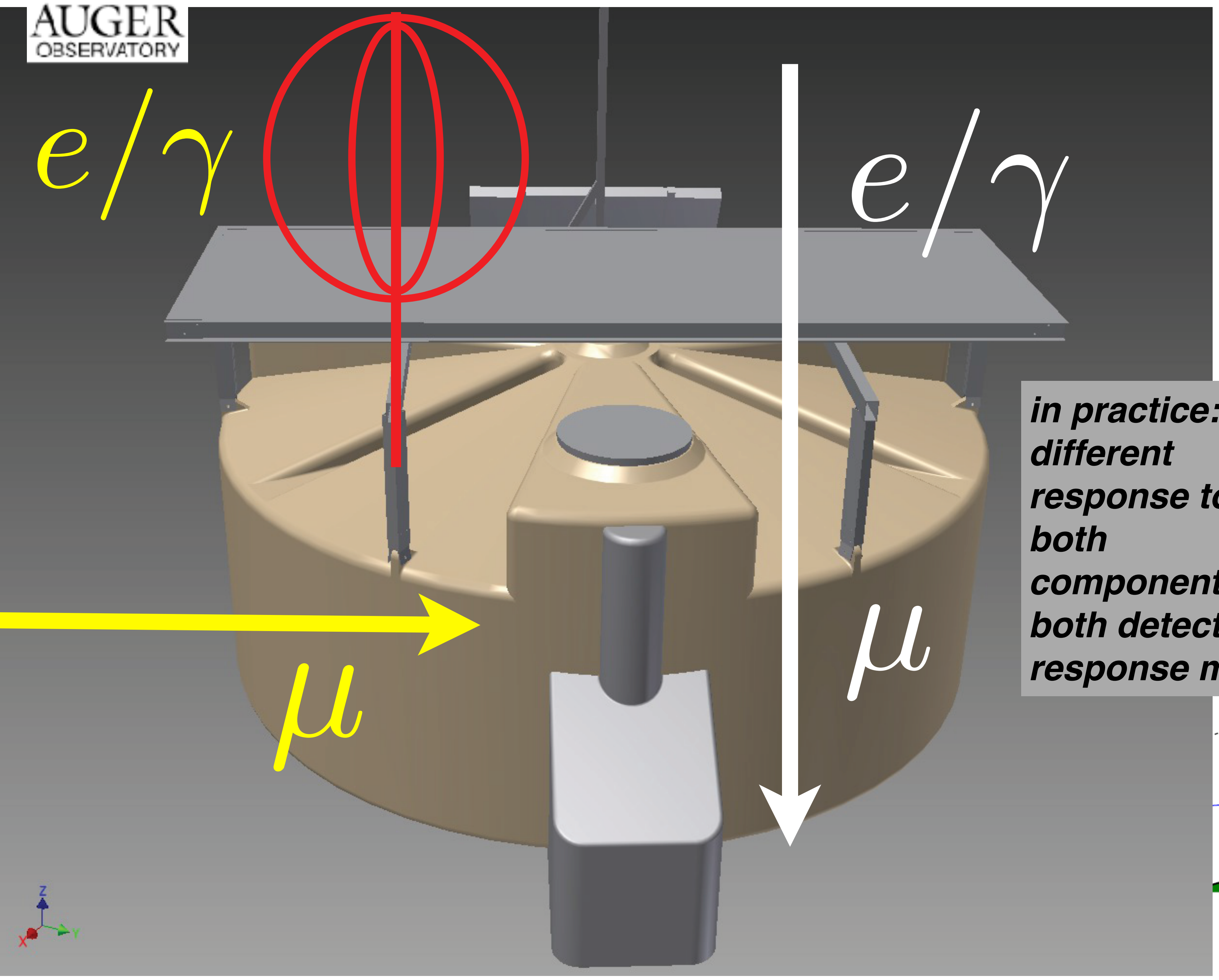
Galactic emission (LFmap)



reference source

- complete signal chain calibration
- systematic uncertainty of Galactic calibration <14% (<77 MHz)
- spectral slope in agreement with CoREAS sim

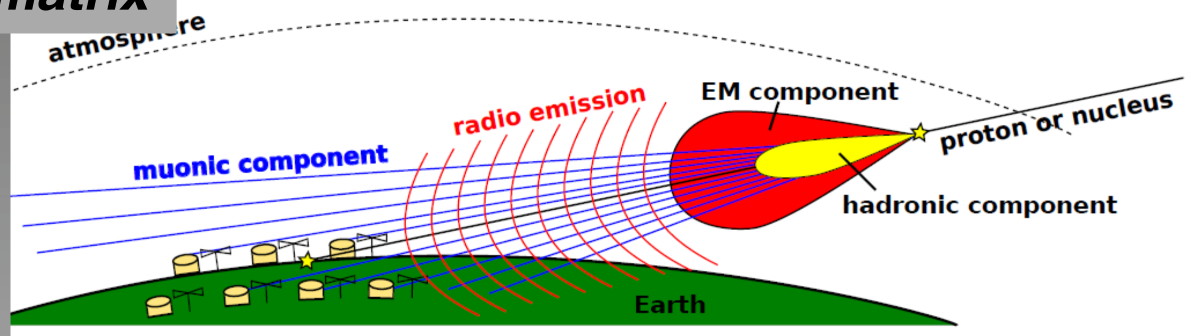
Upgrade of the Pierre Auger Observatory
(astro-)physics of the highest-energy particles in nature



in practice: different response to both components in both detectors: response matrix

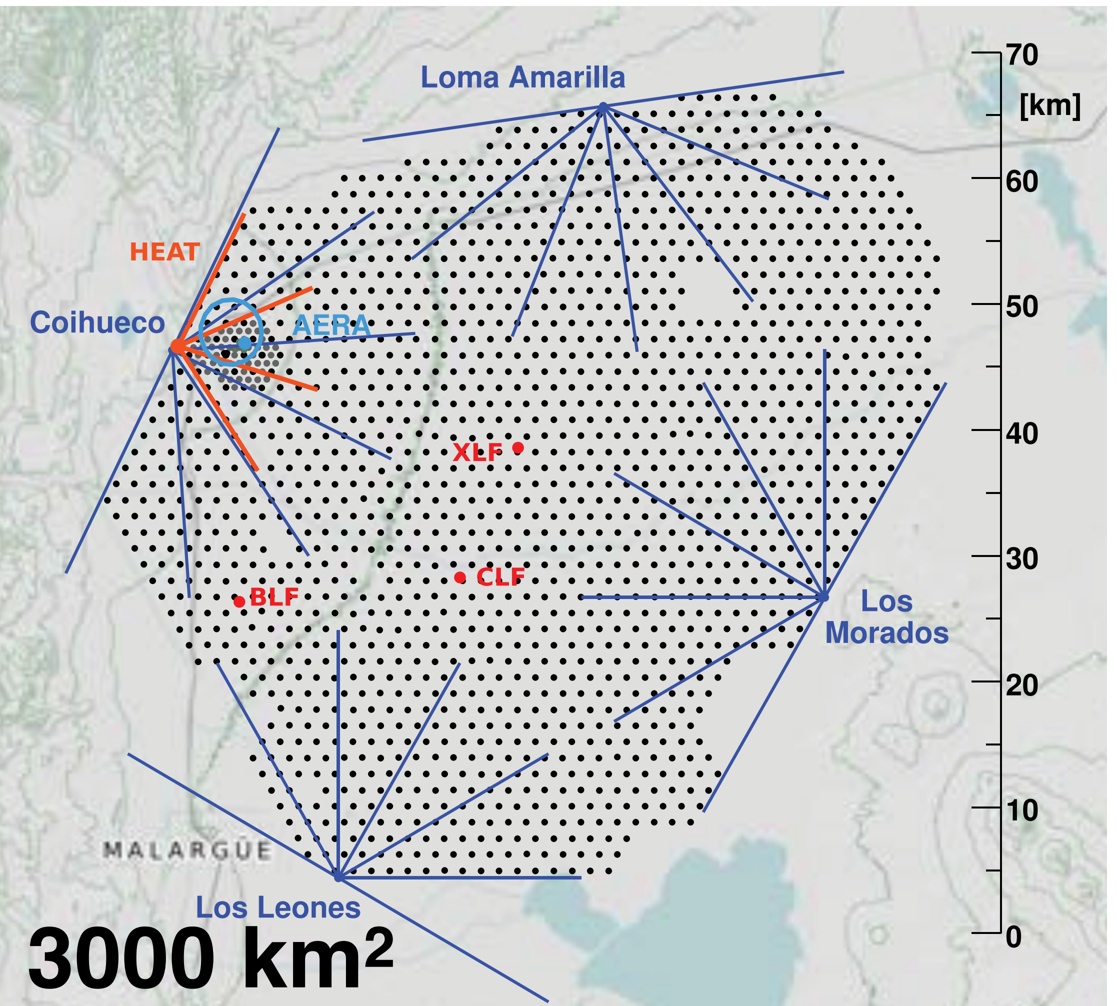
upgrade PAO

- electronics
- scintillator layer
- radio detector



Key science questions

- What are the sources and acceleration mechanisms of ultra-high-energy cosmic rays (UHECRs)?
- Do we understand particle acceleration and physics at energies well beyond the LHC (Large Hadron Collider) scale?
- What is the fraction of protons, photons, and neutrinos in cosmic rays at the highest energies?



