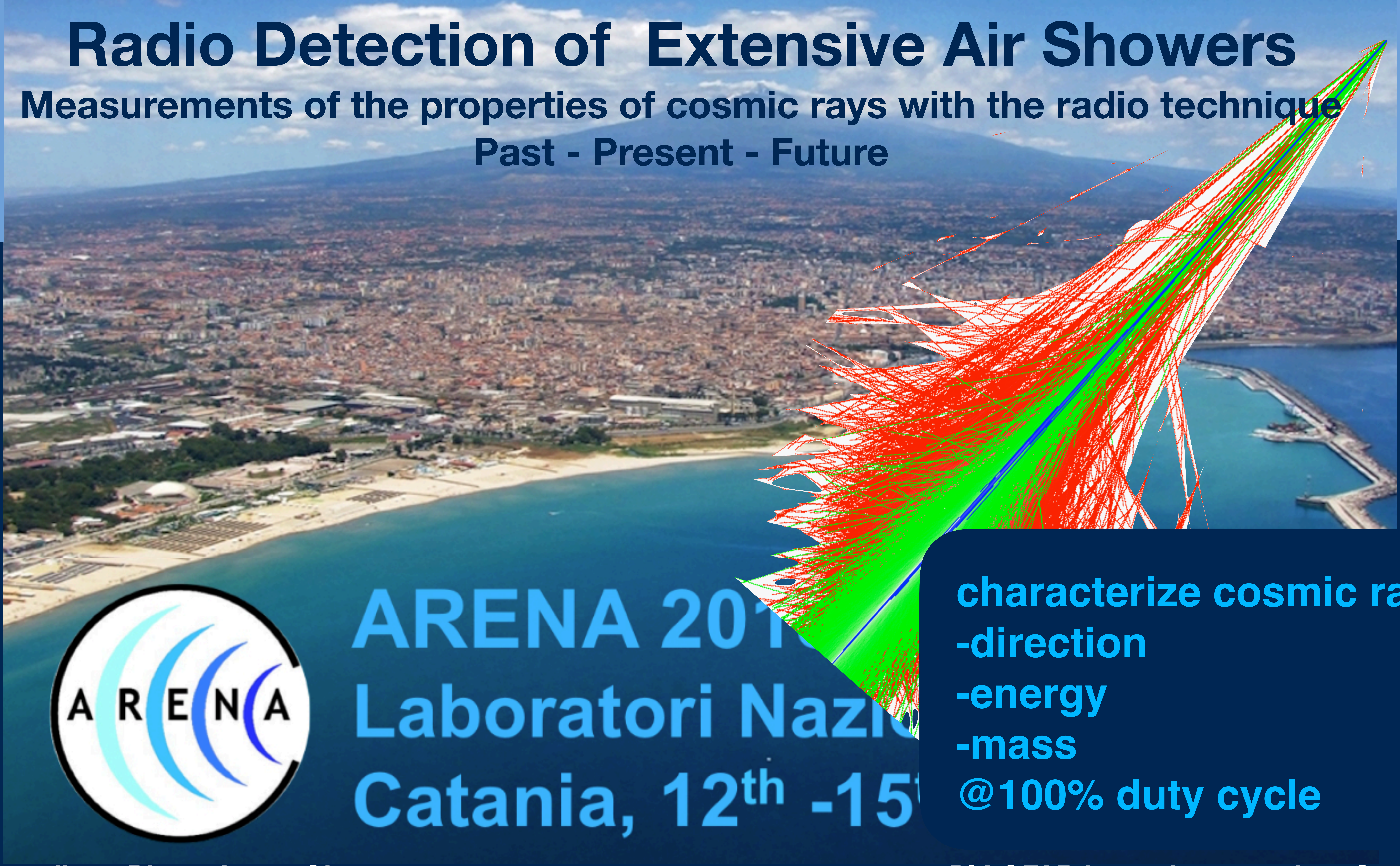
Radio Detection of Extensive Air Showers

Measurements of the properties of cosmic rays with the radio technique

Past - Present - Future



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

Radio Detection of Extensive Air Showers

Measurements of the properties of cosmic rays with the radio technique

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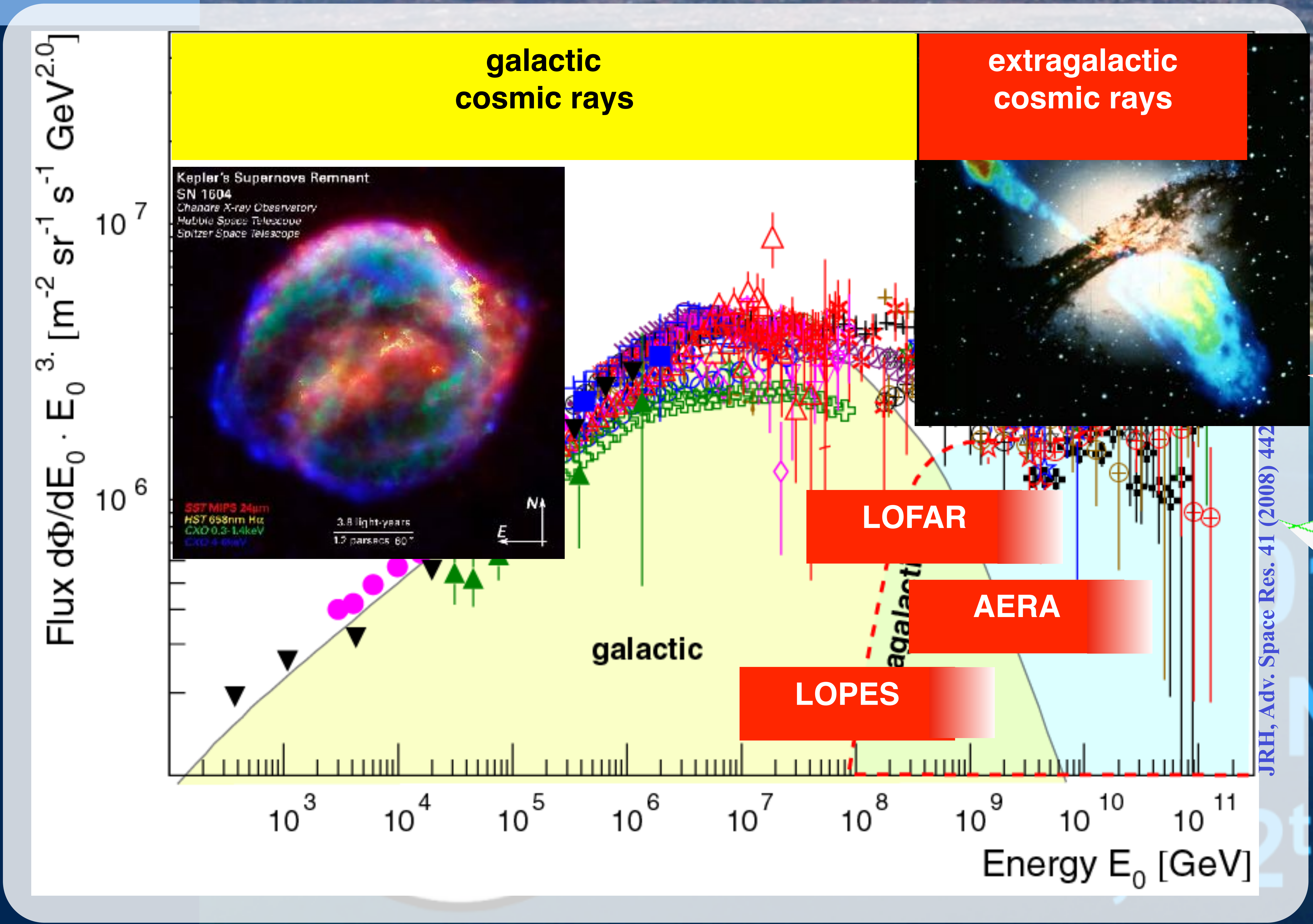

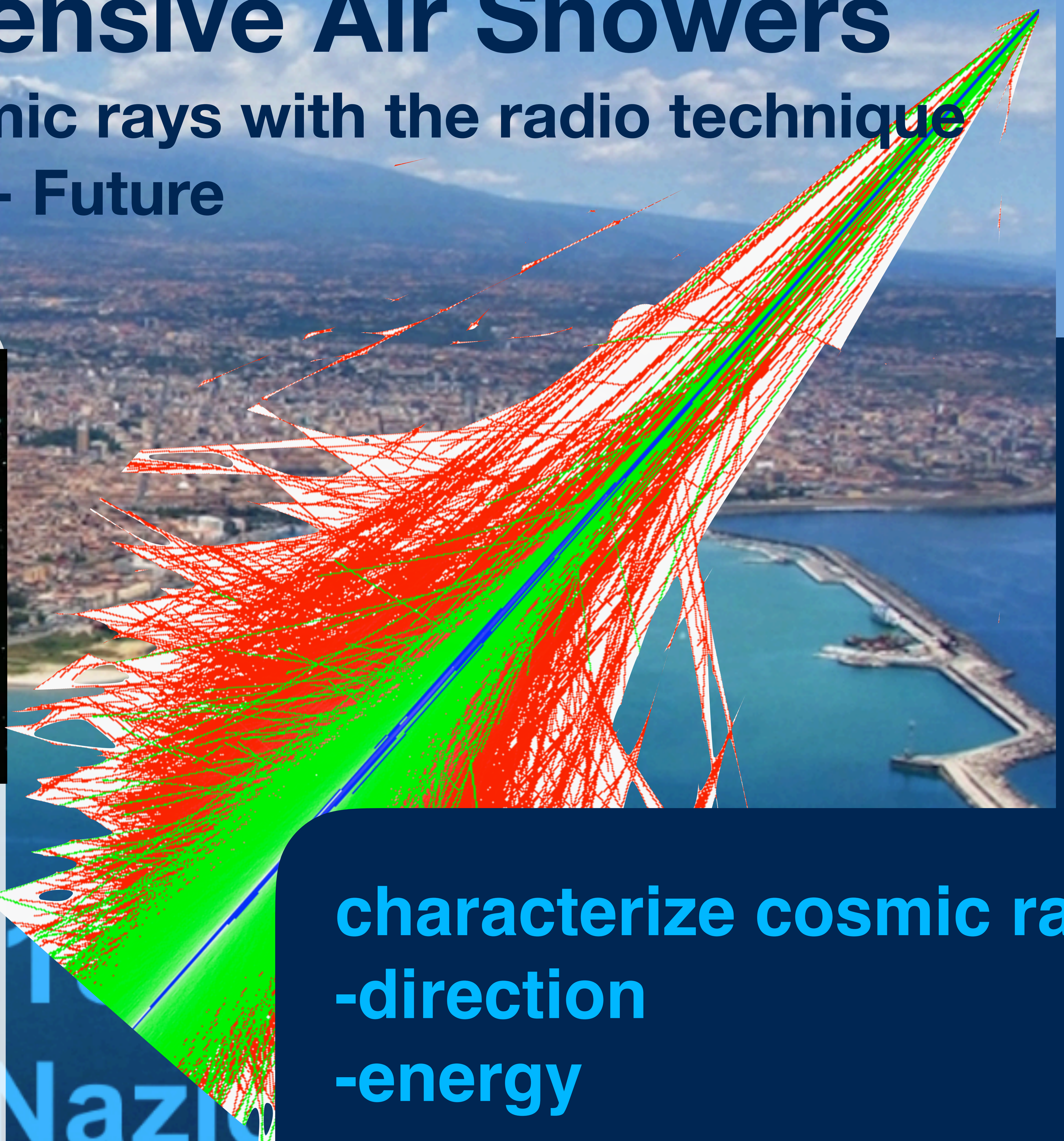

characterize cosmic rays:
- -direction
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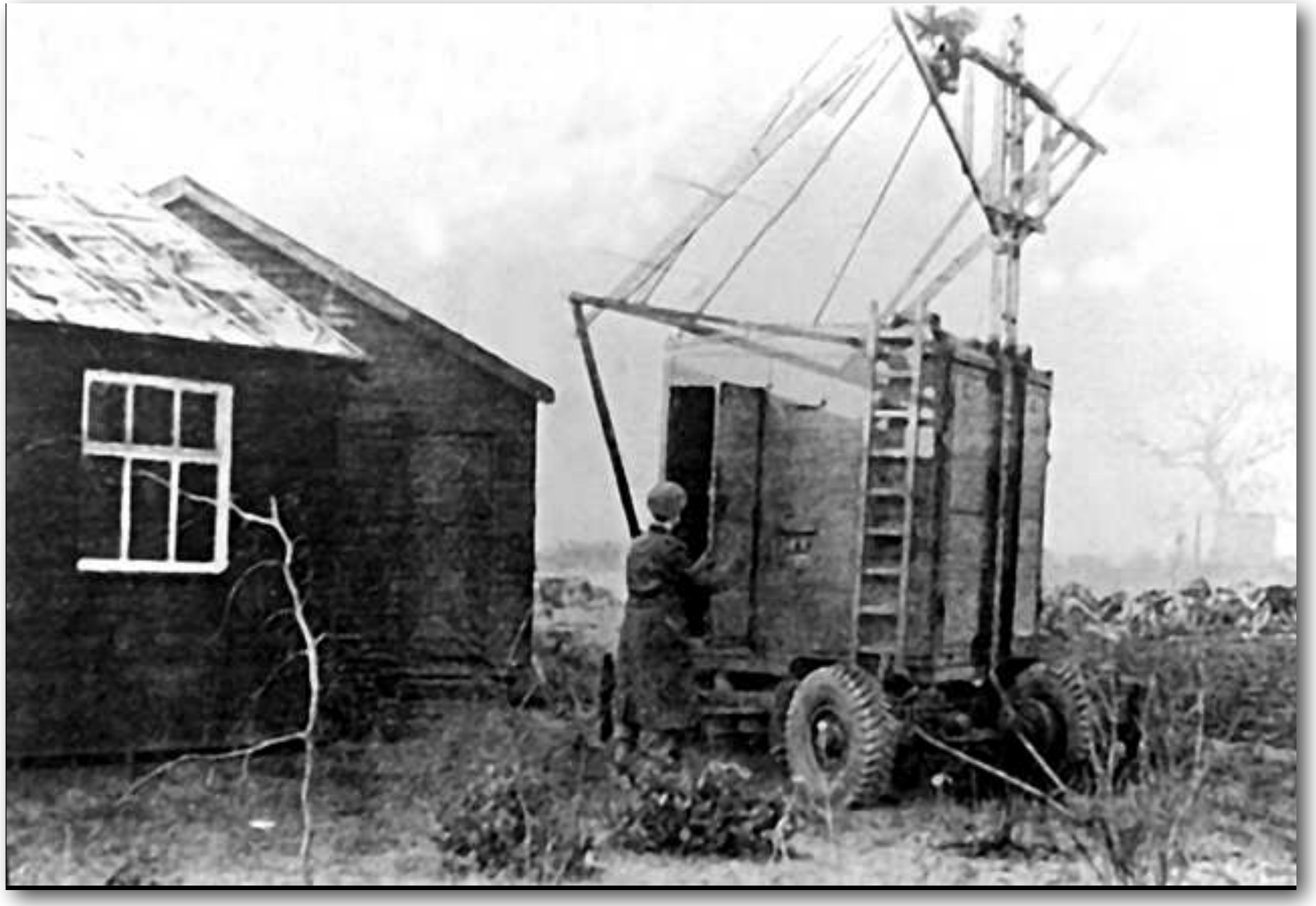
Jodrell Bank 1946

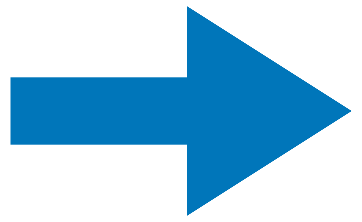


No air showers detected

No luck due to rapid attachment time (ns) of free electrons in the lower atmosphere (damping factor)

$O_2 + e \rightarrow O_2^-$

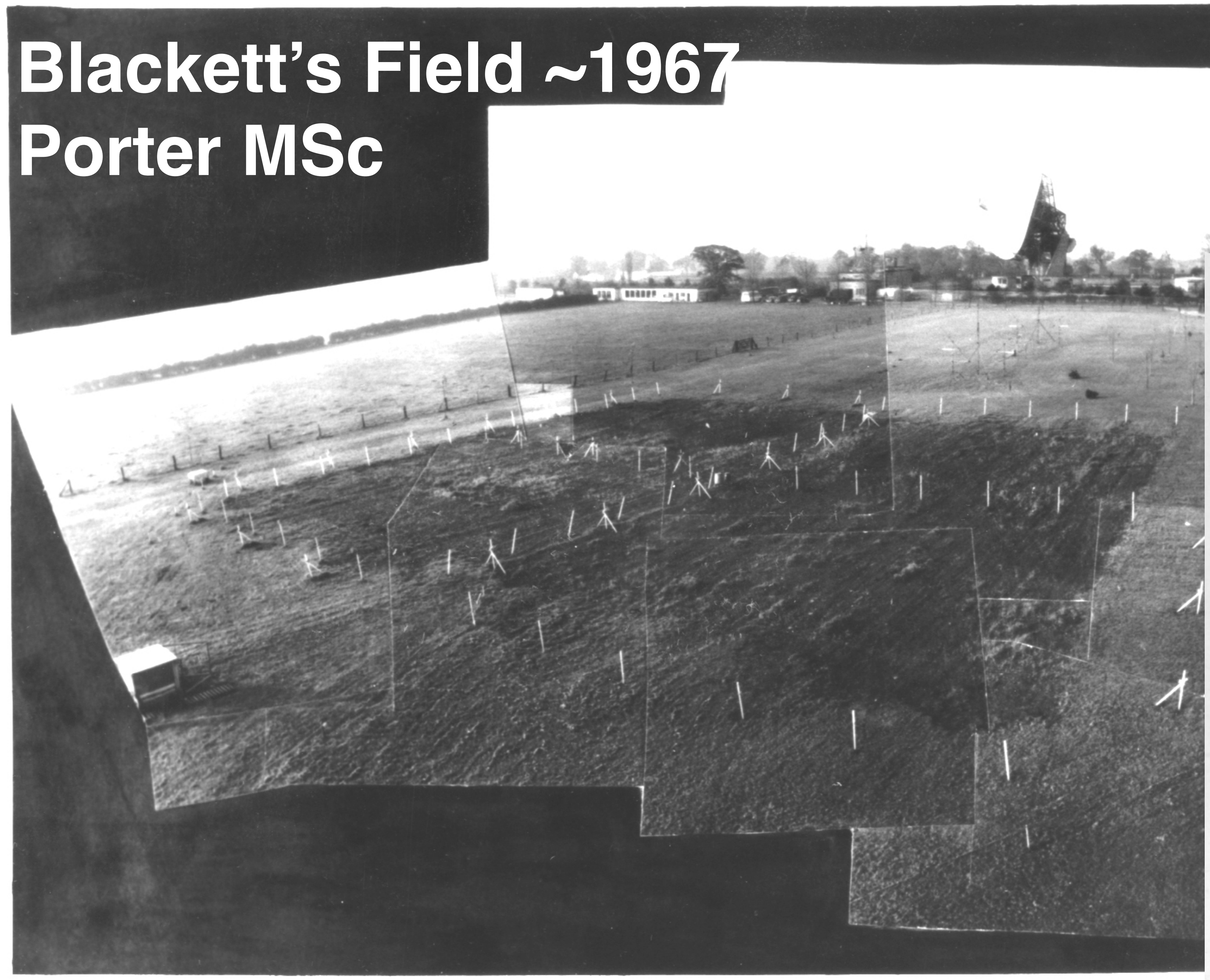
Echos from meteor trails
Radio emission from M31



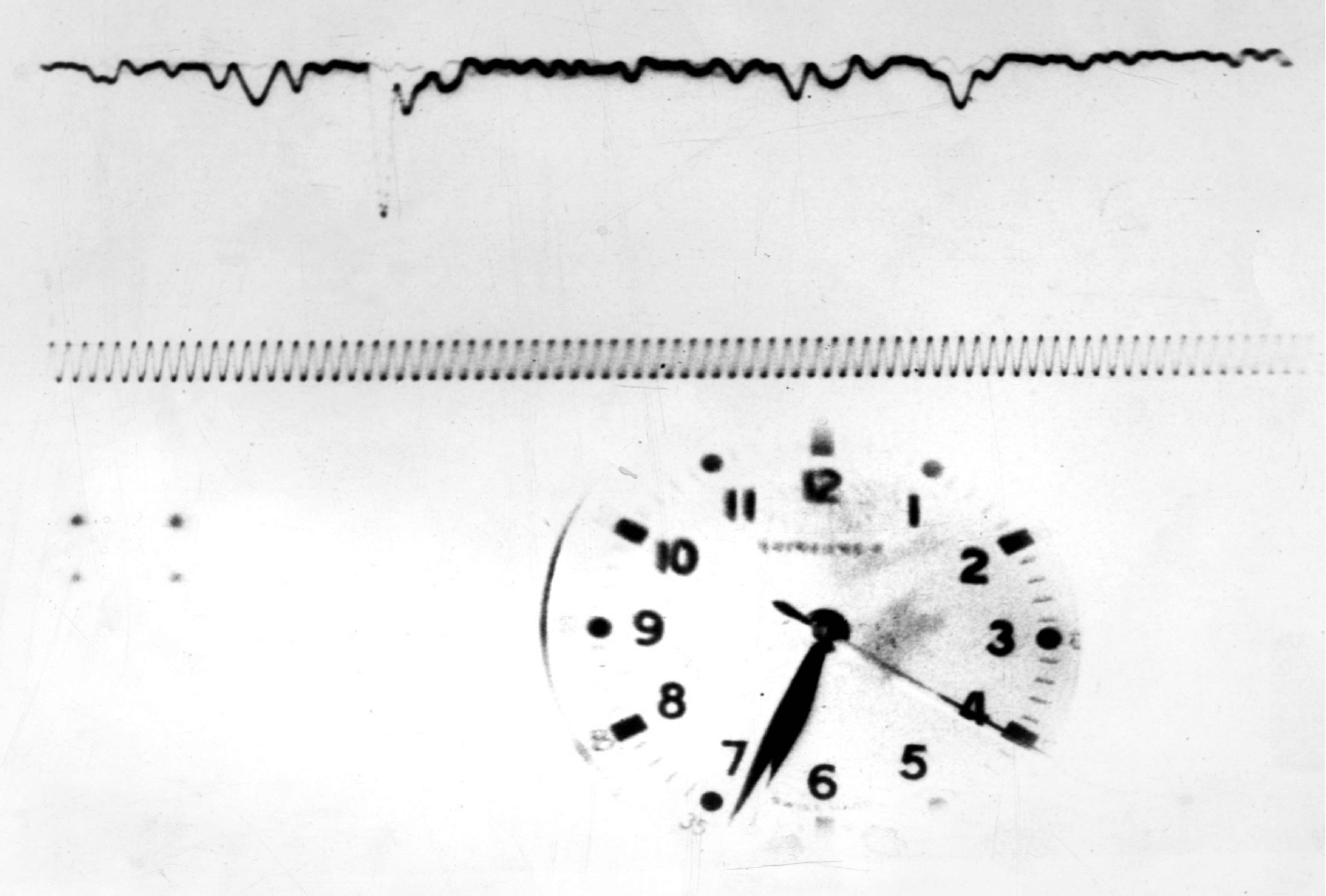
radio astronomy

First radio detection of air showers 1965

First radio detection of air showers 1965

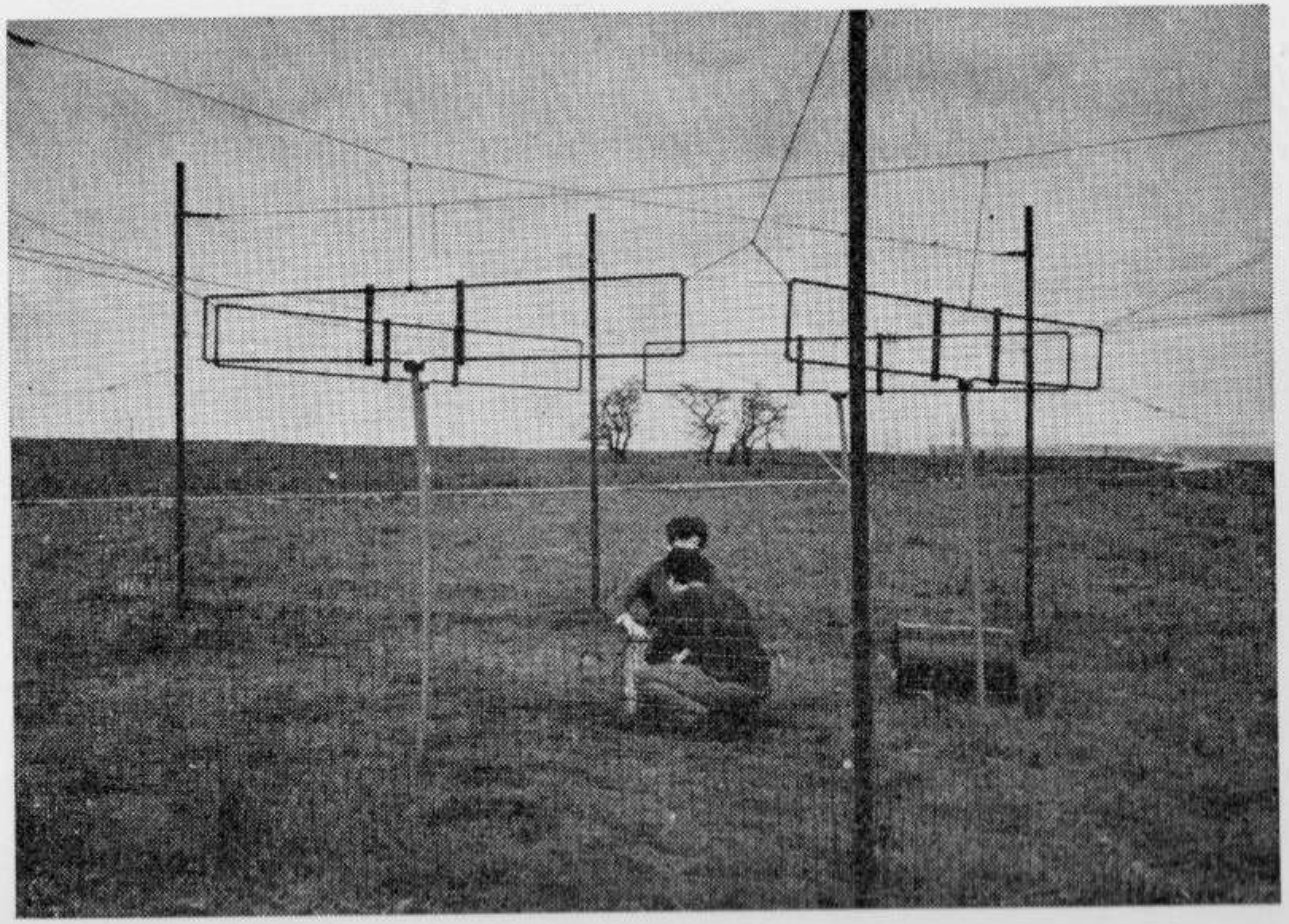


Blackett's Field ~1967
Porter MSc



Jelley et al Nature 1965
R. A. Porter MSc Thesis 1967

Haverah Park (Leeds) Allan 1971

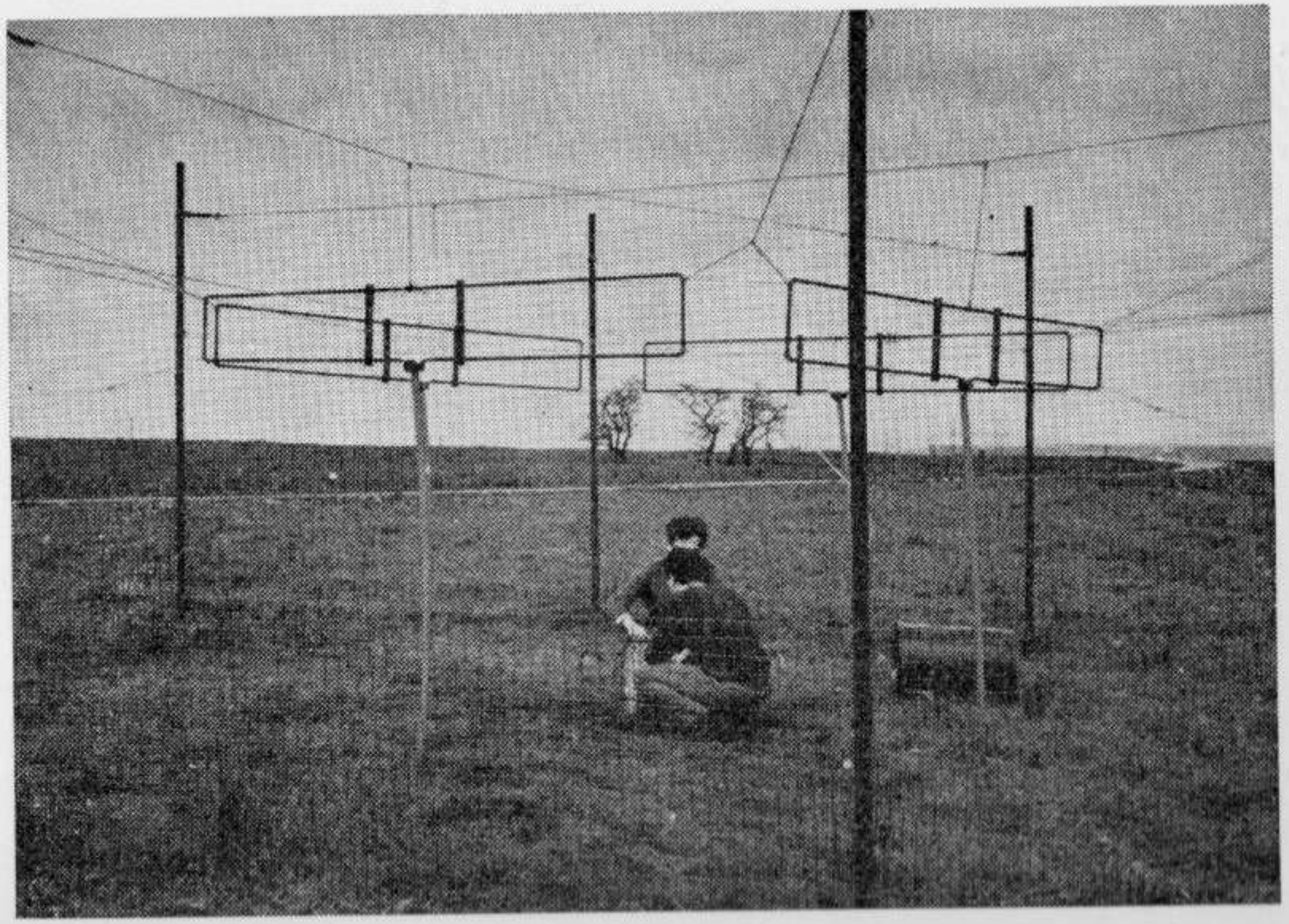


Recent receiving antennas (44 MHz) forming part of the Haverah Park Extensive Air Shower Array.