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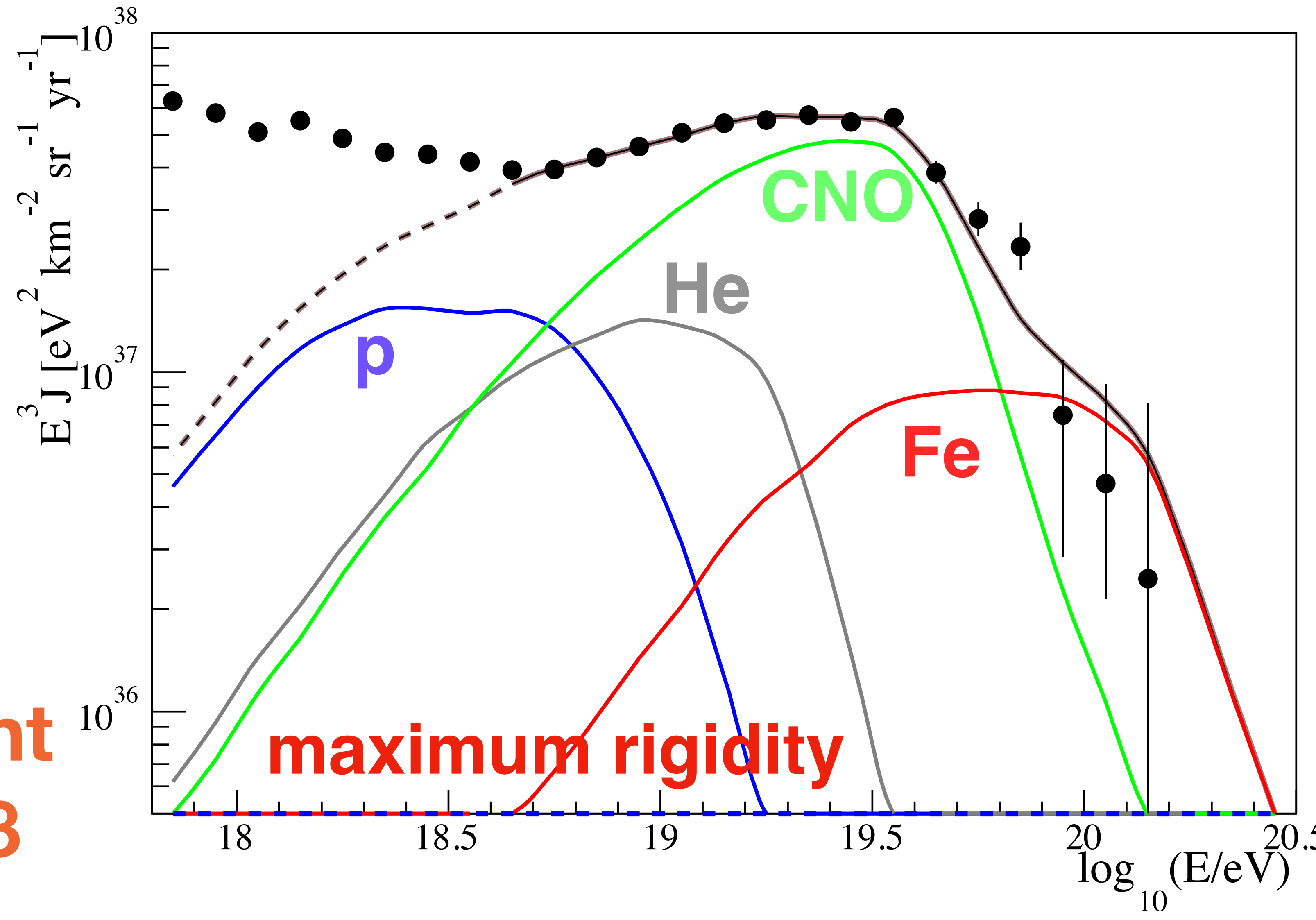