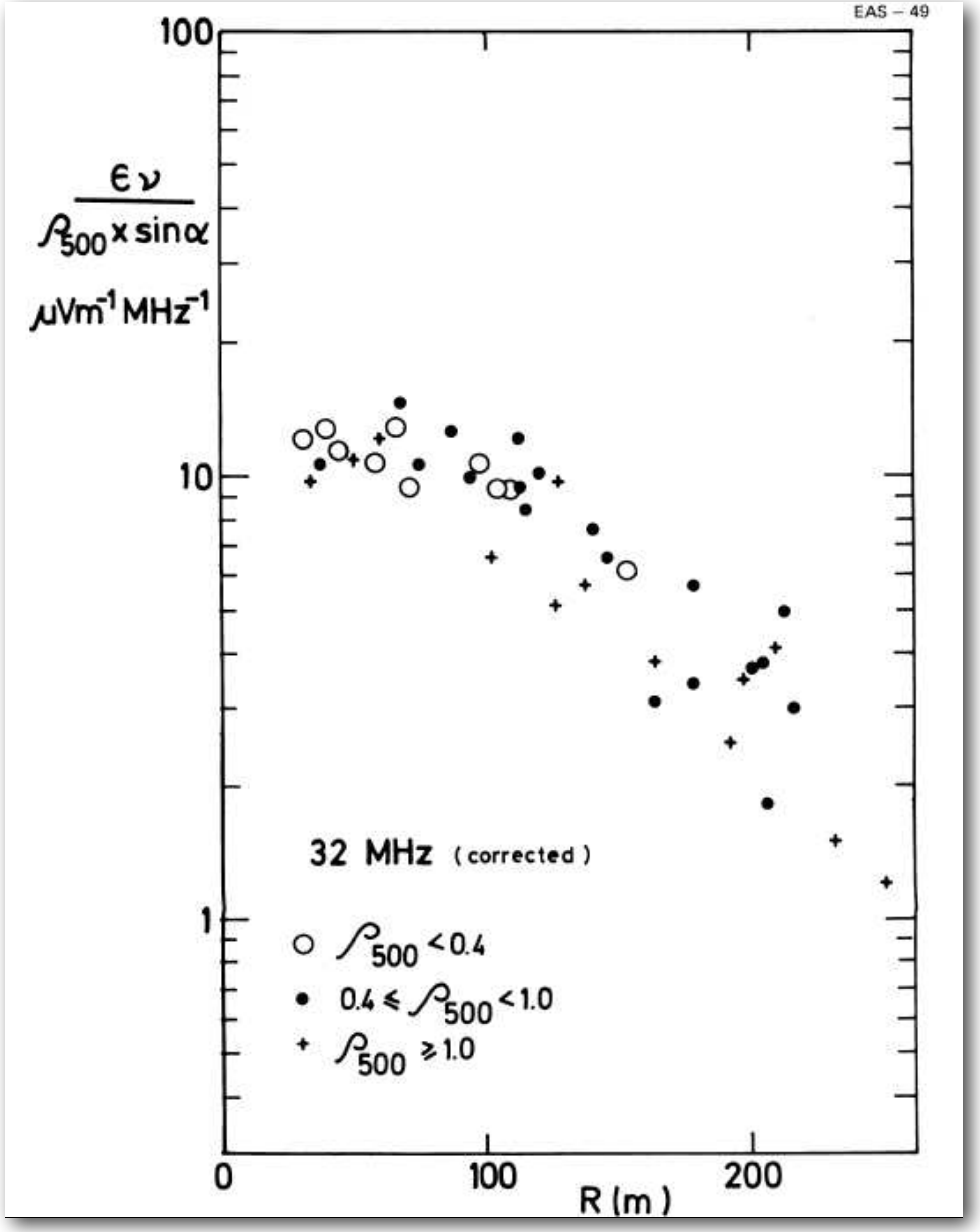
H.R. Allan, Prog. Element. Part. Cosmic Ray Phys (1971) 169

Haverah Park (Leeds)

Allan 1971



Recent receiving antennas (44 MHz) forming part of the Haverah Park Extensive Air Shower Array.



$$\varepsilon_\nu = 2\left(\frac{E_p}{10^{17}}\right)\left(\frac{\sin\alpha\cos\theta}{\sin 45\cos 30}\right)\exp\left(\frac{-r}{r_0}\right)\left(\frac{\nu}{50}\right)^{-1} \quad \mu\text{V/m/MHz}$$

$r_0 = 110$ m at ν=55 MHz. α=angle to B, θ=Zenith angle

H.R. Allan, Prog. Element. Part. Cosmic Ray Phys (1971) 169

First European Symposium on High Energy Interactions and Extensive Air Shower: Lodz, Poland April 1968

33RD INTERNATIONAL COSMIC RAY CONFERENCE, RIO DE JANEIRO 2013
THE ASTROPARTICLE PHYSICS CONFERENCE

The renaissance of radio detection of cosmic rays

TIM HUEGE[1]

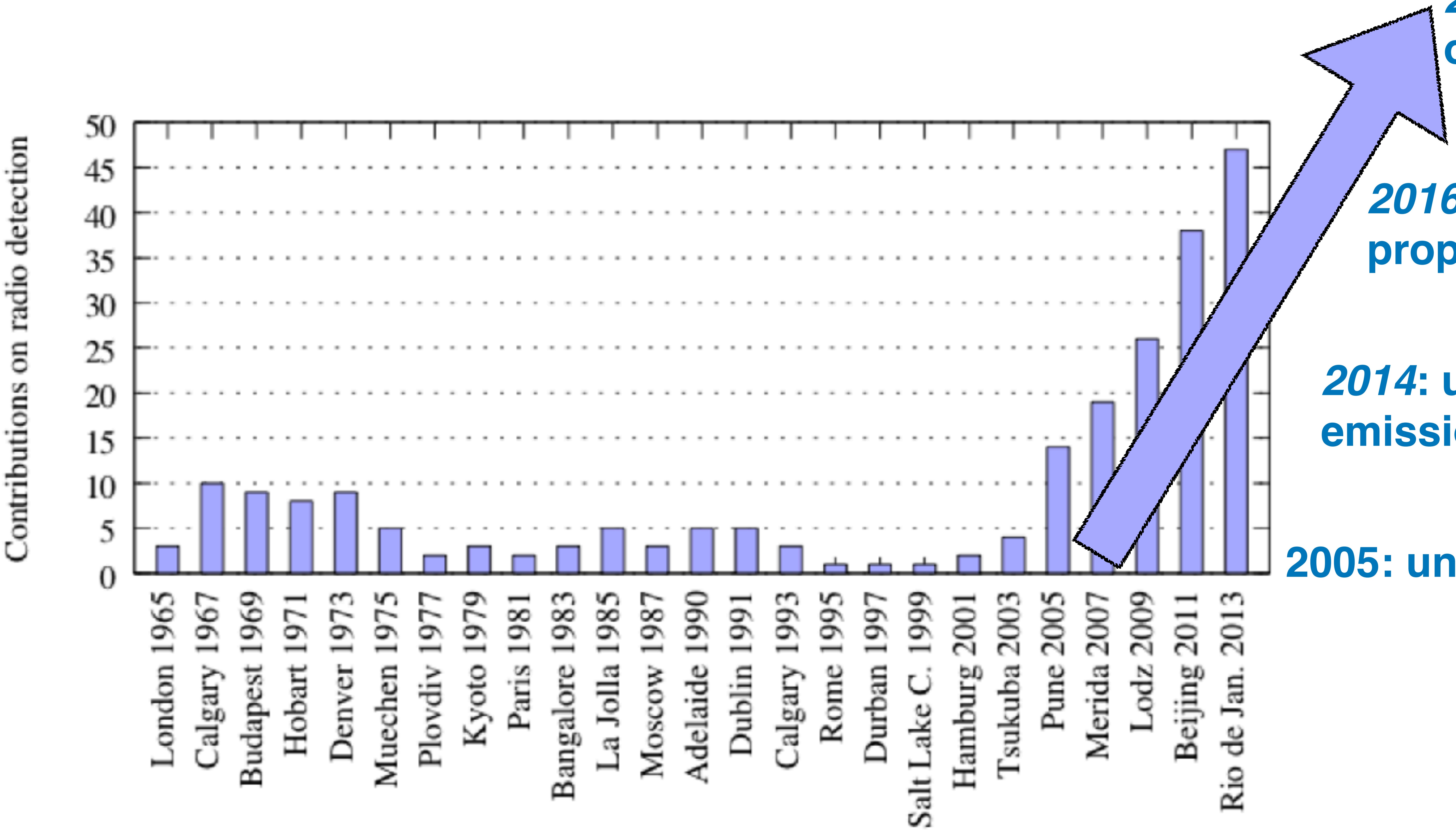


Figure 1: Number of contributions related to radio detection of cosmic rays or neutrinos to the ICRCs since 1965. The field has grown very impressively since the modern activities started around 2003. Data up to 2007 were taken from [11].

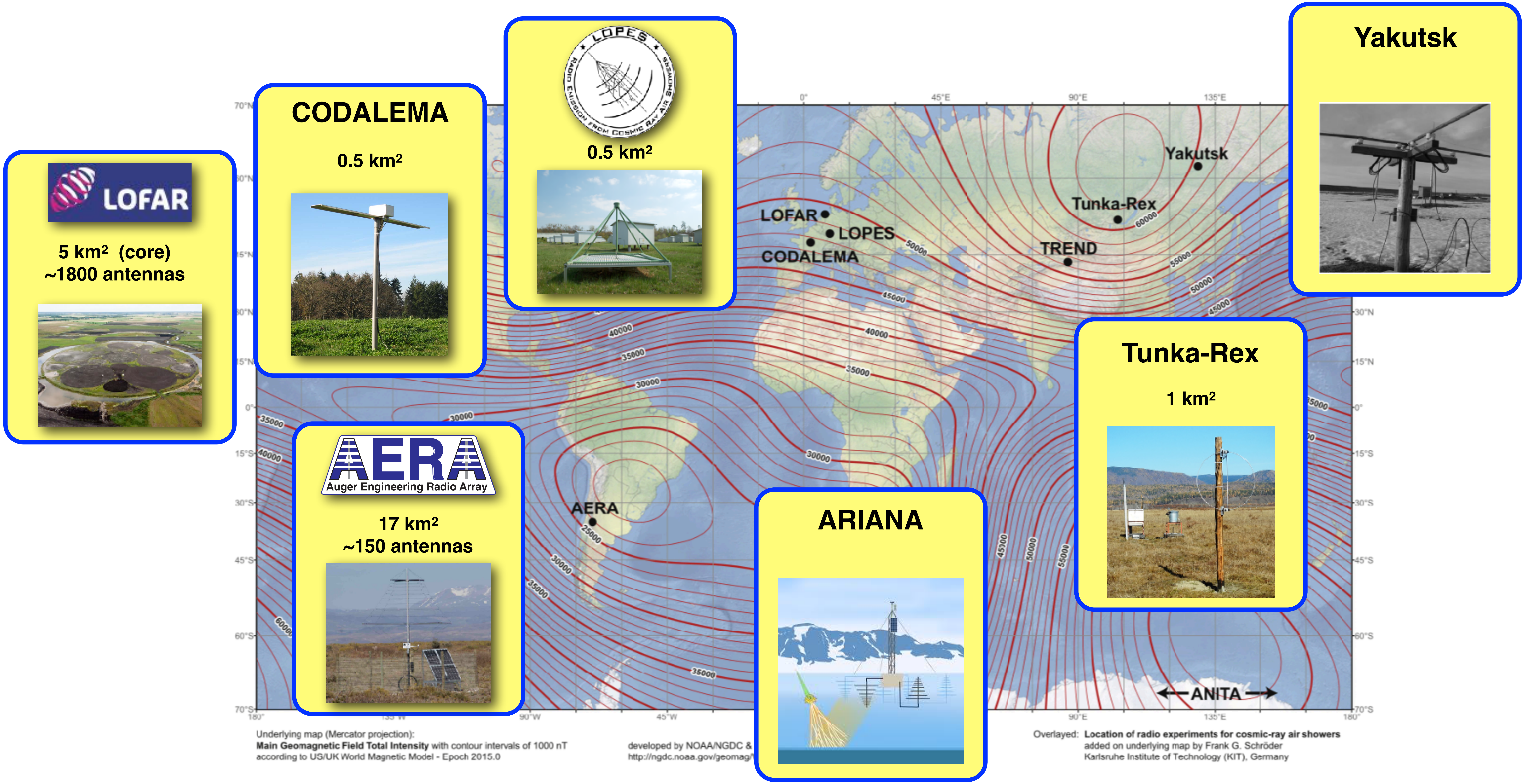
***2018*: beyond capabilities of standard installations**

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

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

2005: understanding the signal

Radio detection of extensive air showers around the world



LOFAR

5 km² (core)
~1800 antennas

CODALEMA

0.5 km²

LOPES

0.5 km²

Yakutsk

Tunka-Rex

1 km²

AERA

Auger Engineering Radio Array

17 km²
~150 antennas

ARIANA

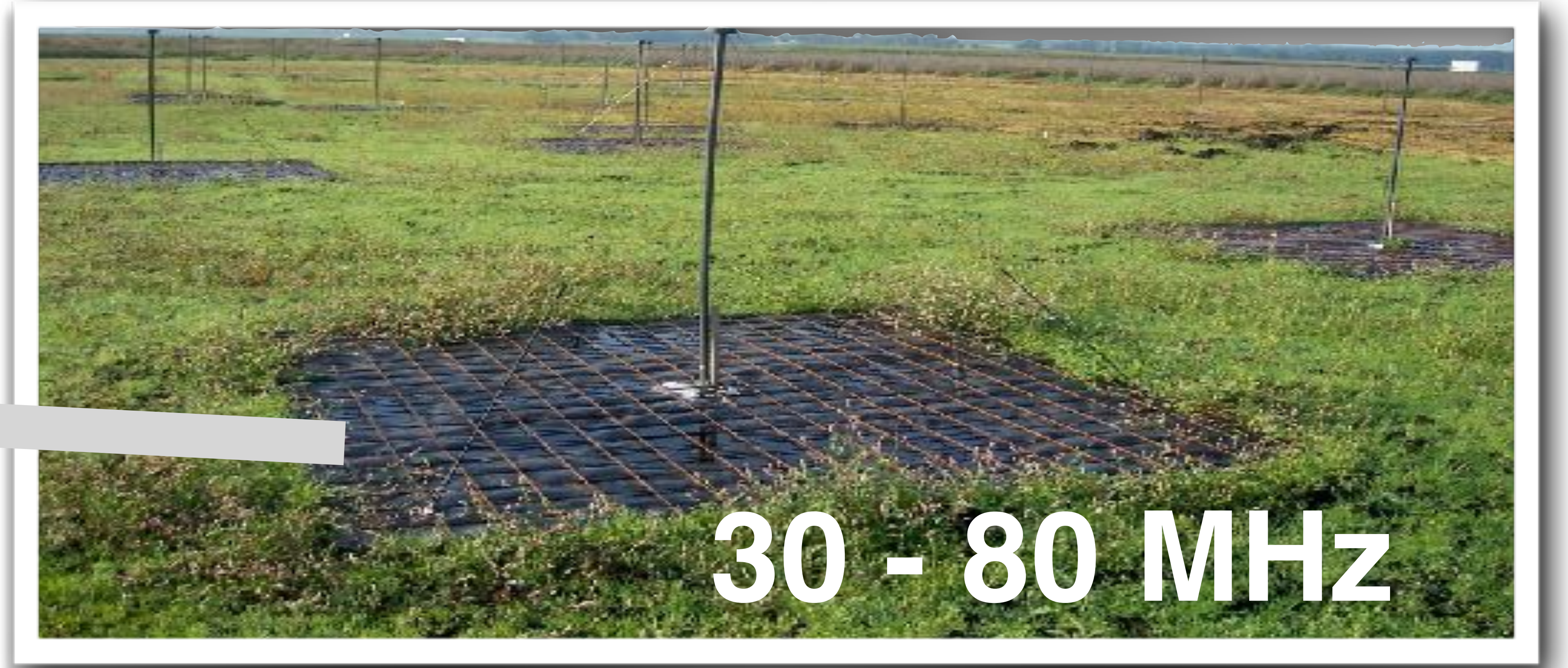
Underlying map (Mercator projection):
Main Geomagnetic Field Total Intensity with contour intervals of 1000 nT
according to US/UK World Magnetic Model - Epoch 2015.0

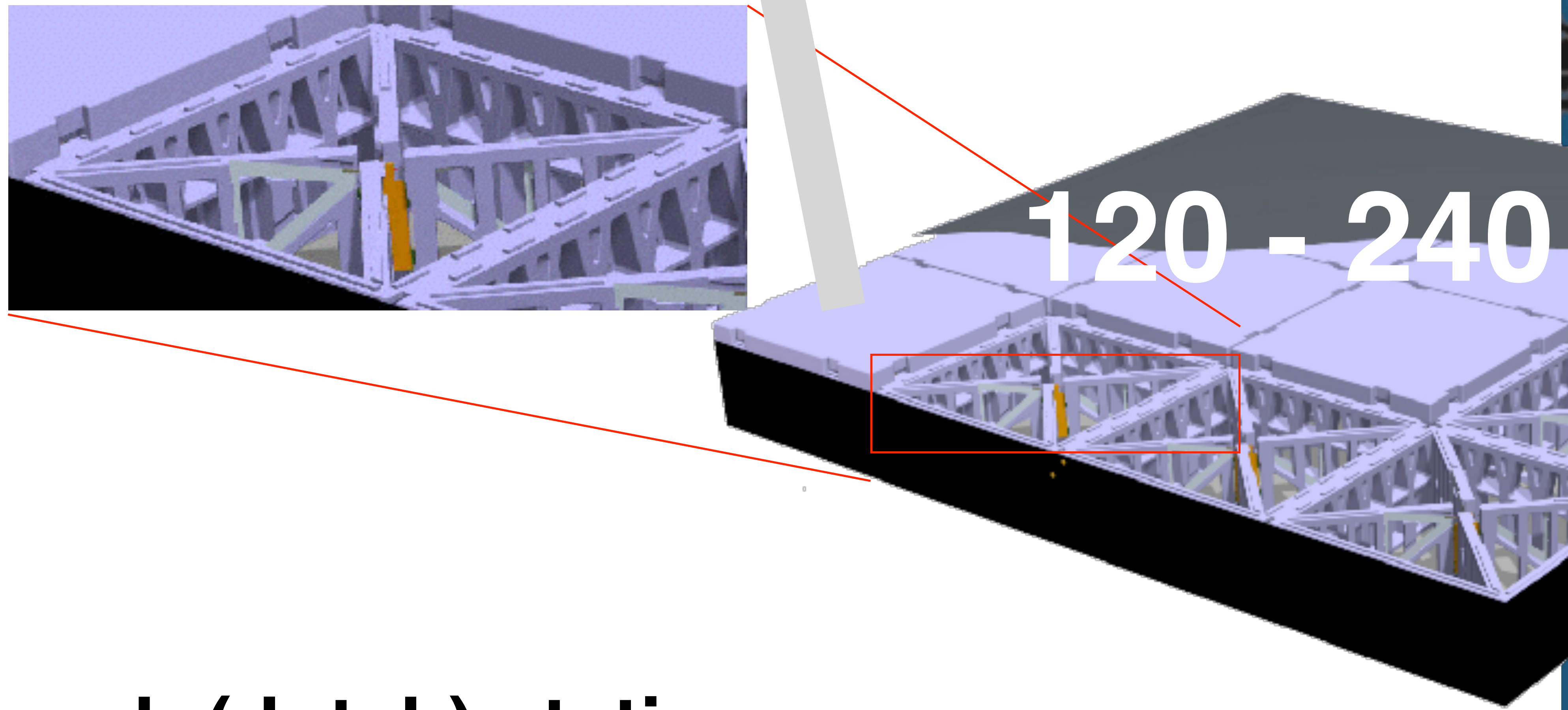
developed by NOAA/NGDC &
http://ngdc.noaa.gov/geomag/

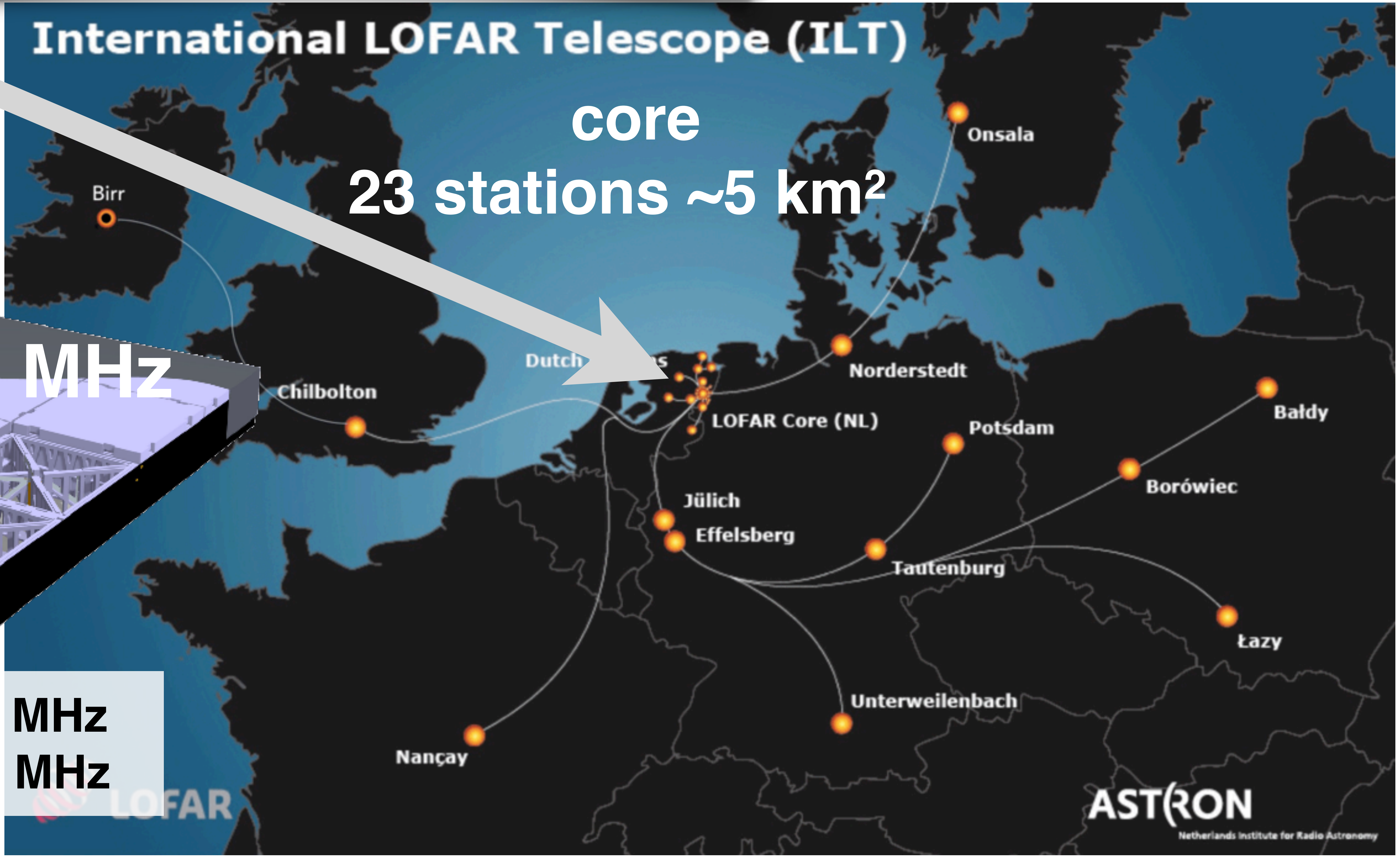
Overlayed: Location of radio experiments for cosmic-ray air showers
added on underlying map by Frank G. Schröder
Karlsruhe Institute of Technology (KIT), Germany

Fig. 21. Map of the total geomagnetic field strengths (world magnetic model [207]) and the location of various radio experiments detecting cosmic-ray air showers.

F.G. Schröder, Prog. Part. Nucl. Phys. 92 (17) 1







core
23 stations ~5 km²

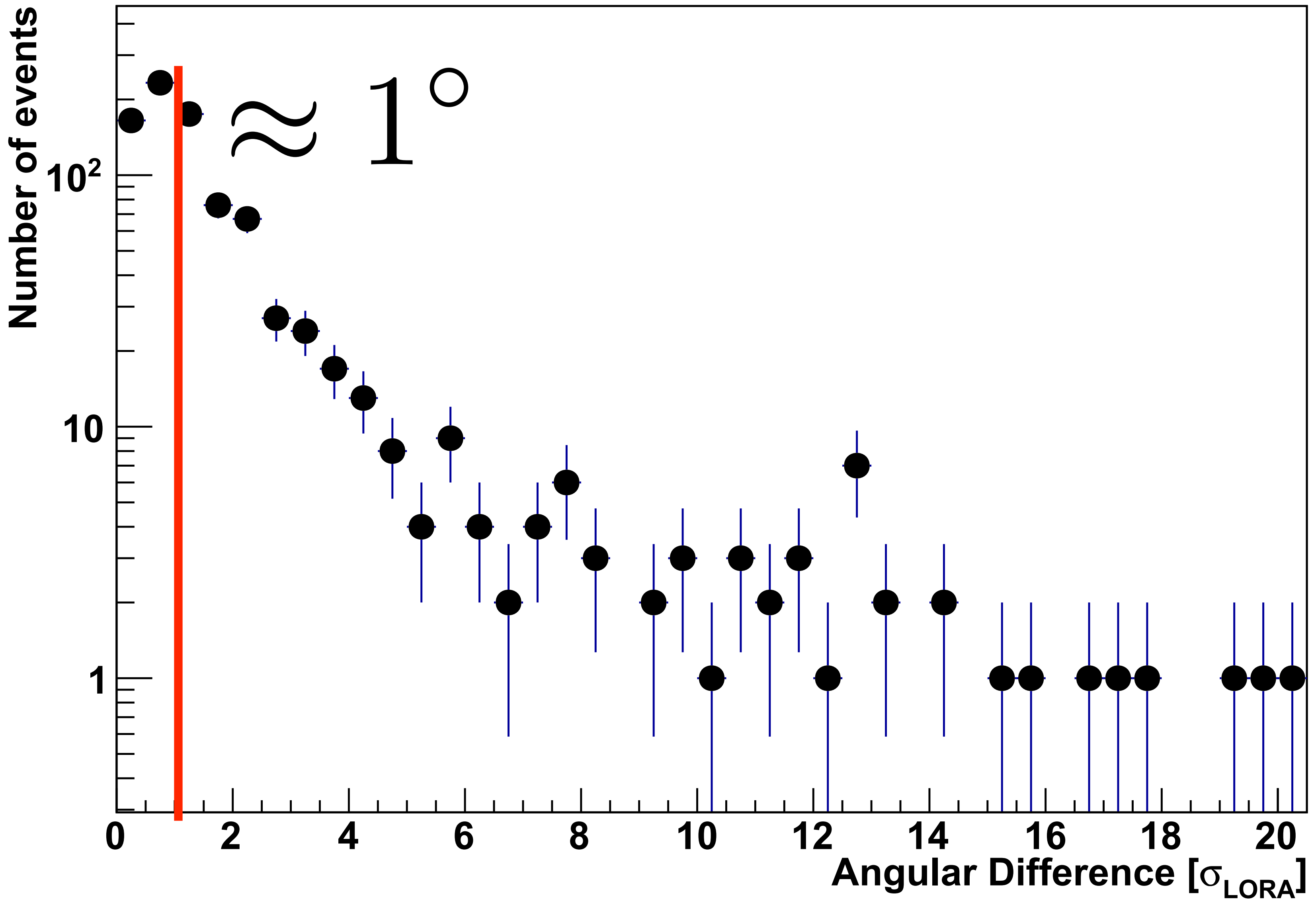
each (dutch) station:

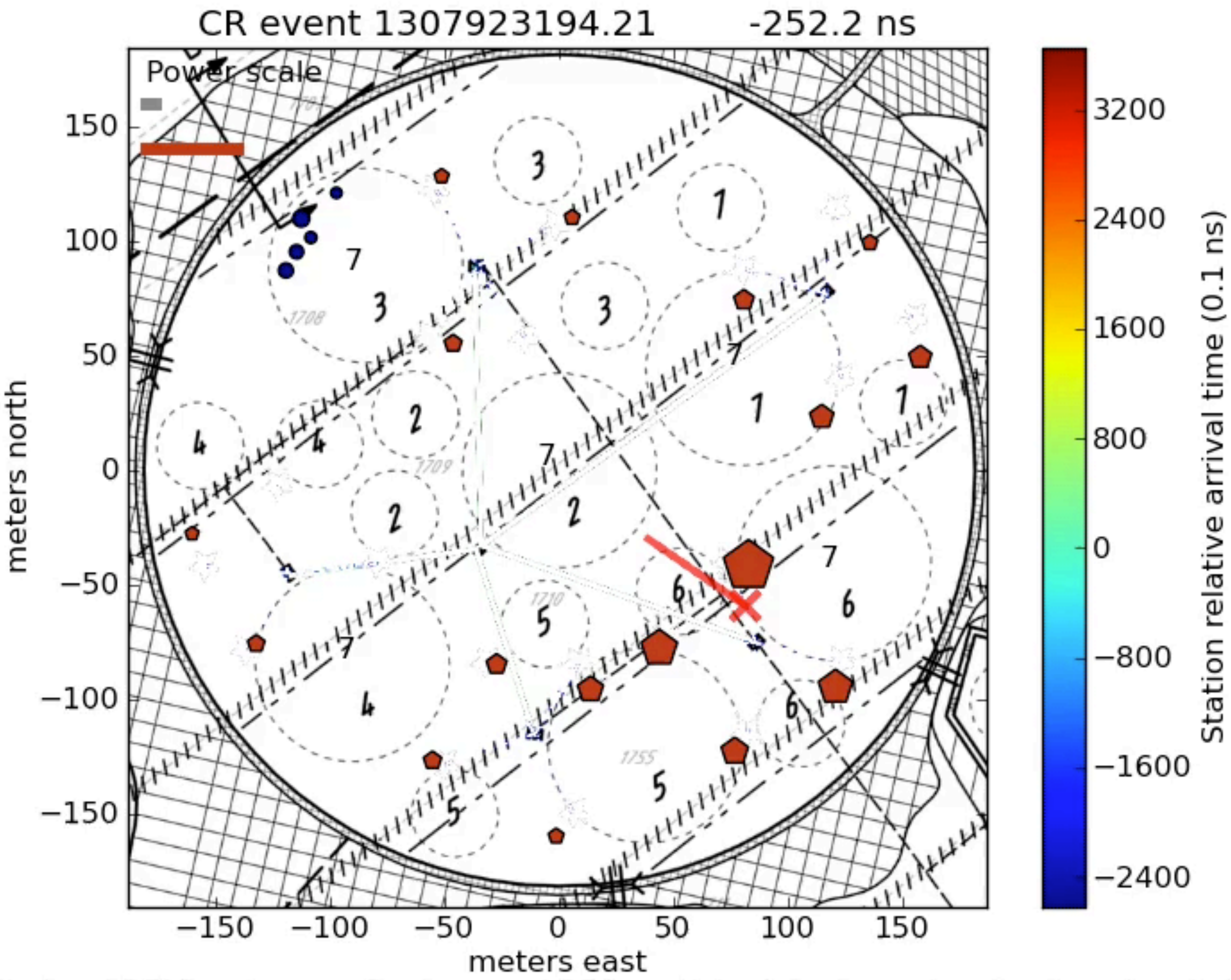
- 96 low-band antennas 30- 80 MHz
- high-band antennas (2x24 tiles) 120-240 MHz

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

A measured air shower

angular difference particles - radio





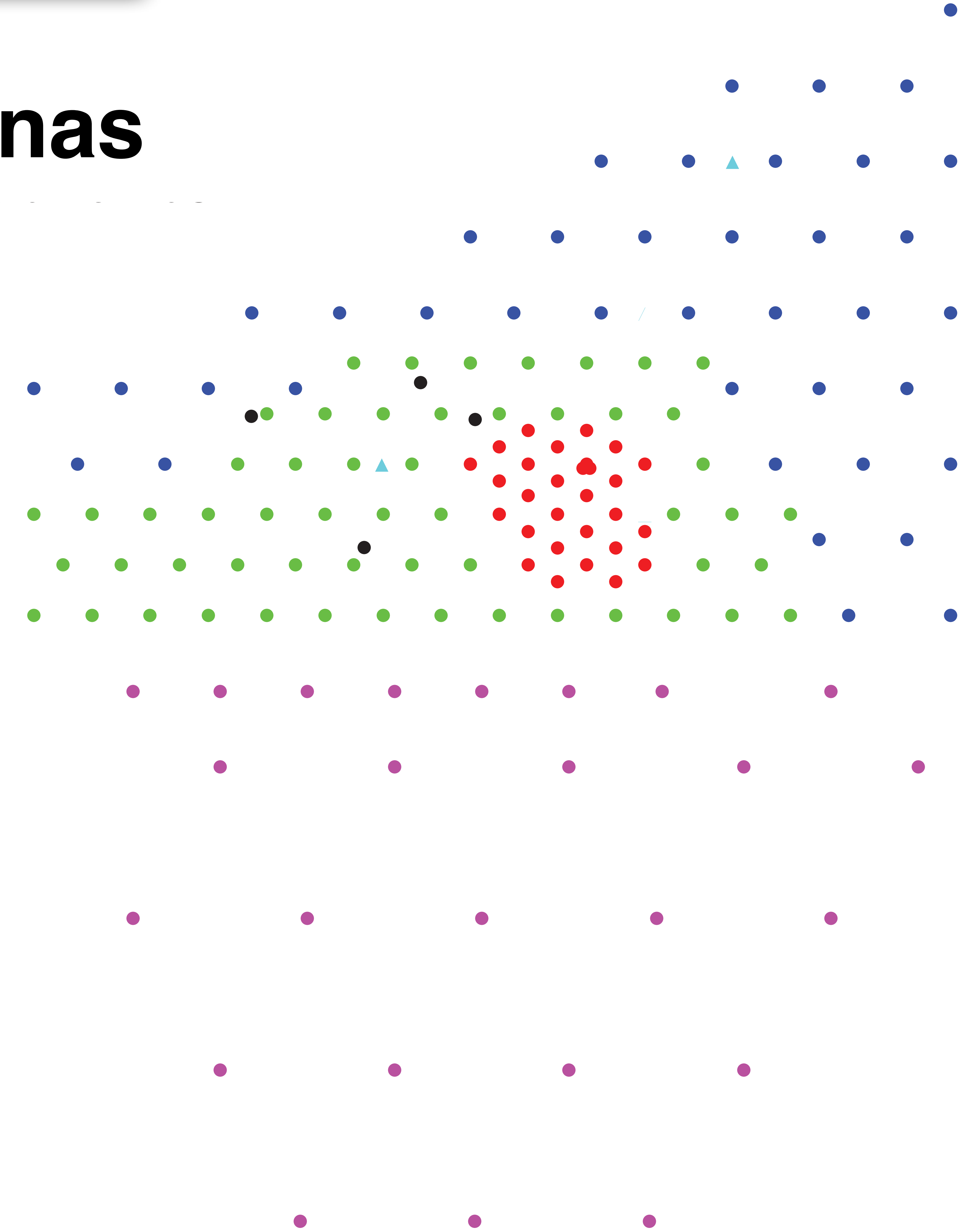
Circles: LOFAR antennas, Pentagons: LORA particle detectors, size denotes signal strength