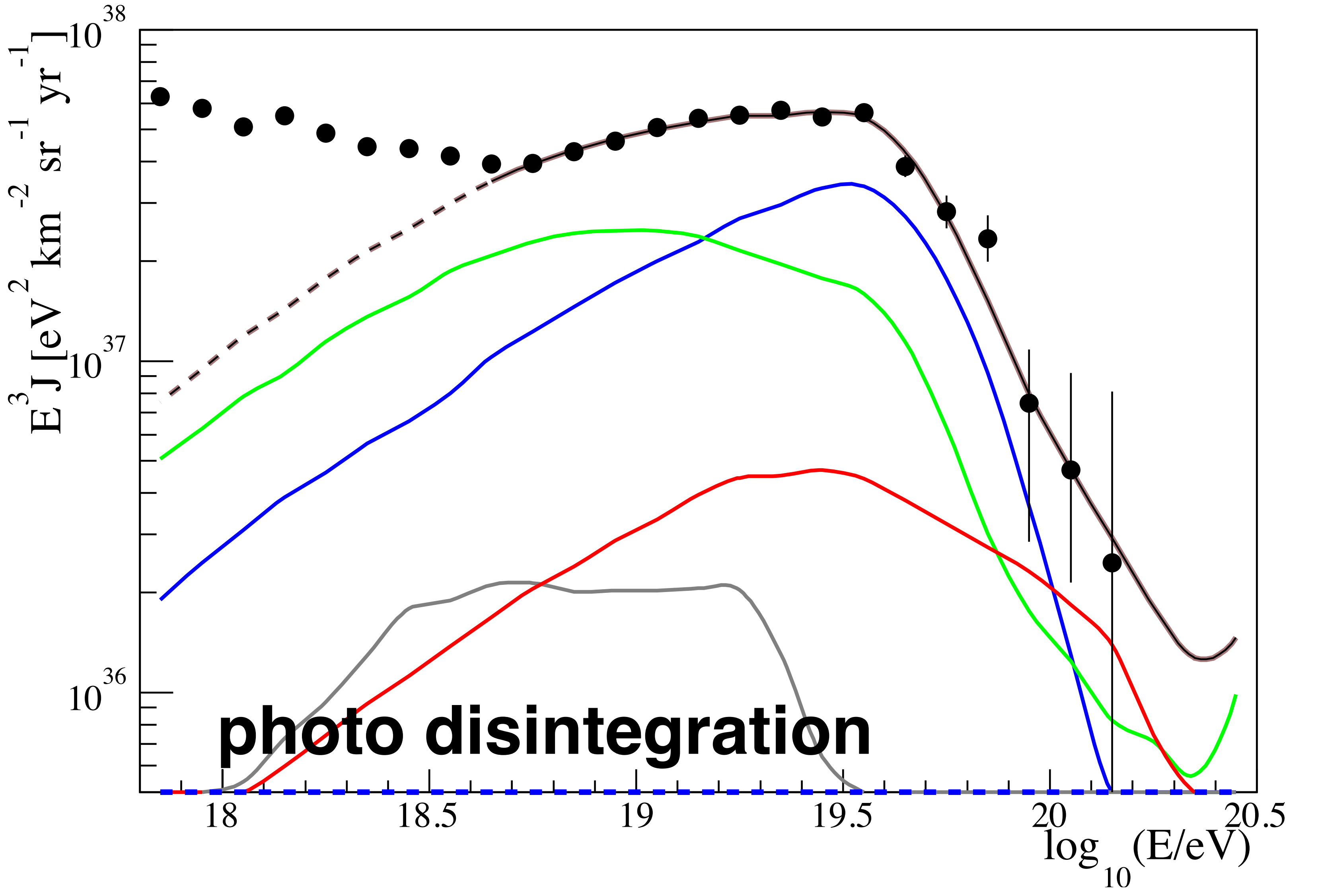
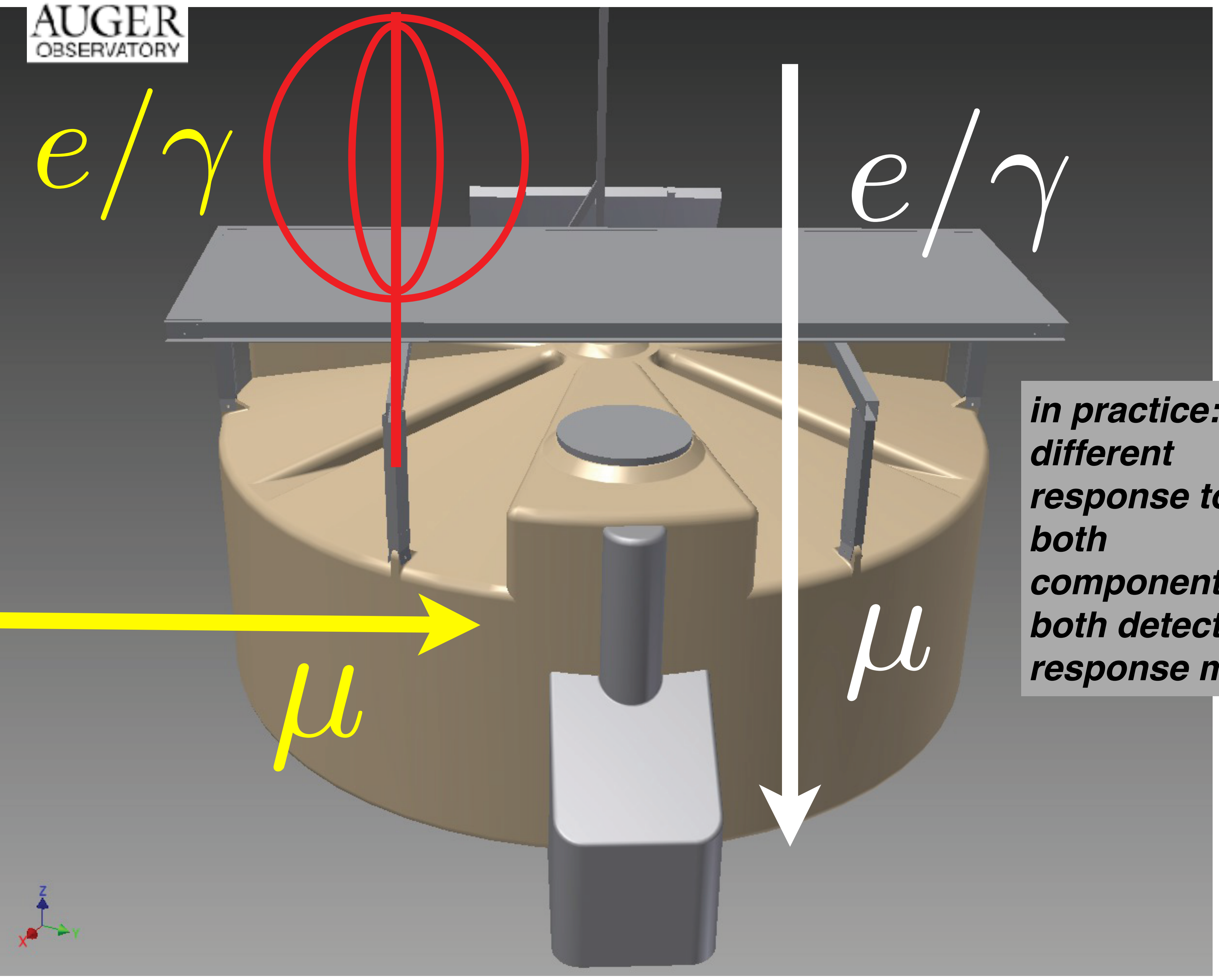
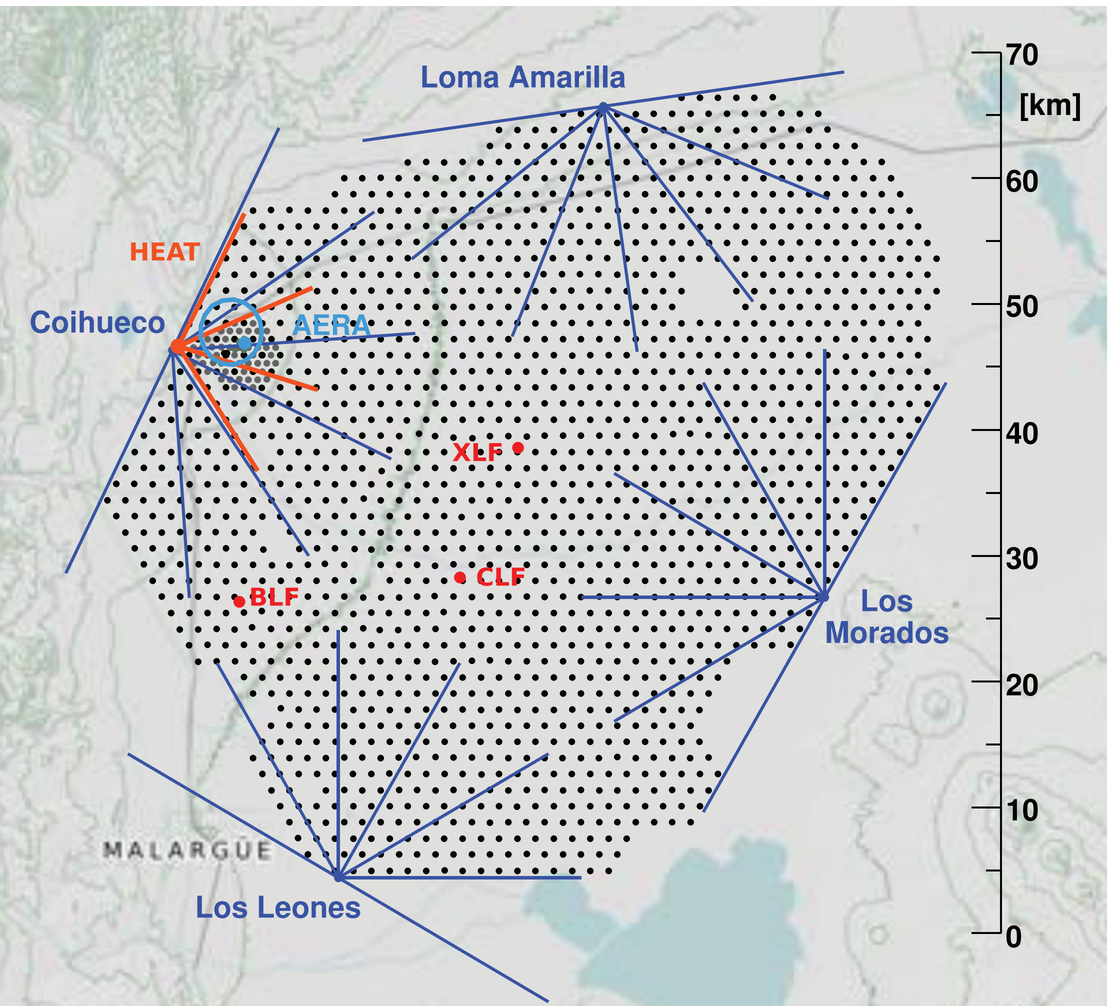