Auger Engineering Radio Array

~150 antennas

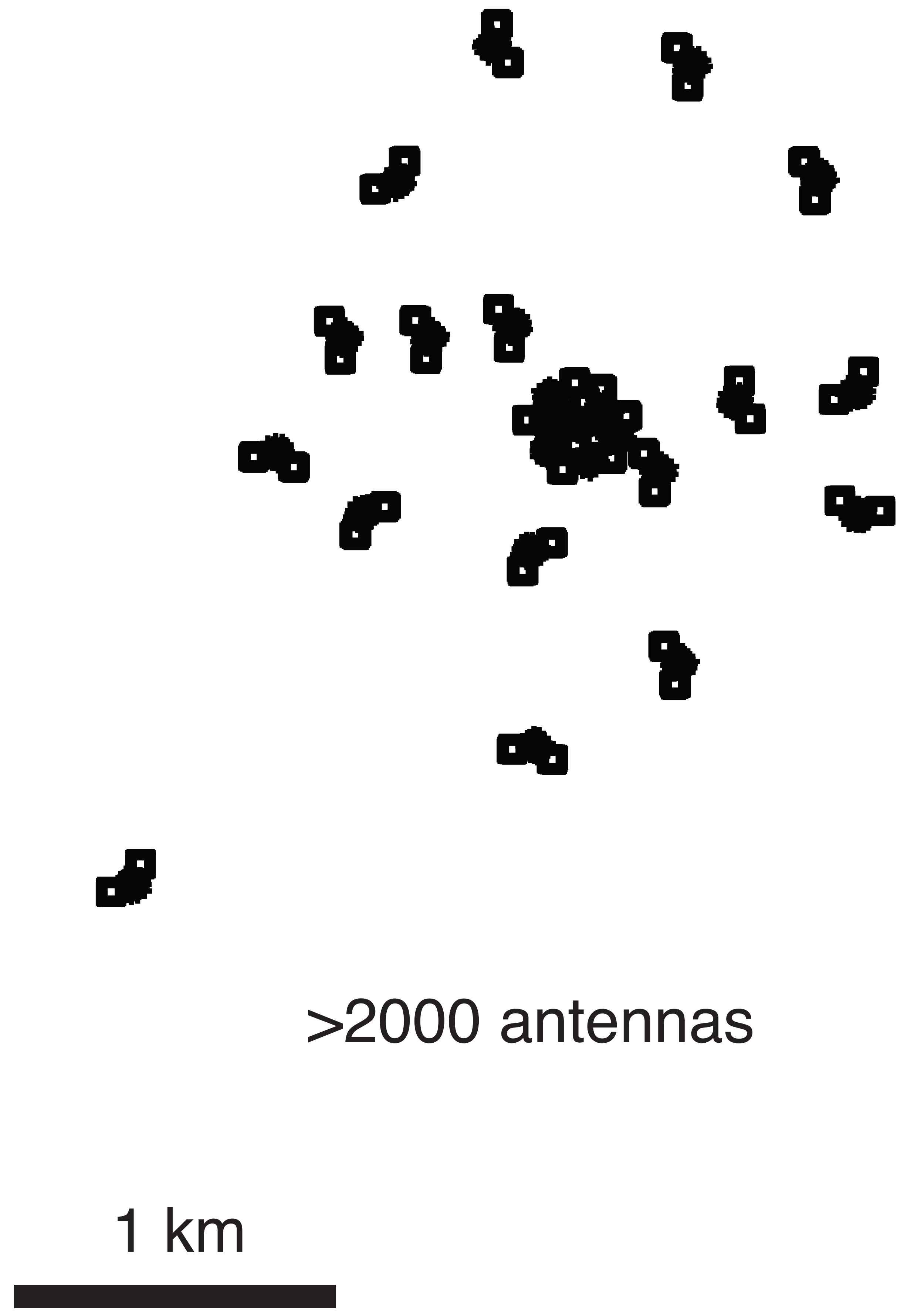
~17 km²

30-80 MHz



LOFAR core

23 stations ~5 km²



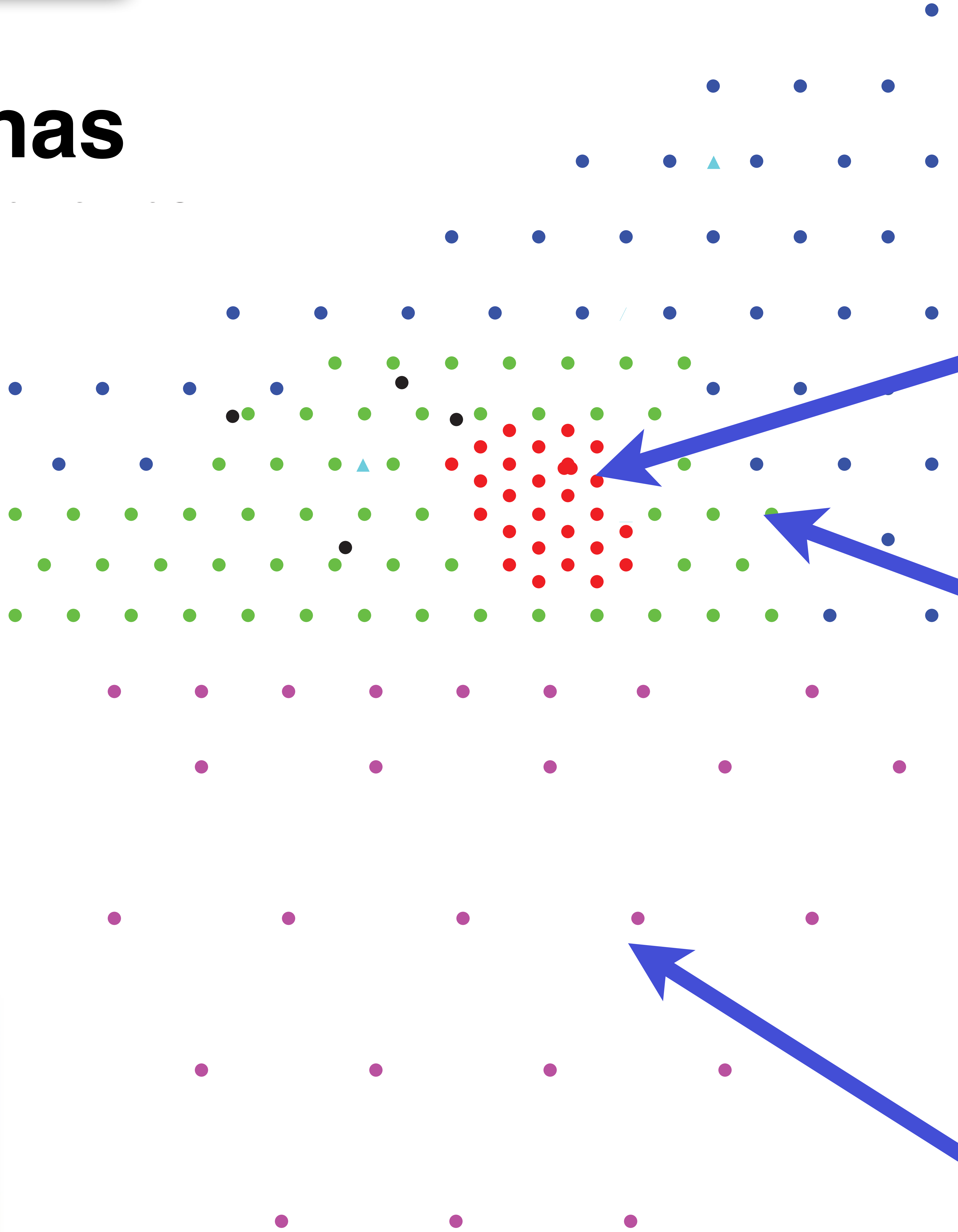
>2000 antennas

1 km

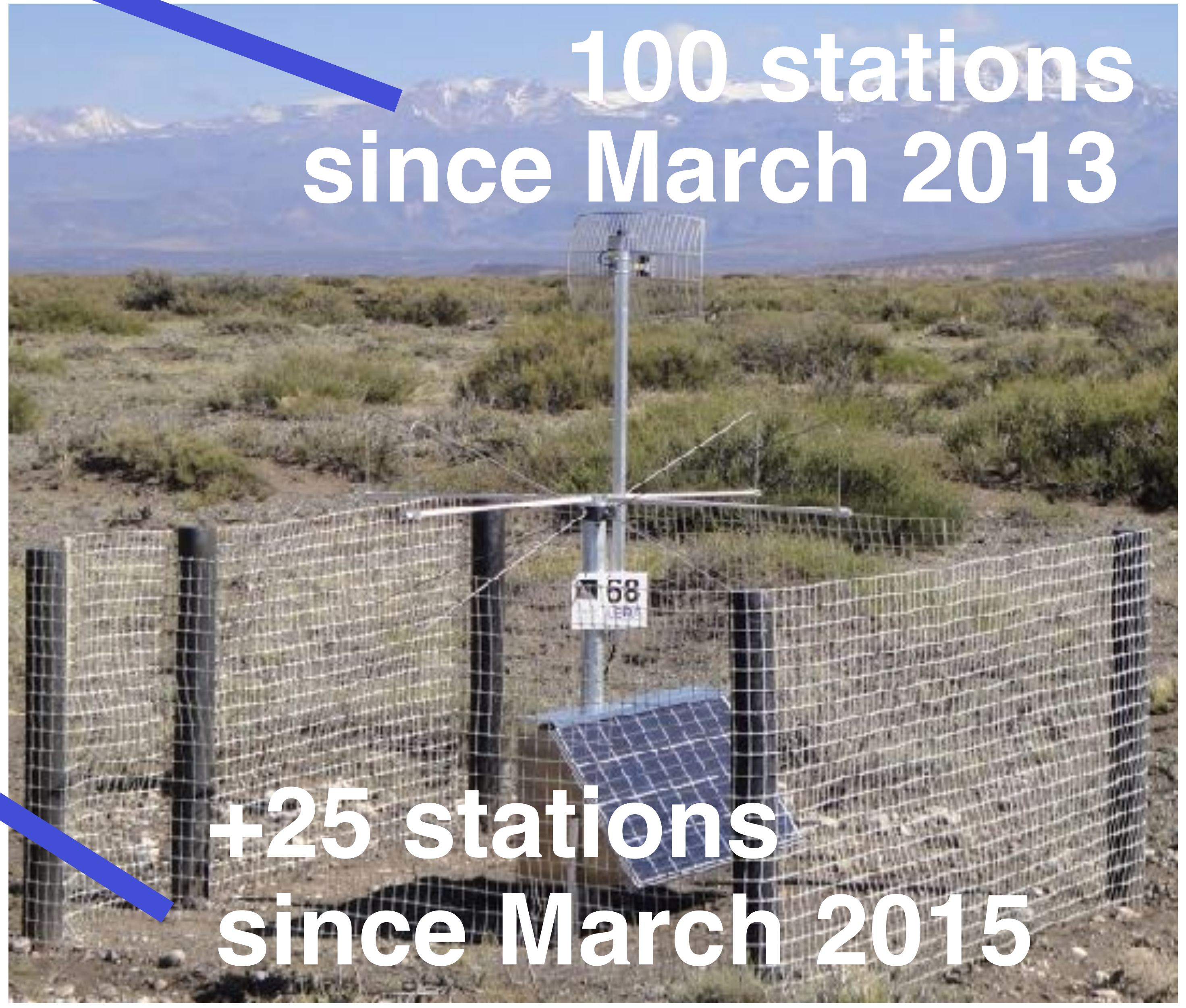
PIERRE AUGER OBSERVATORY

AERA
Auger Engineering Radio Array

~150 antennas
~17 km^2
30-80 MHz

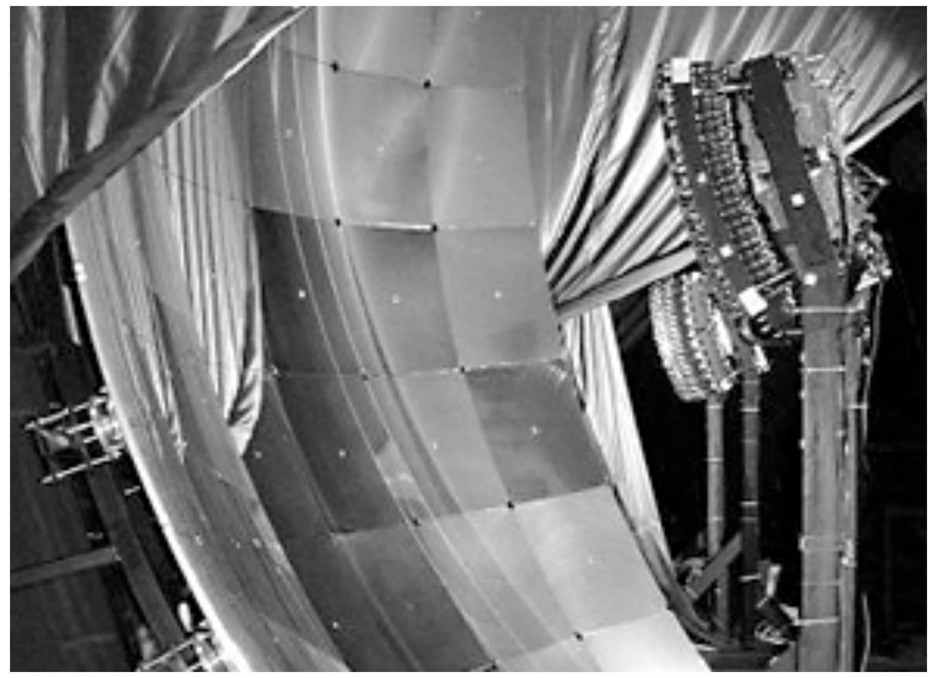


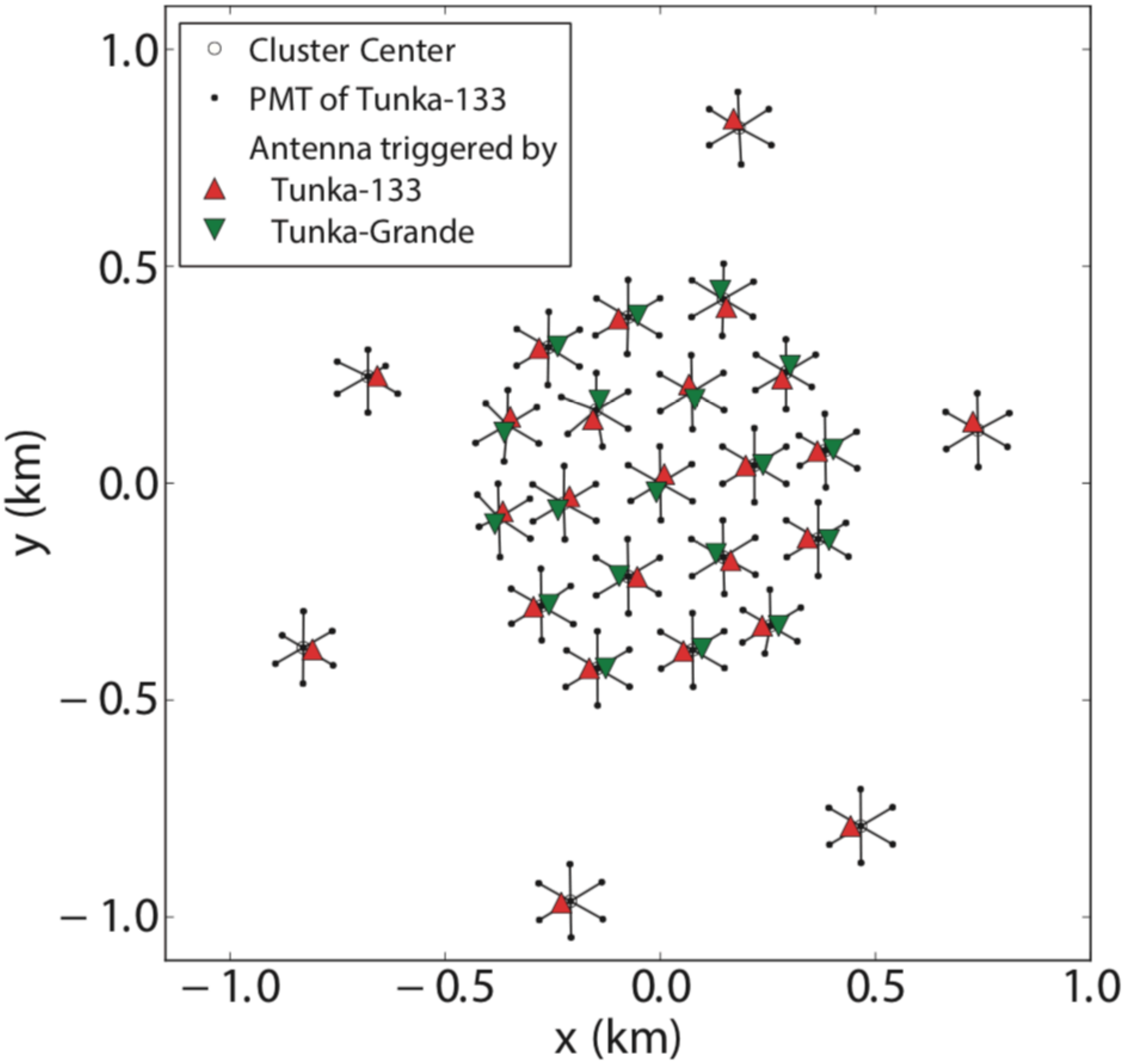
25 stations
since August 2010



100 stations
since March 2013

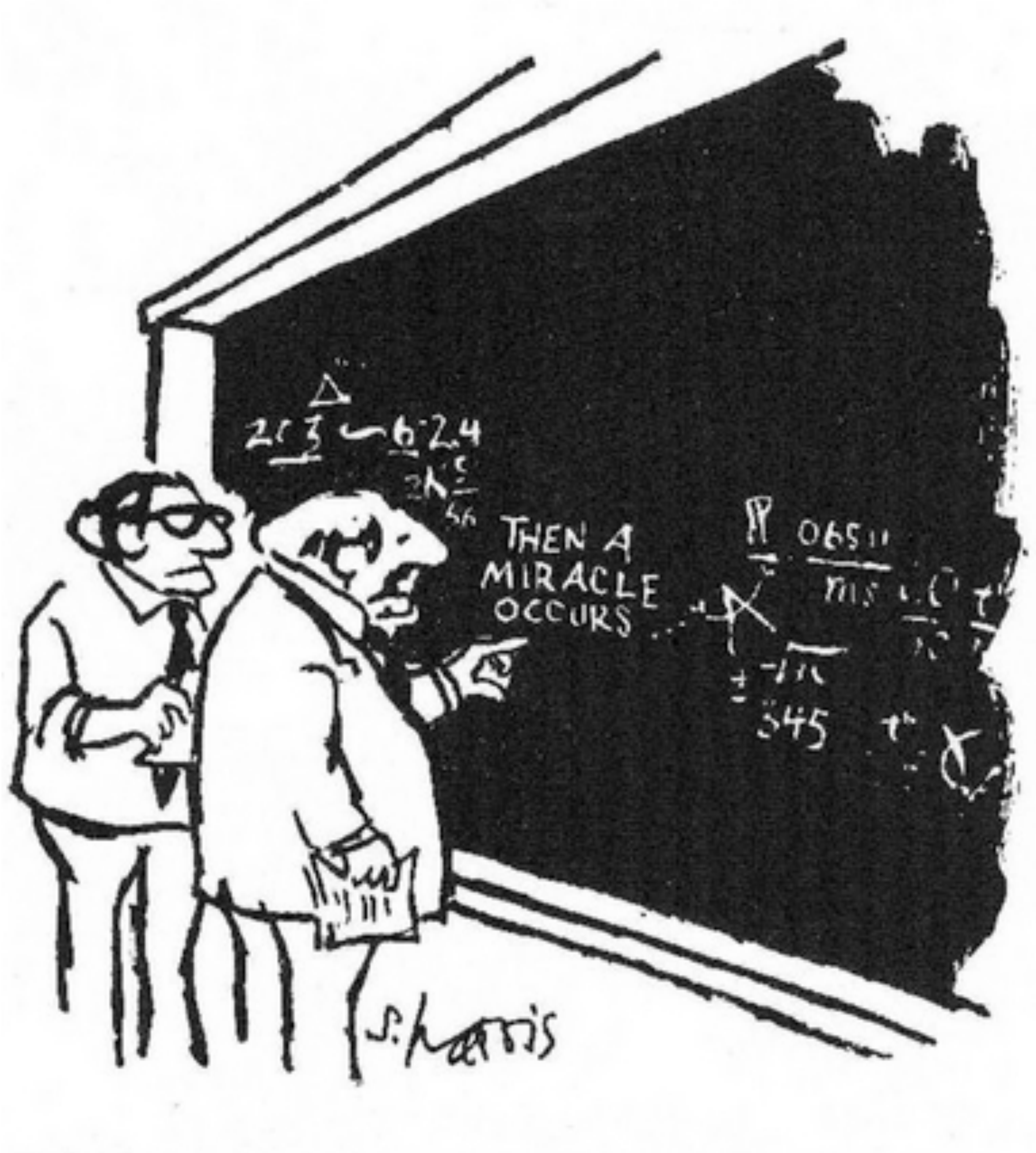
+25 stations
since March 2015




○ Cluster Center
• PMT of Tunka-133
Antenna triggered by
▲ Tunka-133
▼ Tunka-Grande
1.0
0.5
0.0
−0.5
−1.0