A large radio array the Pierre Auger Observatory



in practice: different response to both components in both detectors: response matrix



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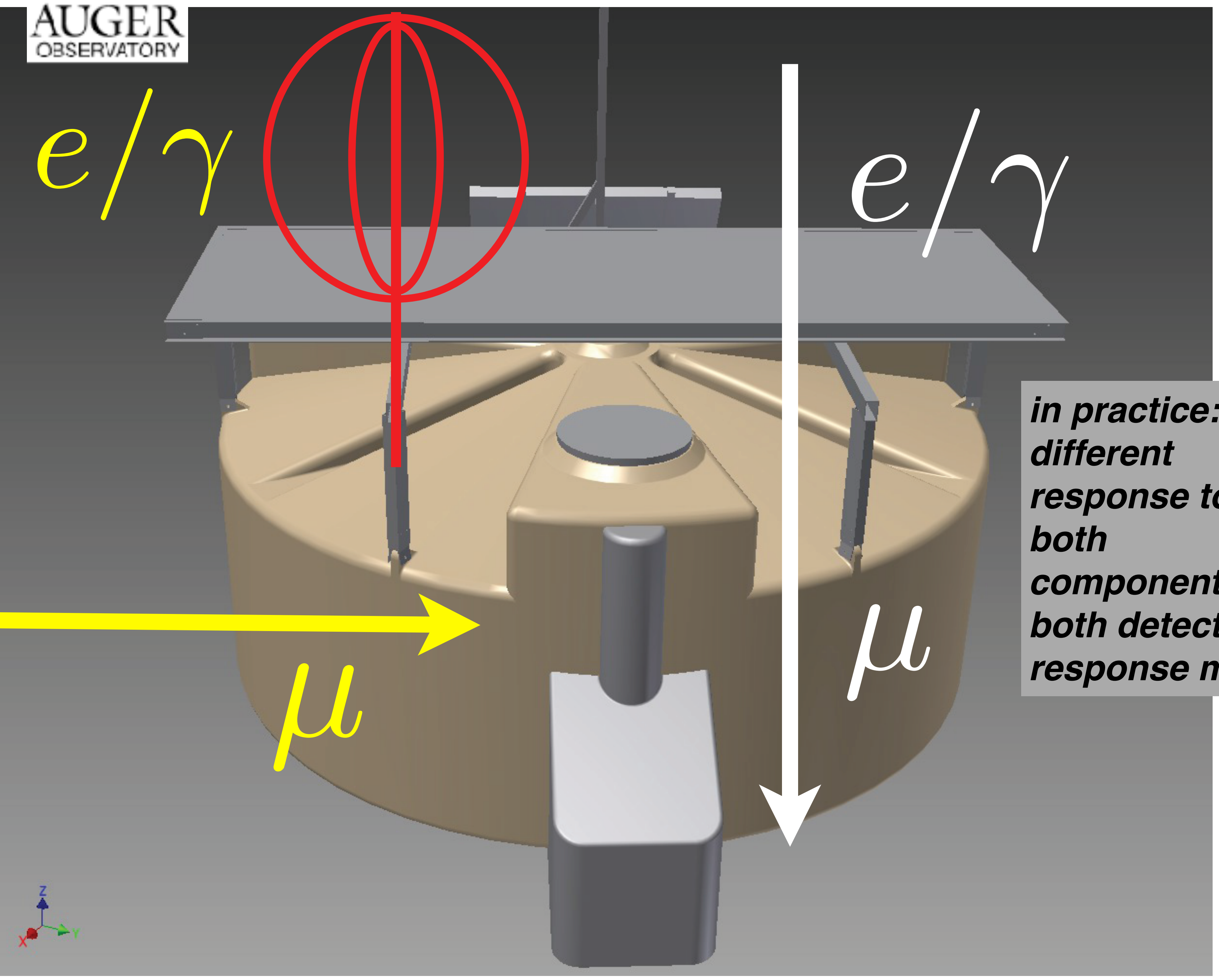
objective

- origin of cosmic rays
- type of particle up to highest energies
- isolate protons, photons, neutrinos
- extend e/m-muon separation to high zenith angles
  --> horizontal air showers
  (i.e. increase exposure of SSD analyses)
- increase the sky coverage/overlap with TA
- absolute energy calibration from 1st principles
- independent mass scale
- clean e/m measurement
  --> shower physics

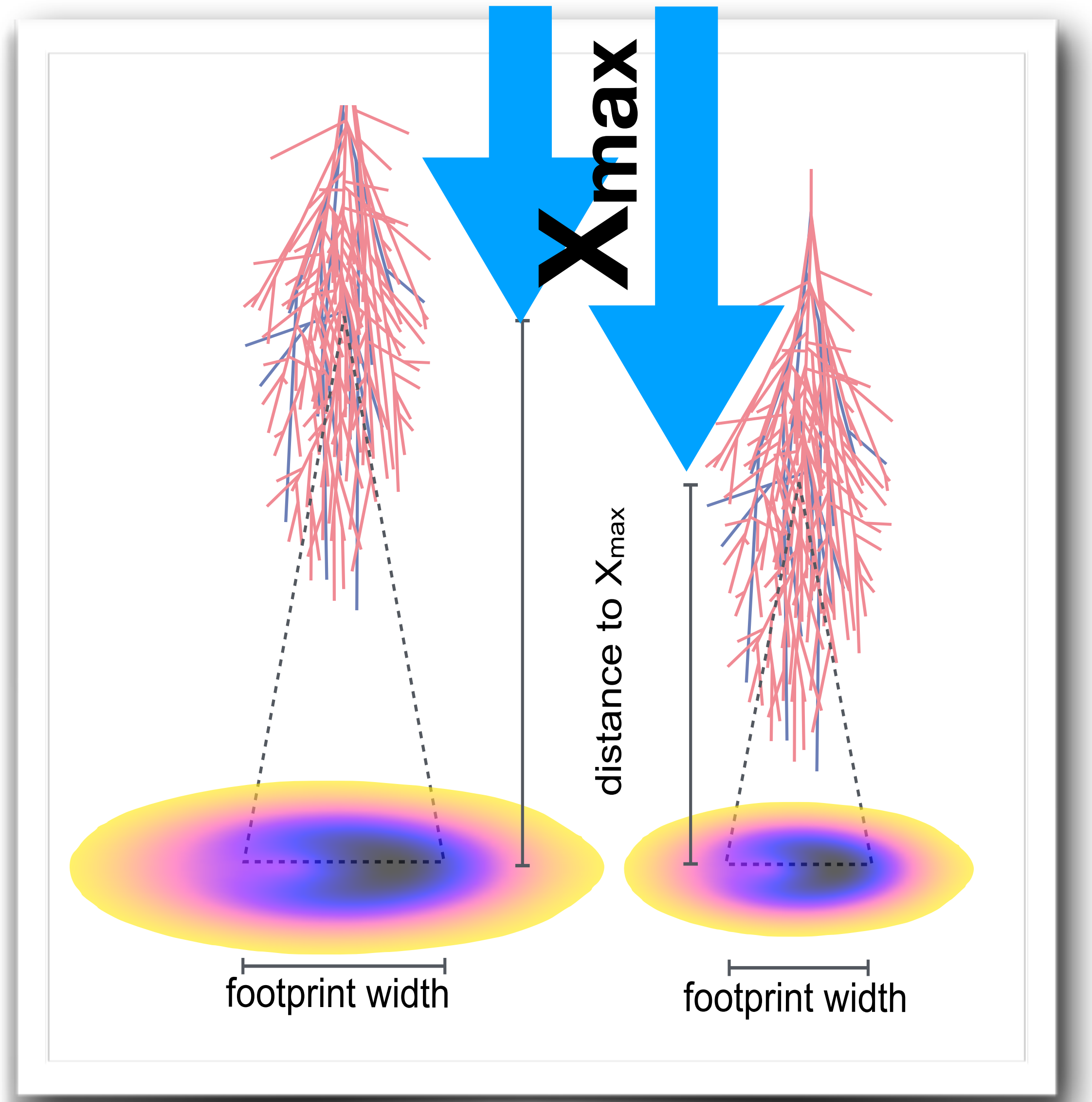
A large radio array the Pierre Auger Observatory



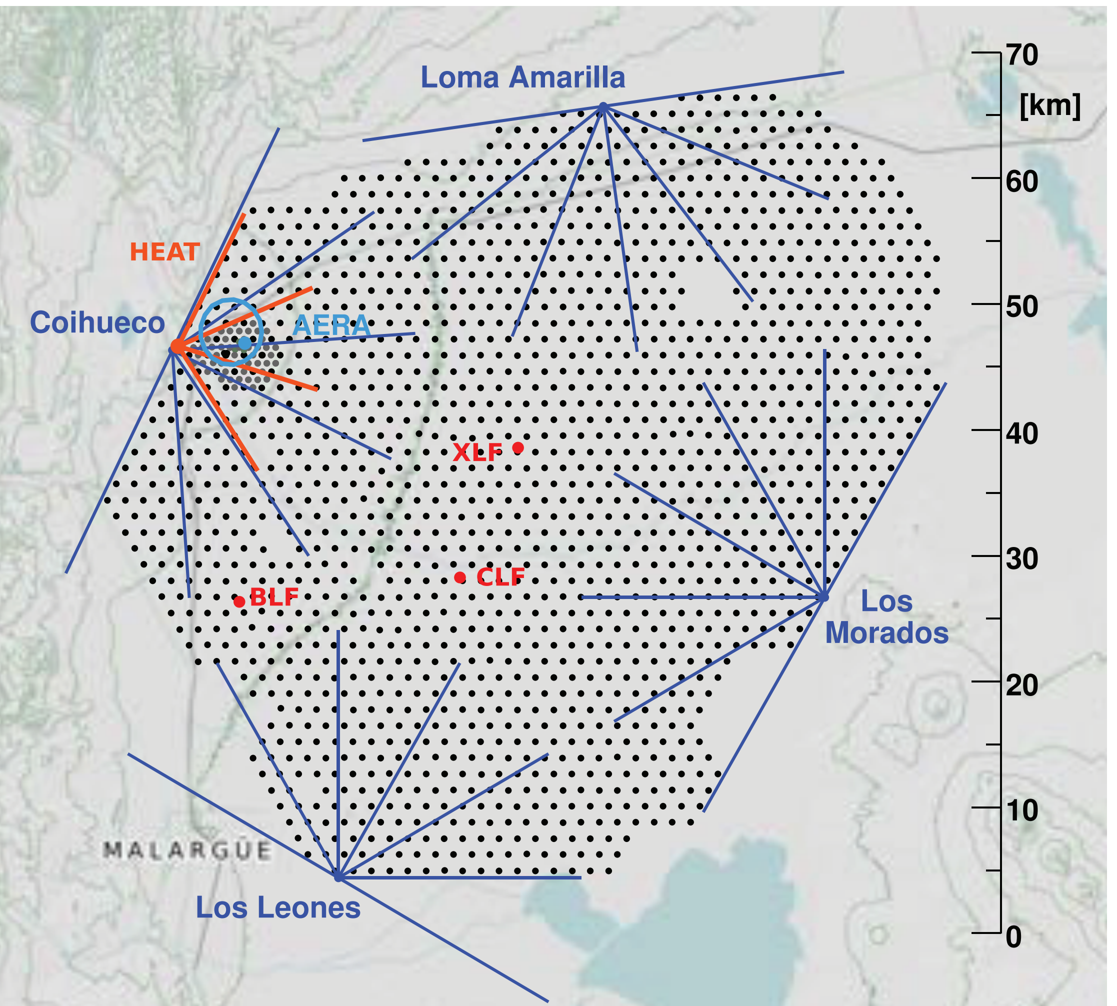
in practice: different response to both components in both detectors: response matrix

attention:
type of particle determined

for vertical showers:
- **size of footprint**
- **geometrical measurement**



for horizontal showers:
- **electron/muon ratio**
- **important: radio emission not absorbed in atmosphere**



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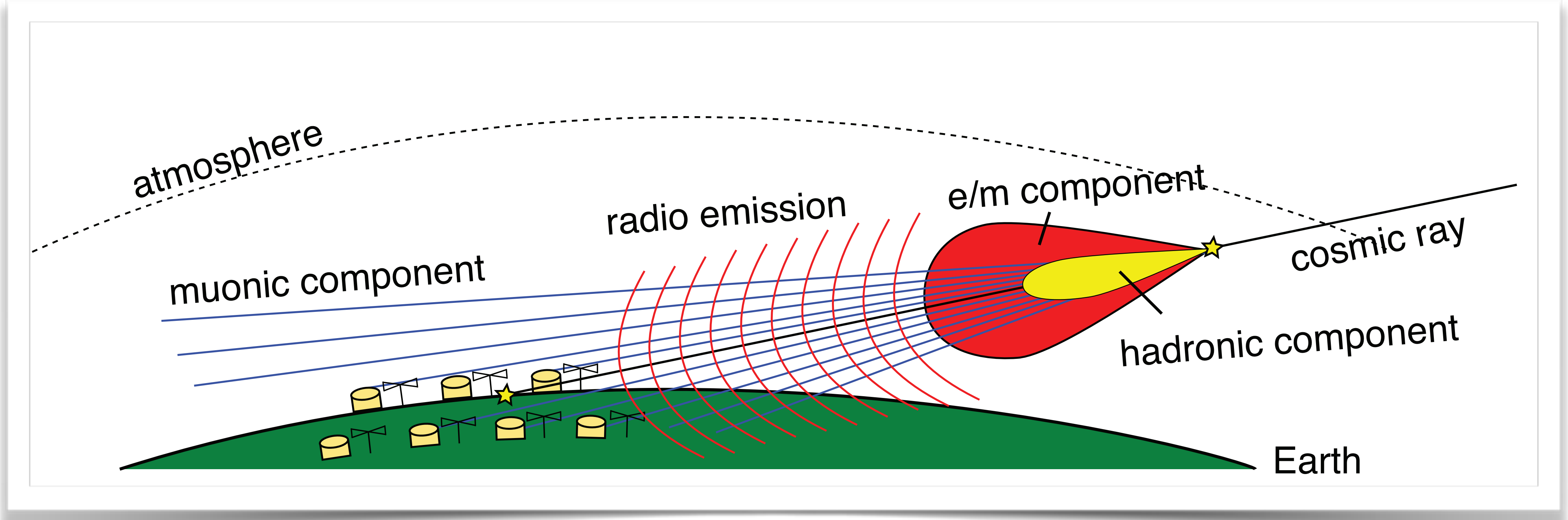
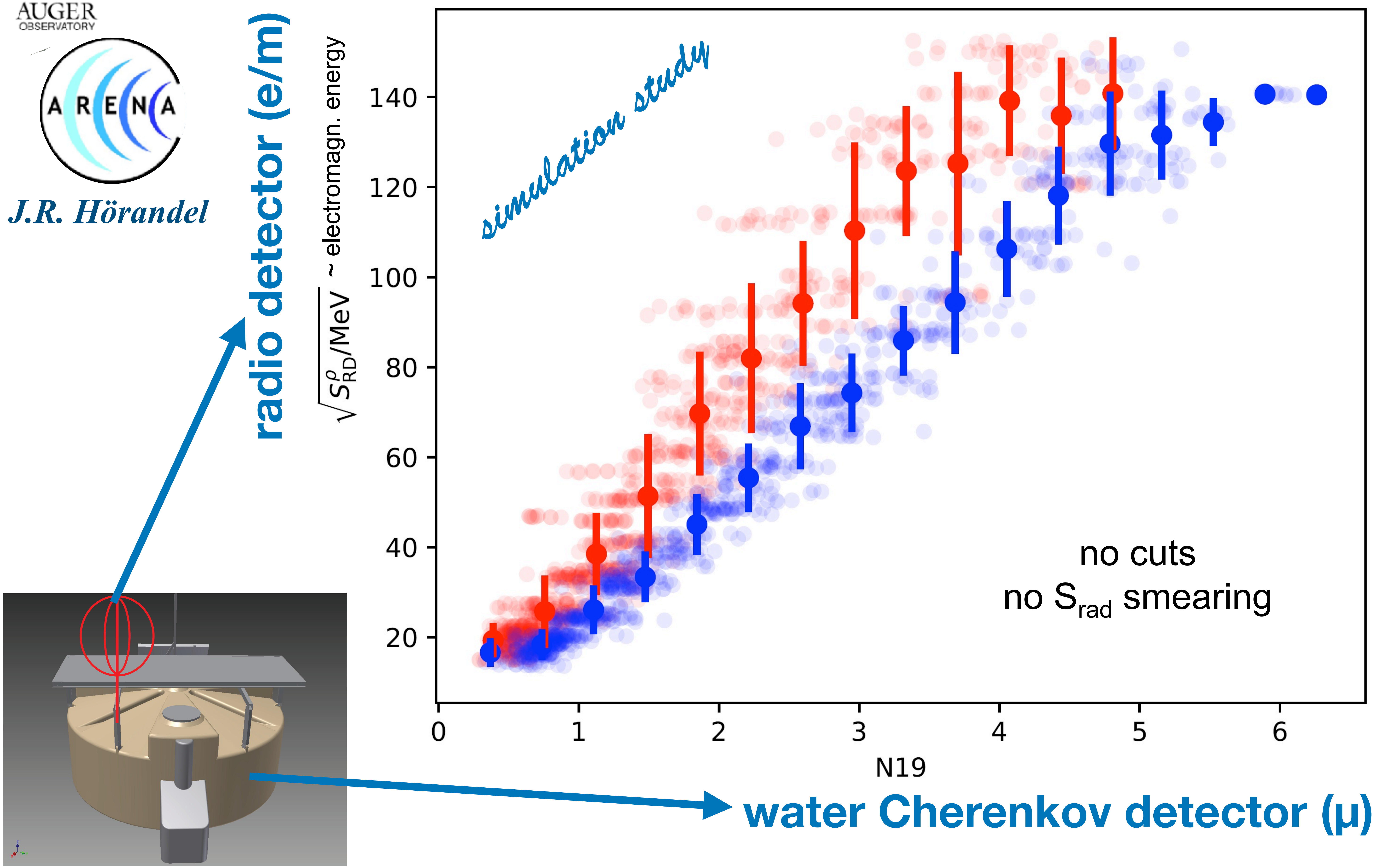