y (km)
−1.0
−0.5
0.0
0.5
1.0
x (km)


SALLA at Tunka-Rex

Radiation Processes

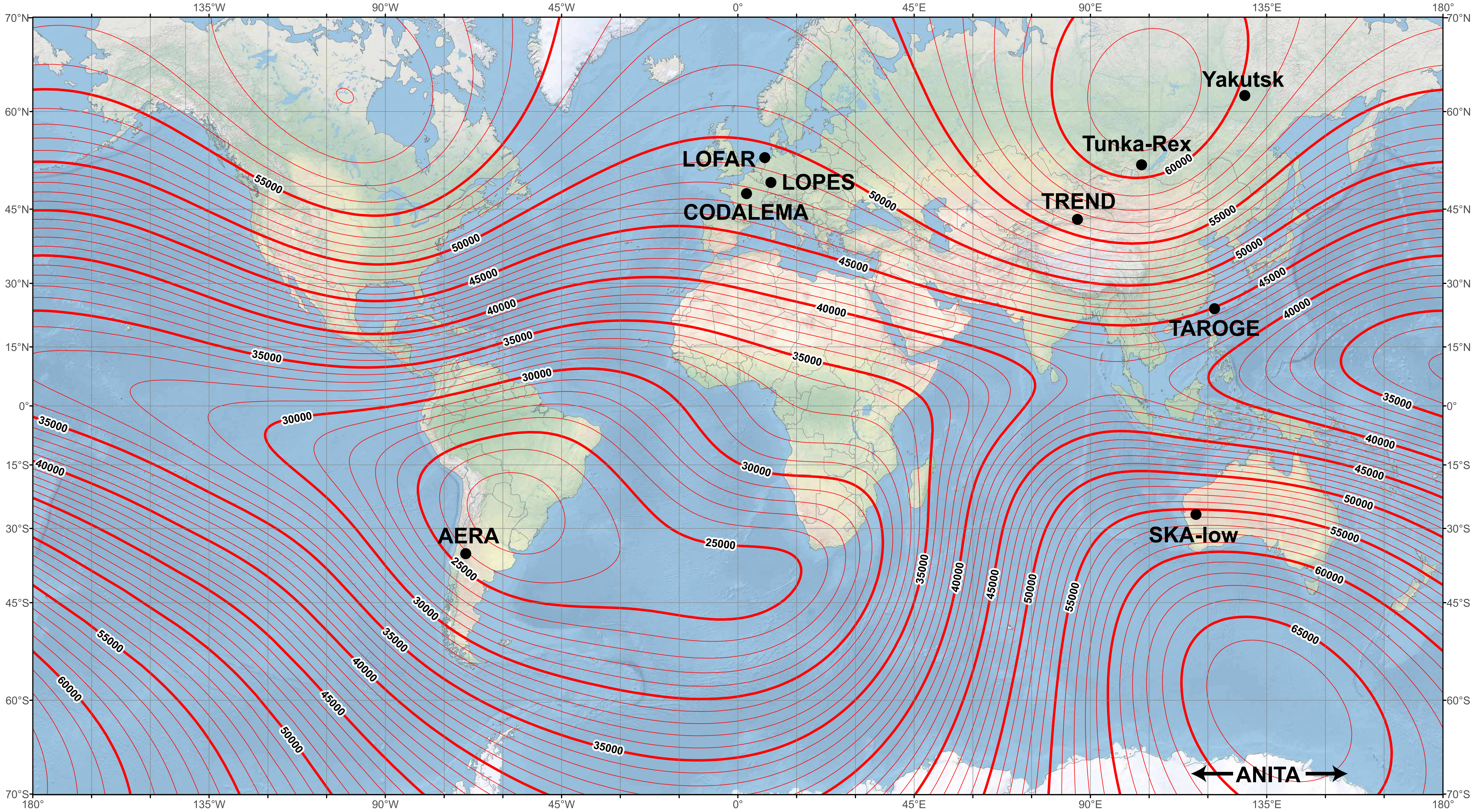


"I think you should be more explicit here in step two."

Radio Emission in Air Showers

Mainly: Charge separation in geomagnetic field

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

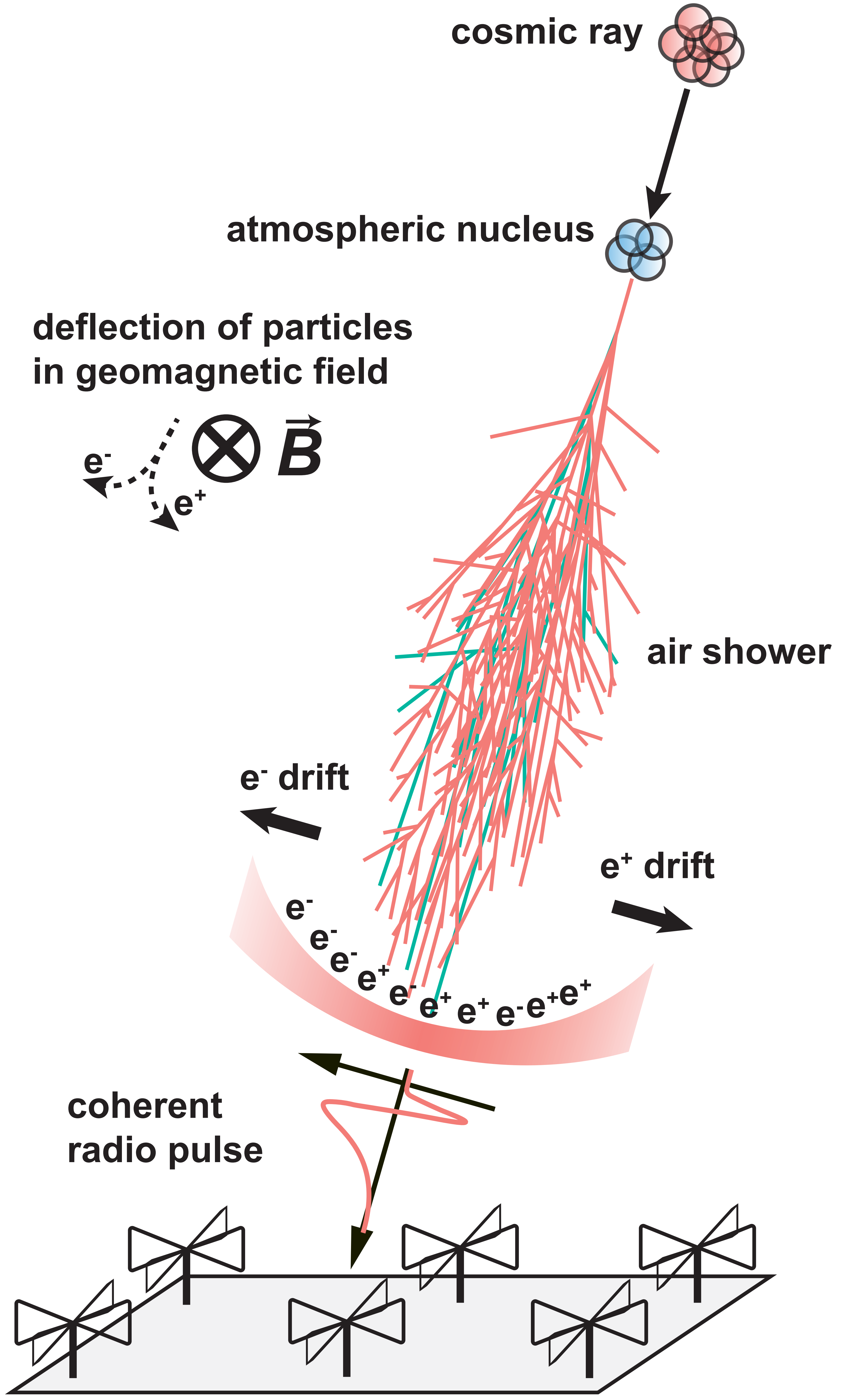


Underlying map (Mercator projection):
Main Geomagnetic Field Total Intensity with contour intervals of 1000 nT
according to US/UK World Magnetic Model - Epoch 2015.0

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



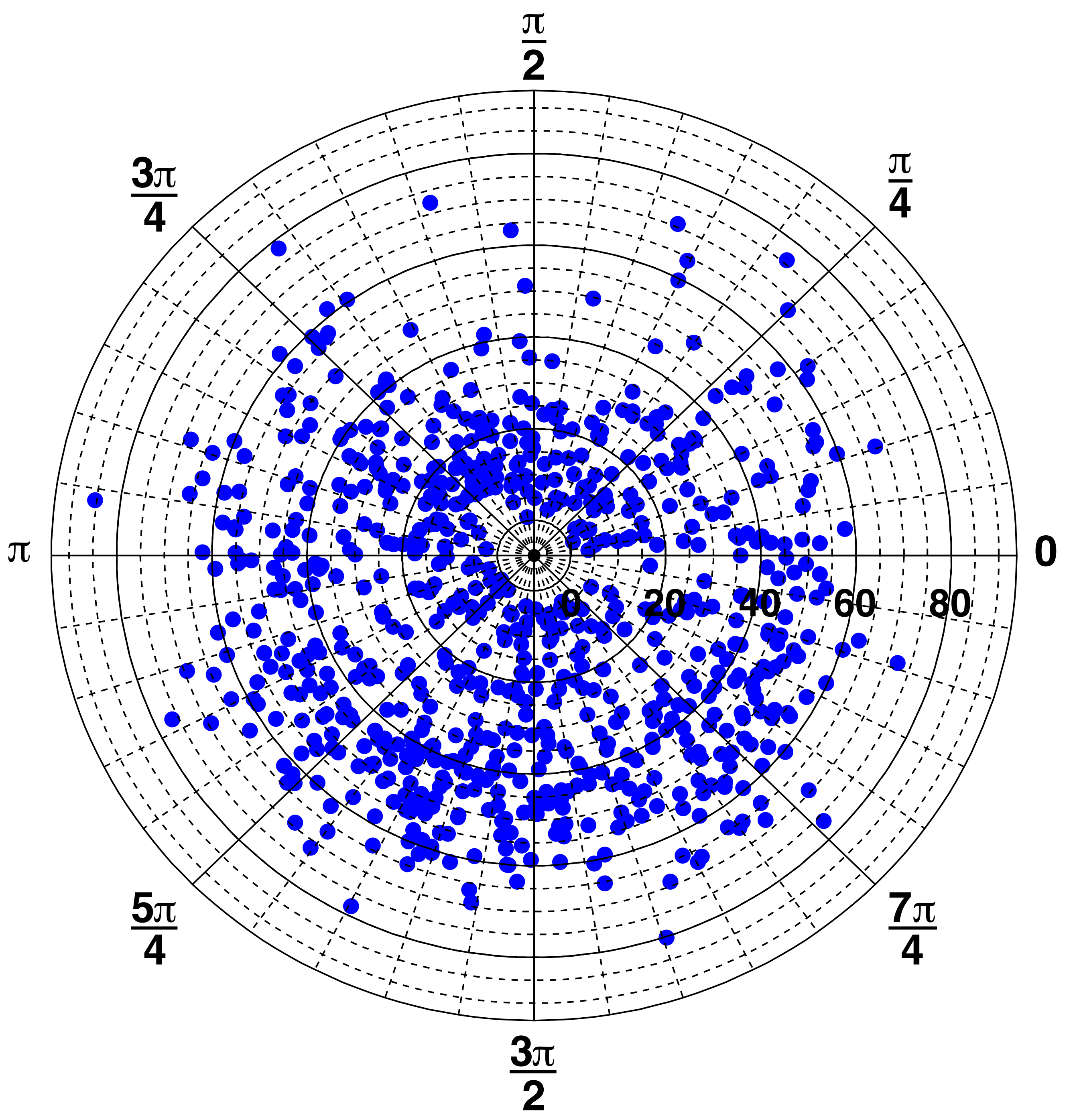
F.G. Schröder, Prog. Part. Nucl. Phys. 92 (17) 1

Arrival direction of showers with strong radio signals

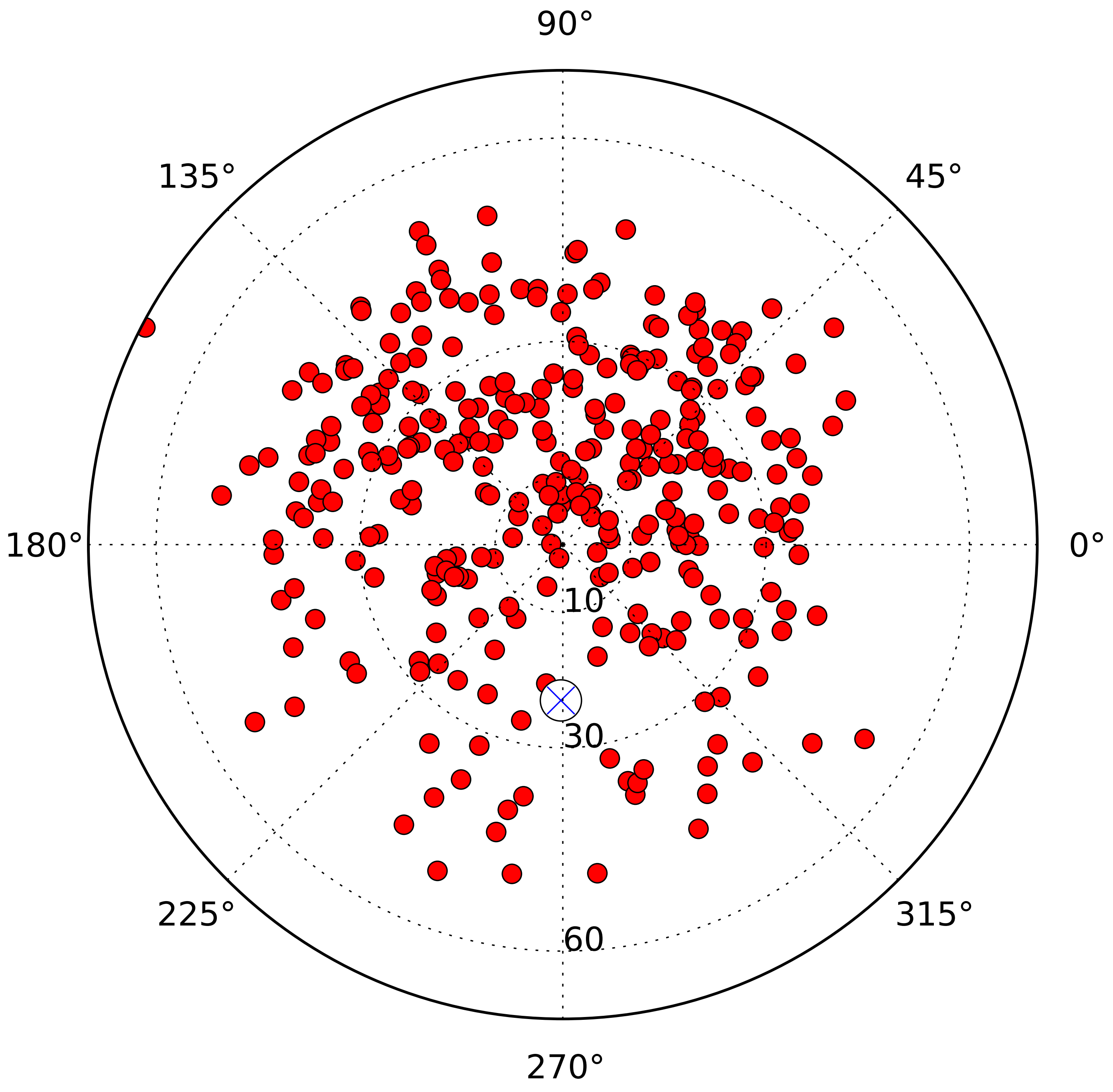
north-south asymmetry
v x B effect

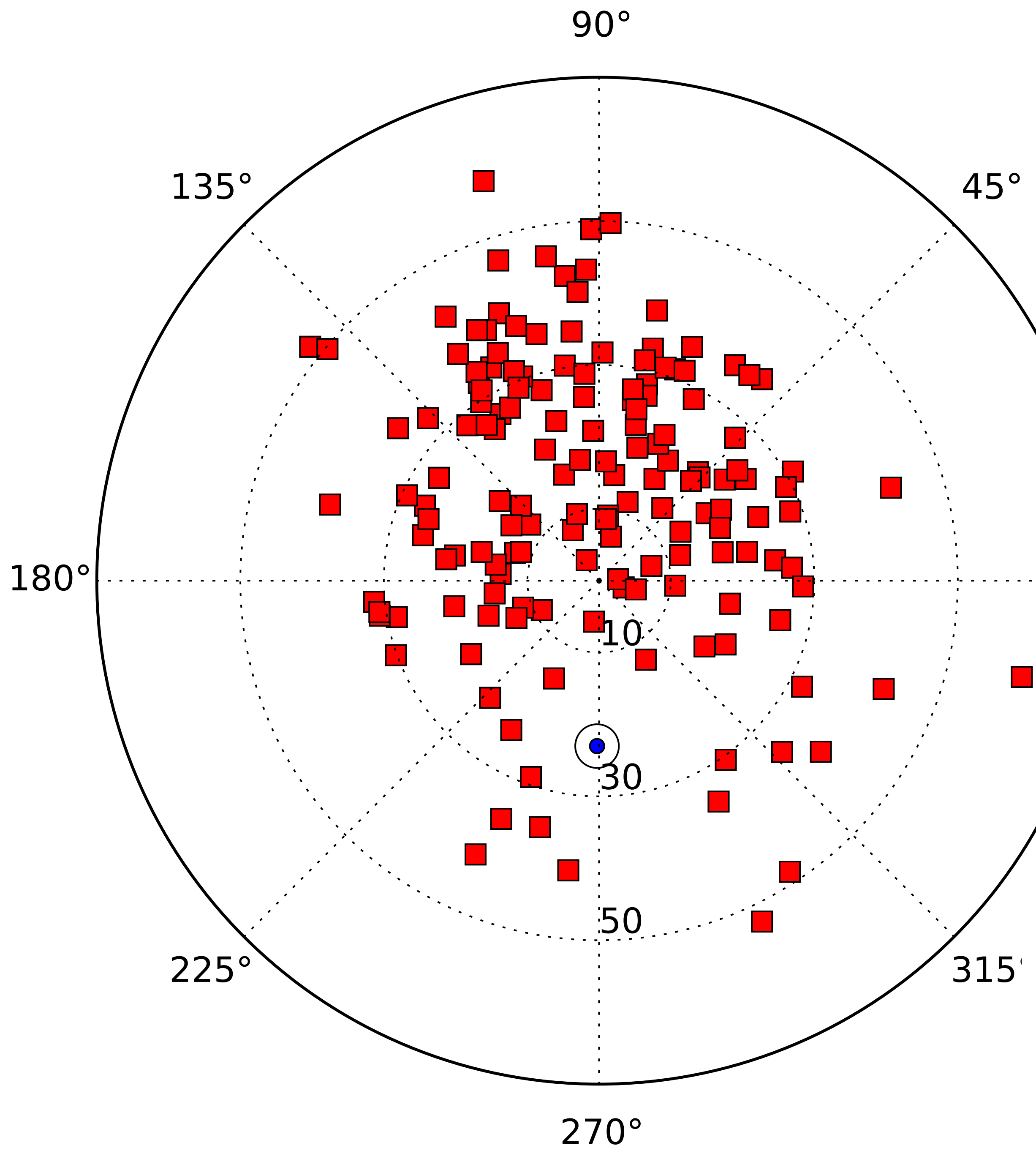
30 - 80 MHz

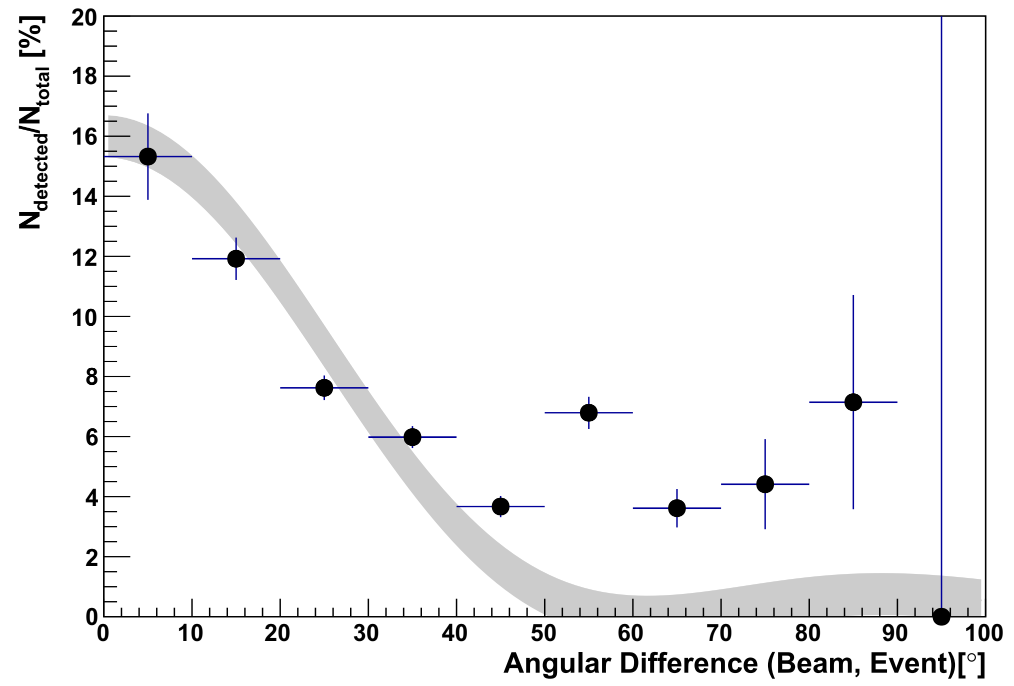
110 - 190 MHz

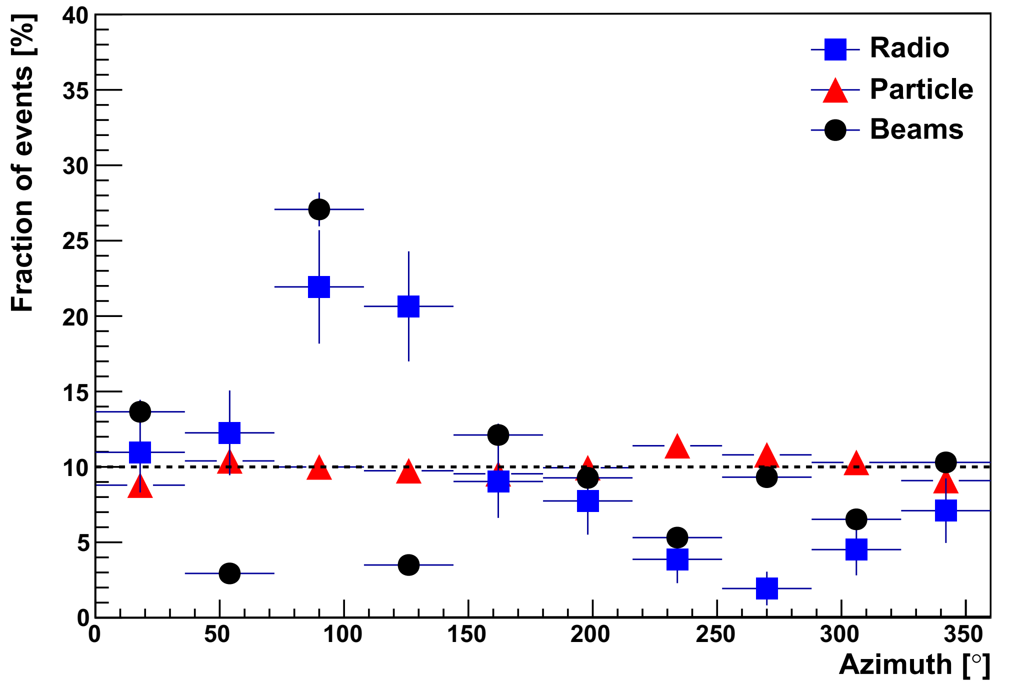


Auger Engineering Radio Array









LOFAR

P. Schellart et al., A&A 560 (2013) A98 A. Nelles et al., Astroparticle Physics 65 (2015) 11

Astroparticle Physics 31 (2009) 192–200

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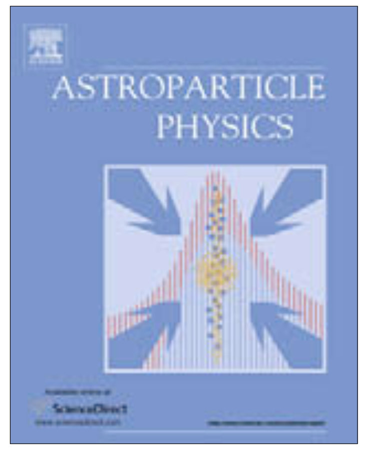
journal homepage: www.elsevier.com/locate/astropart



Geomagnetic origin of the radio emission from cosmic ray induced air showers observed by CODALEMA

D. Ardouin [a], A. Belletoile [a,c], C. Berat [c], D. Breton [d], D
S. Dagoret-Campagne [d], R. Dallier [a], L. Denis [b], C. Dur
N. Gautherot [f], T. Gousset [a], F. Haddad [a], D.H. Koang [c],
F. Lefeuvre [g], L. Martin [a,*], E. Meyer [f], F. Meyer [f], N. M
K. Payet [c], G. Plantier [e], O. Ravel [a], B. Revenu [a], C. Rivi
S. Valcares [a]

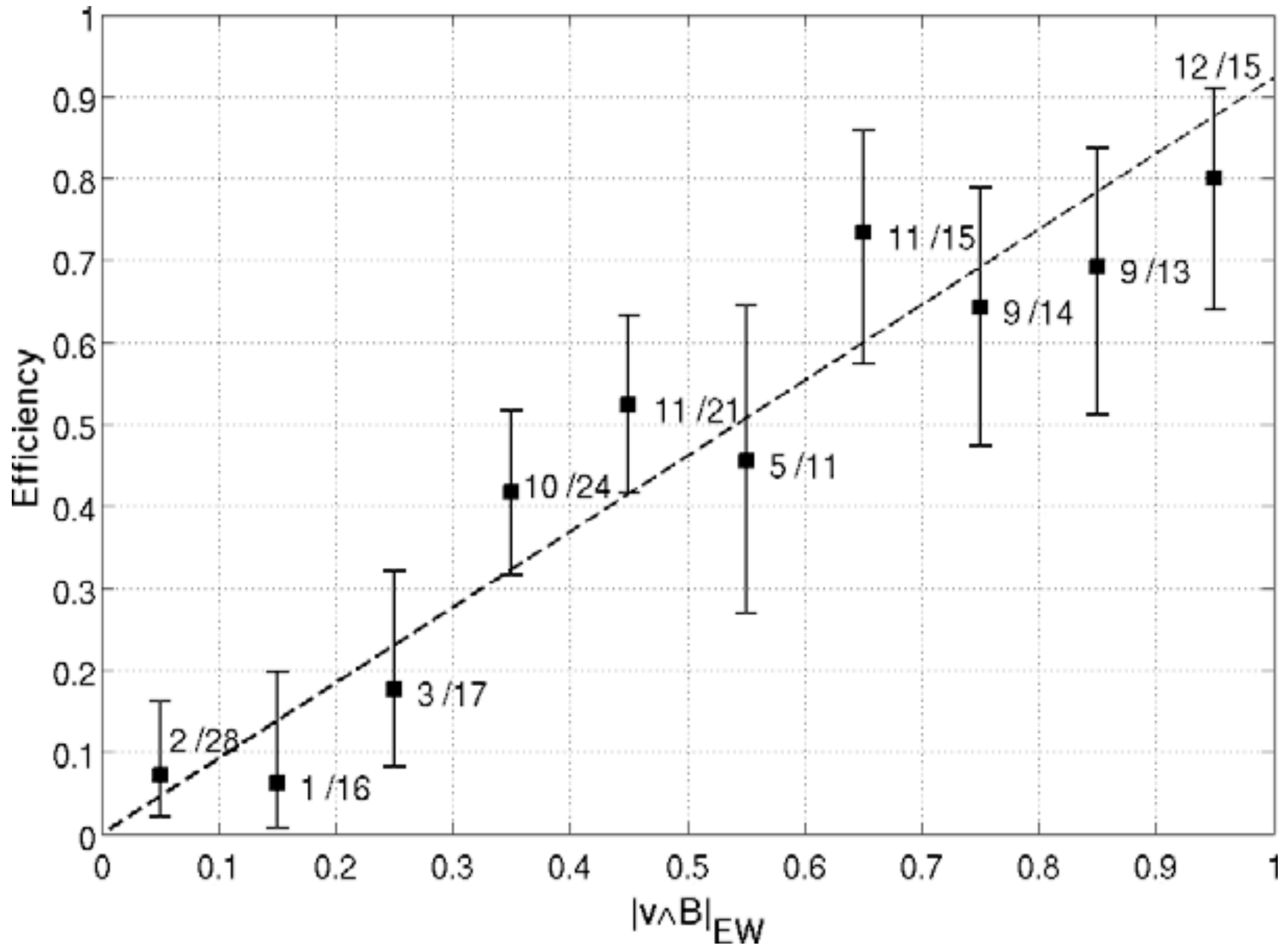


Fig. 11. Number of radio events relative to the number of scintillator events ($E > 10^{17}$ eV) with respect to $|(\mathbf{v} \wedge \mathbf{B})_{EW}|/(vB)$.