Radio detector provides good mass separation

J.R. Hörandel

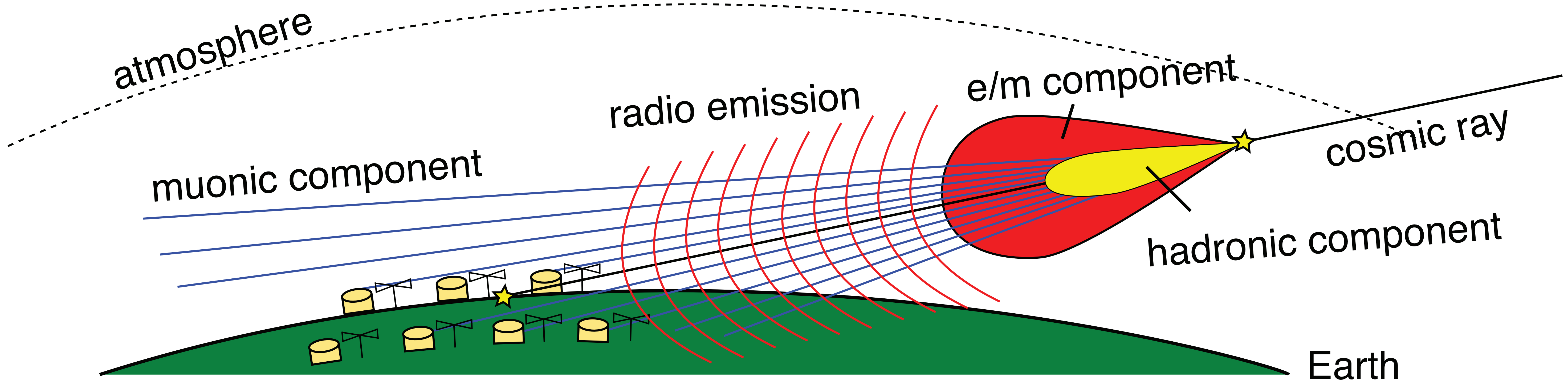


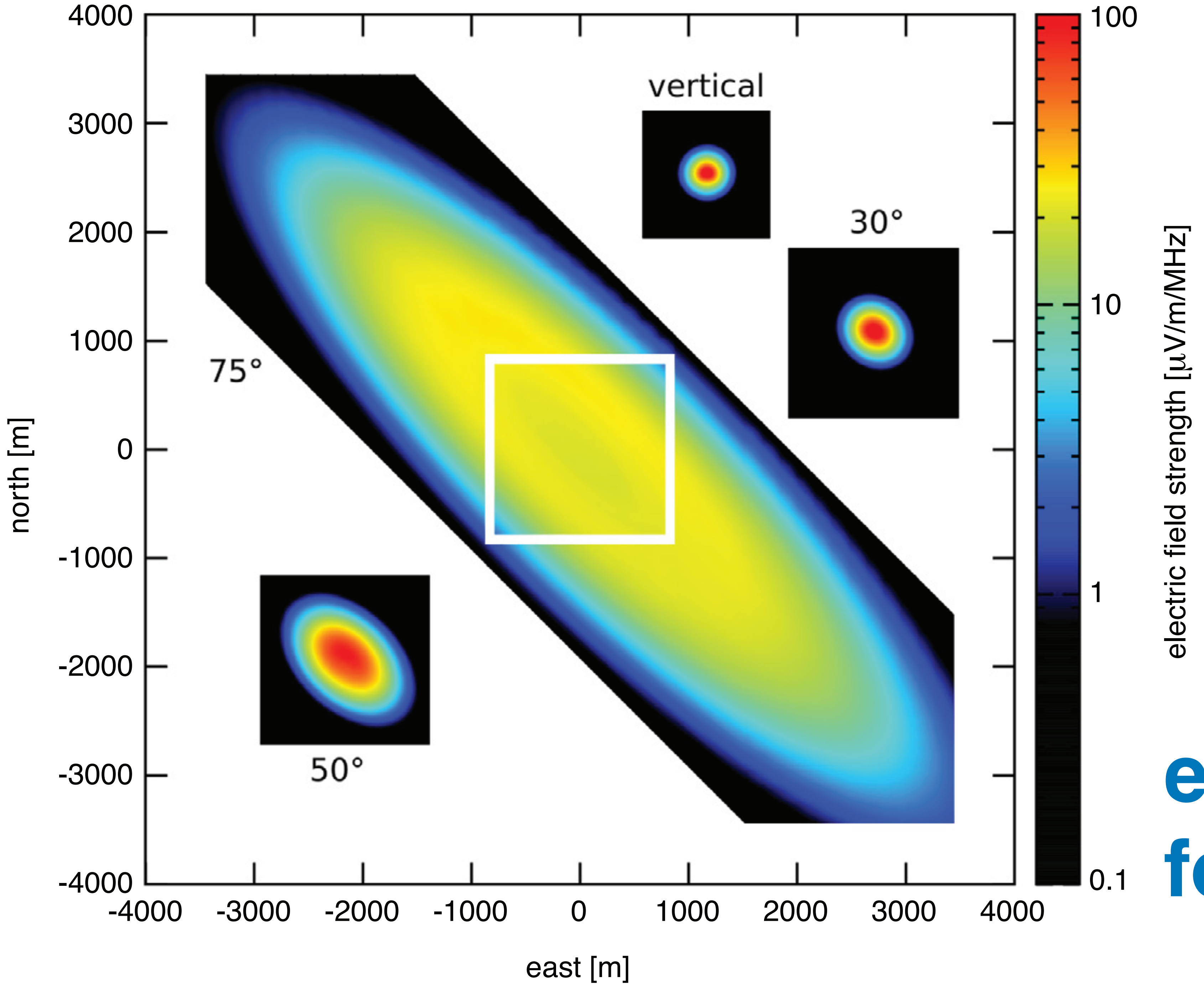
- can separate species with S_{rad} and N19
- separation increases with energy
- scaling at highest energies probably artifact of maximum simulated energy

A large radio array at the Pierre Auger Observatory

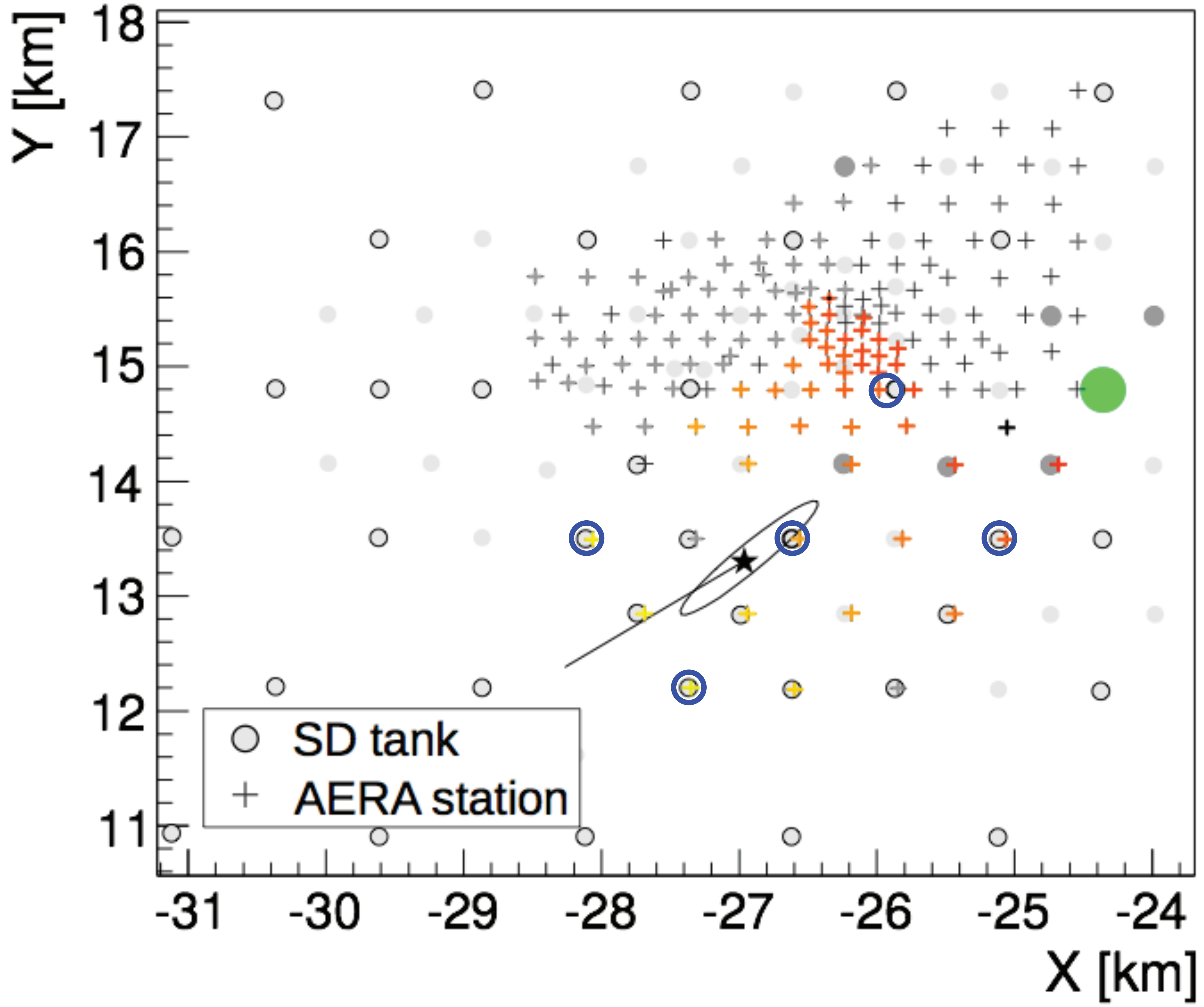
preparatory work & feasibility

AERA 17 km² --> 3000 km²





expect large radio footprint from simulations

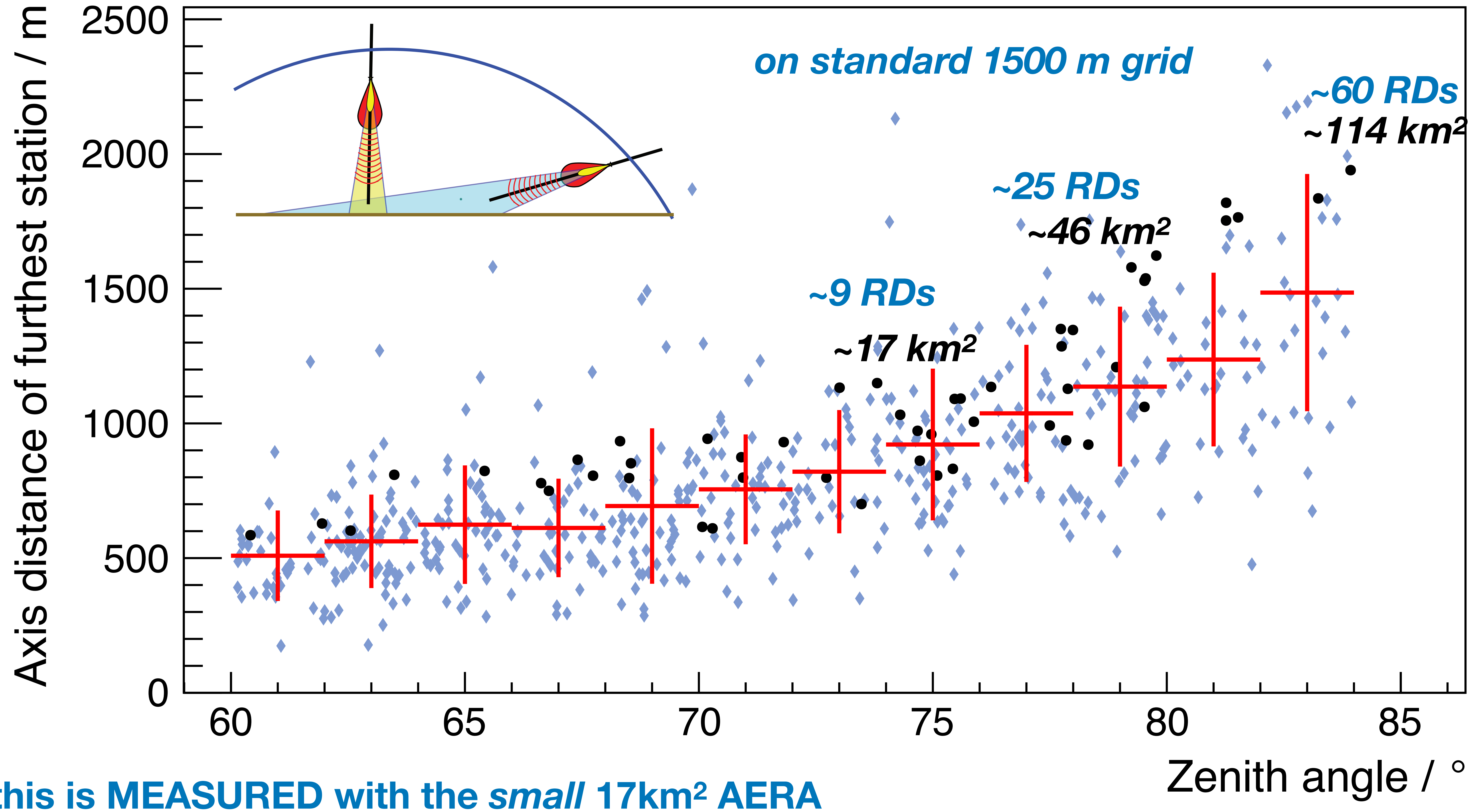


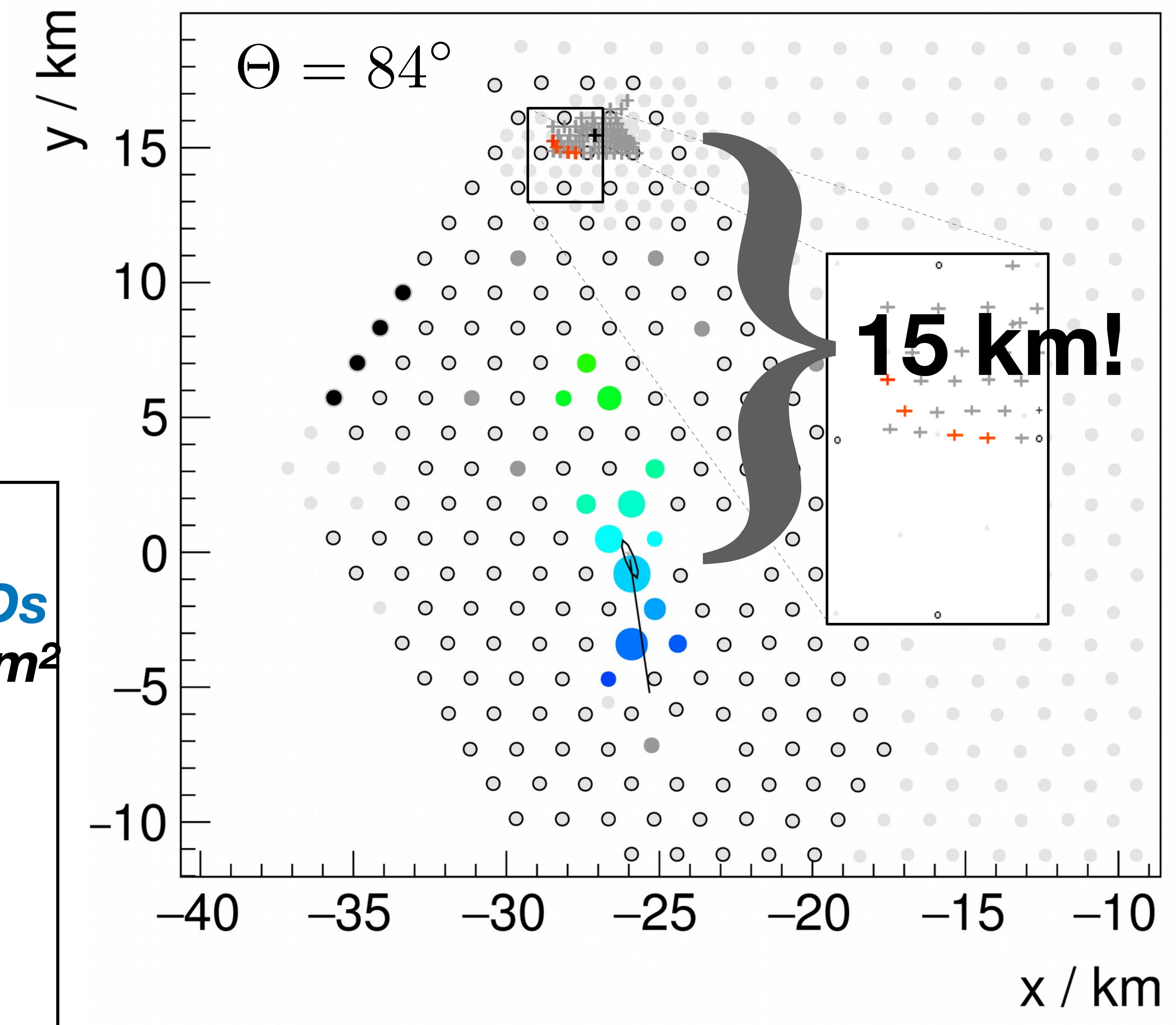
horizontal air showers registered and reconstructed with existing AERA

see e.g. T. Huege, Phys. Rep. 620 (2016) 1

Horizontal air showers have large footprints in radio emission

M. Gottowik





Pierre Auger coll. submitted (2018)
arXiv: 1806.05386

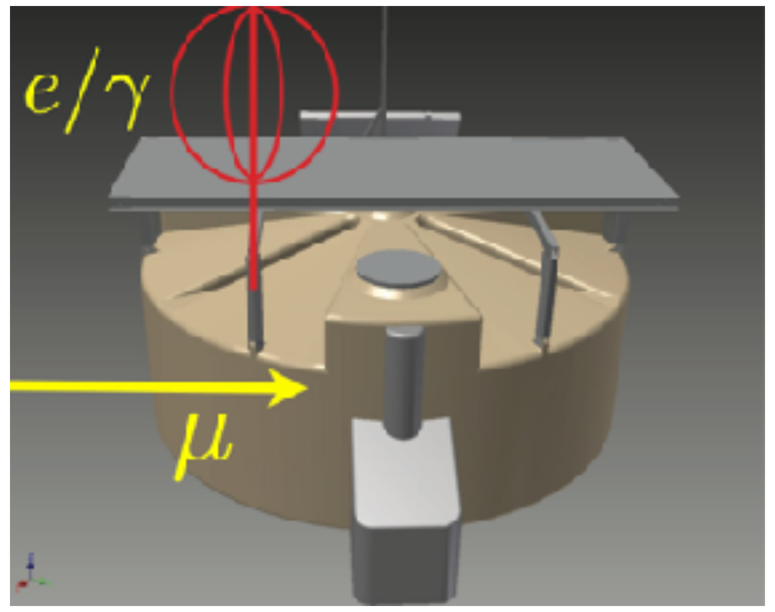
this is MEASURED with the *small* 17km² AERA

Radio Detection of Extensive Air Showers

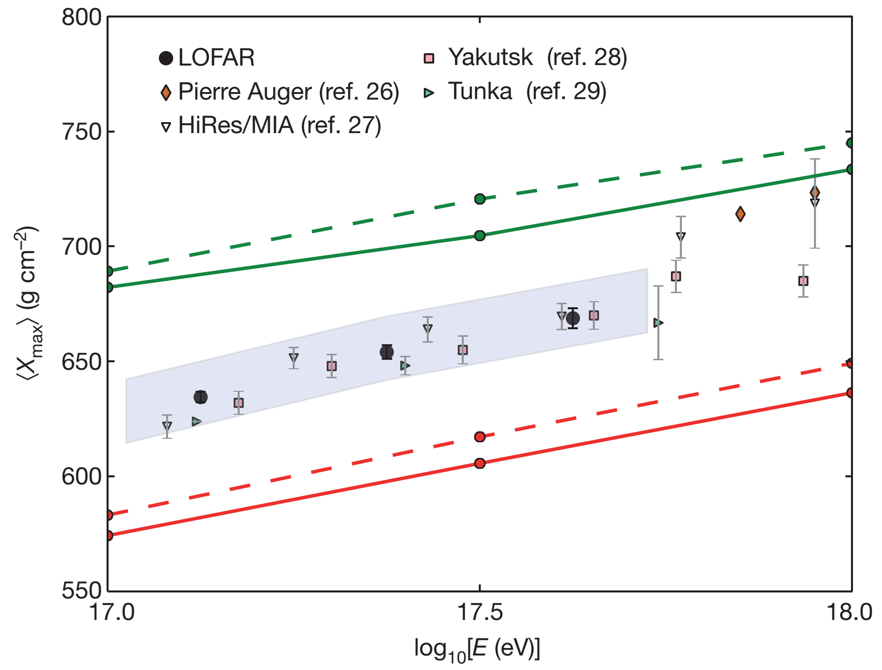
Measurements of the properties of cosmic rays with the radio technique at LOFAR and the Pierre Auger Observatory

huge progress in last decade

***2018*: beyond capabilities of standard installations**

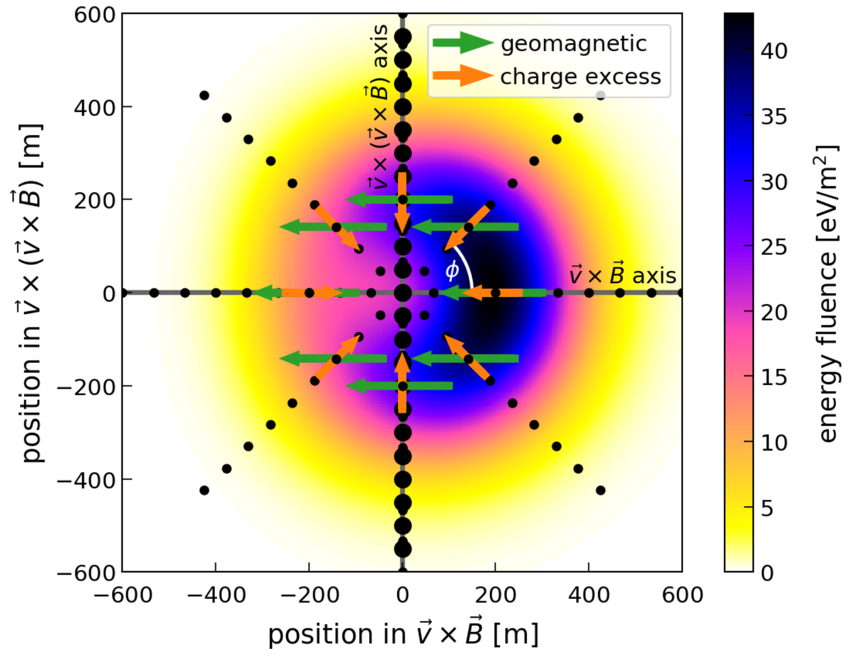


***2016*: radio technique mature: properties of cosmic rays**



***2014*: understanding the emission processes**

2013: CoREAS radio simulation in CORSIKA



2011: endpoint formalism

2005: understanding the radio signal

taskleader radio at Pierre Auger Observatory

PI LOFAR key science project Cosmic Rays

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Radboud University Nijmegen, Nikhef

http://particle.astro.ru.nl