Radio Emission in Air Showers

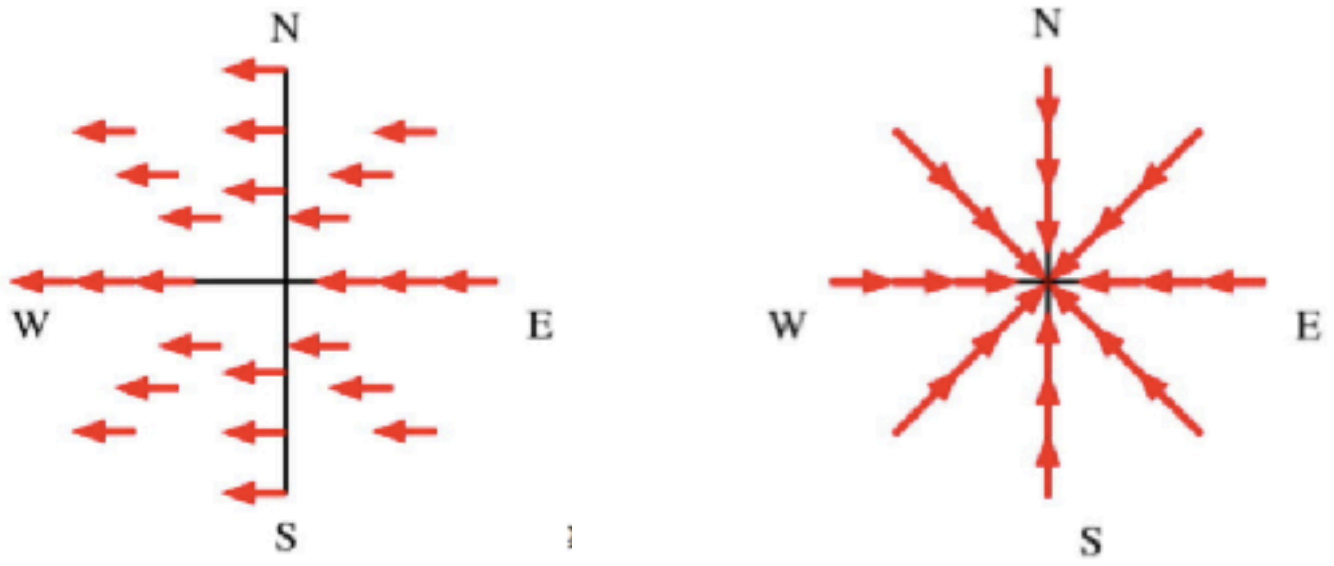
- **Mainly: Charge separation in geomagnetic field**

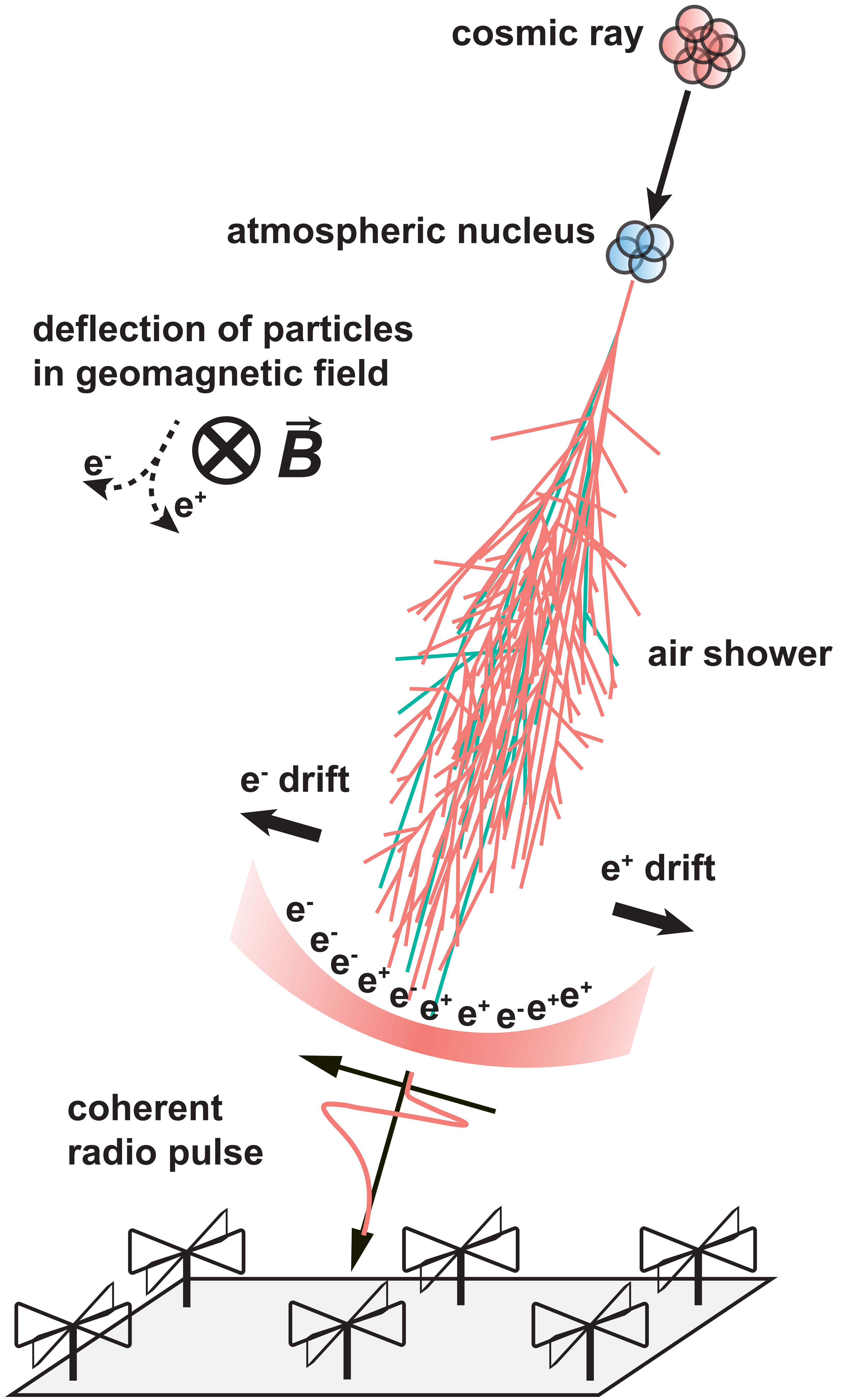
$$\vec{E} \propto \vec{v} \times \vec{B}$$

Theory predicts additional mechanisms:

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

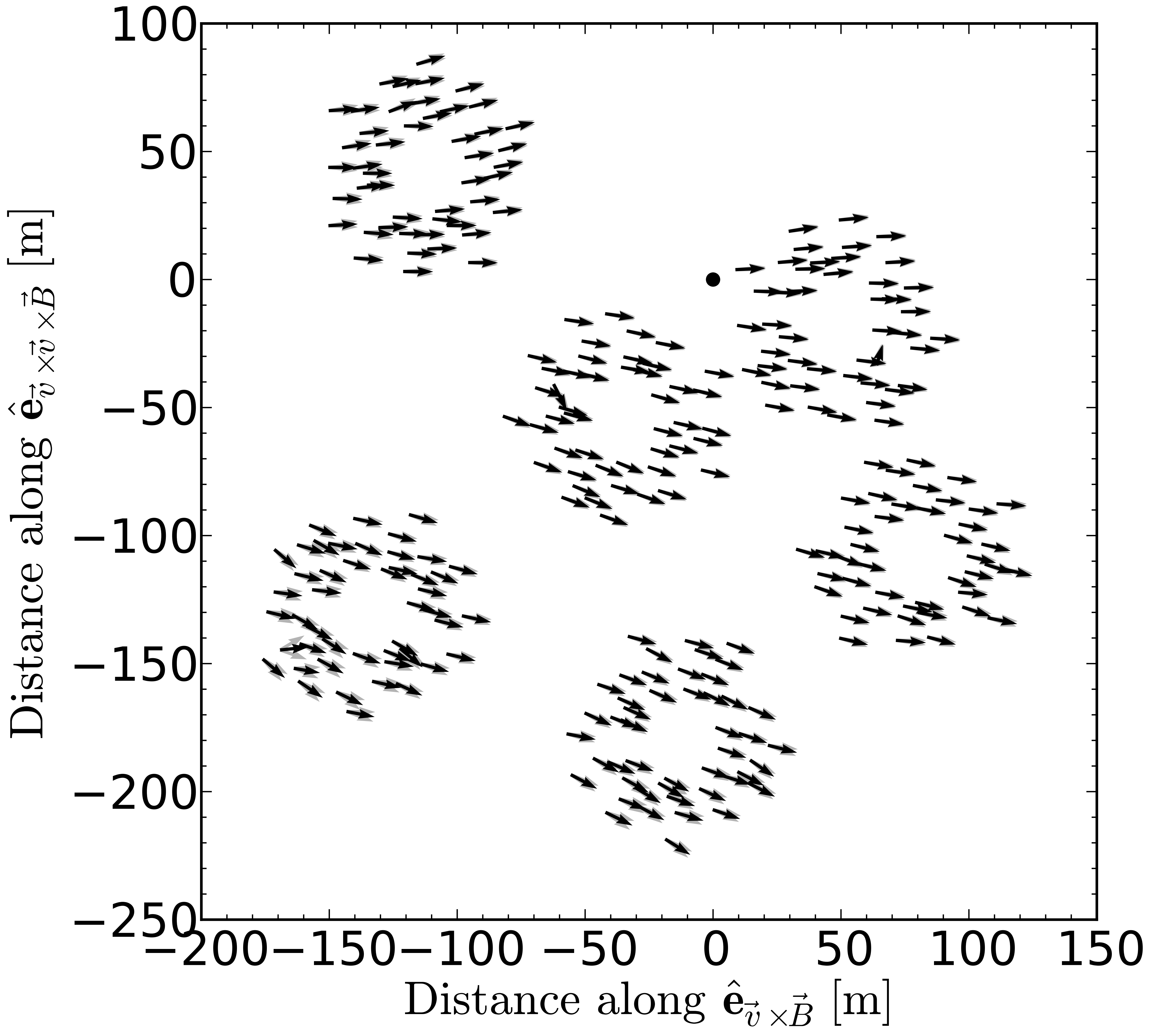
polarization of radio signal


geomagnetic **Askaryan**

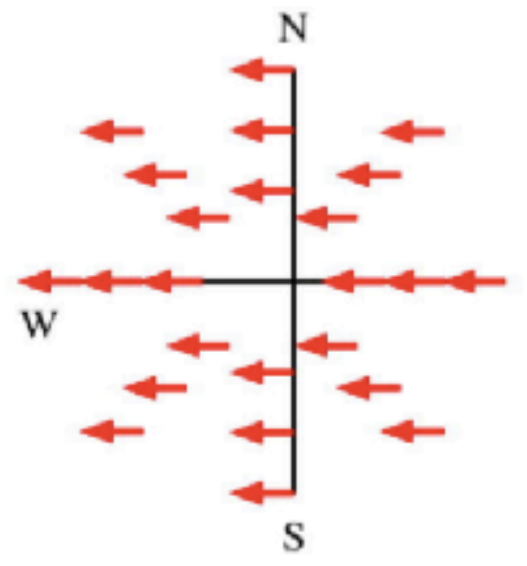


Polarization footprint

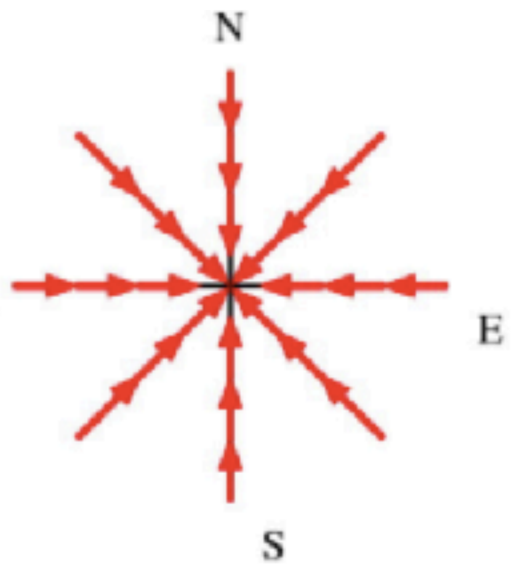
of an individual air shower



geomagnetic

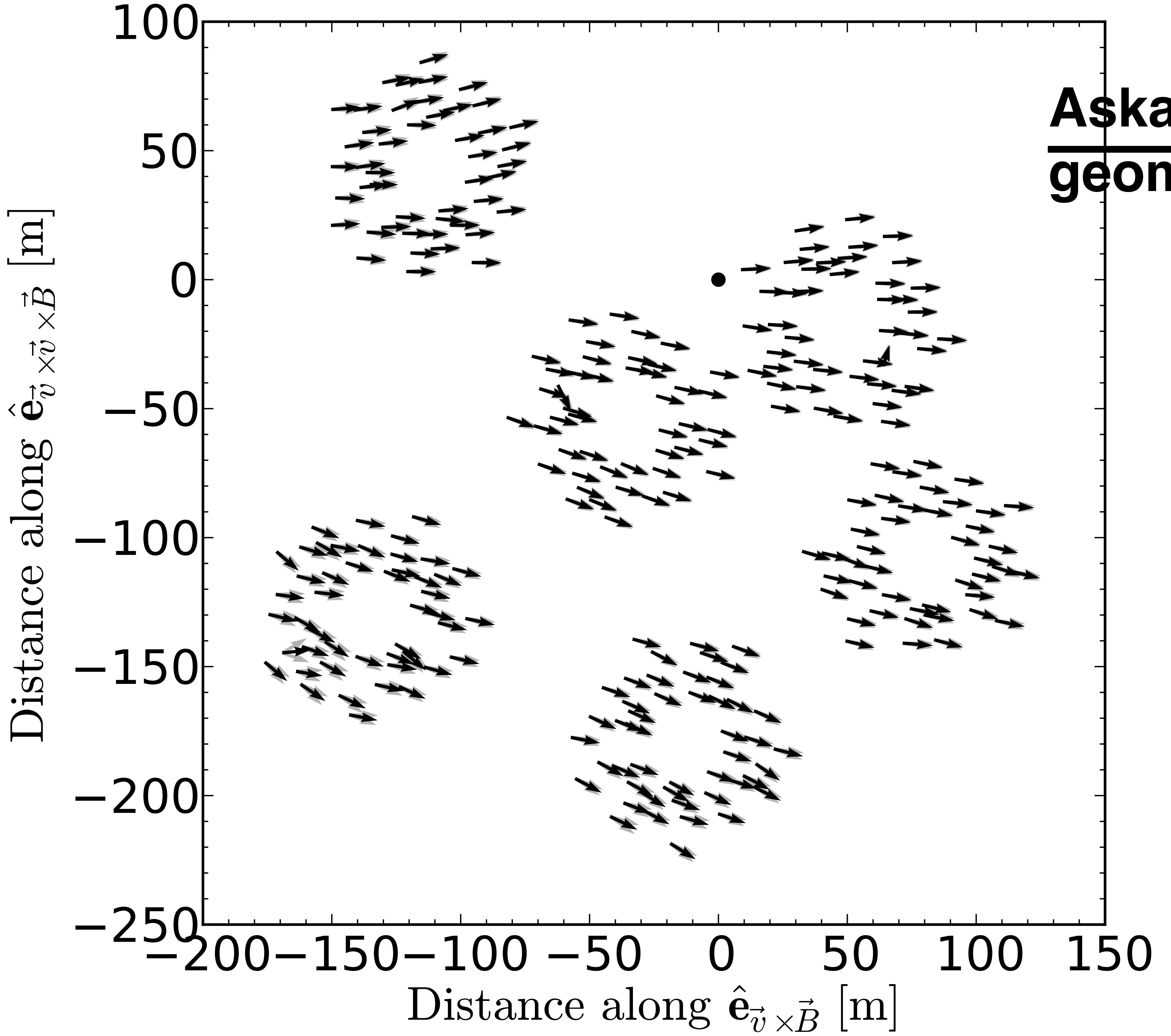


Askaryan



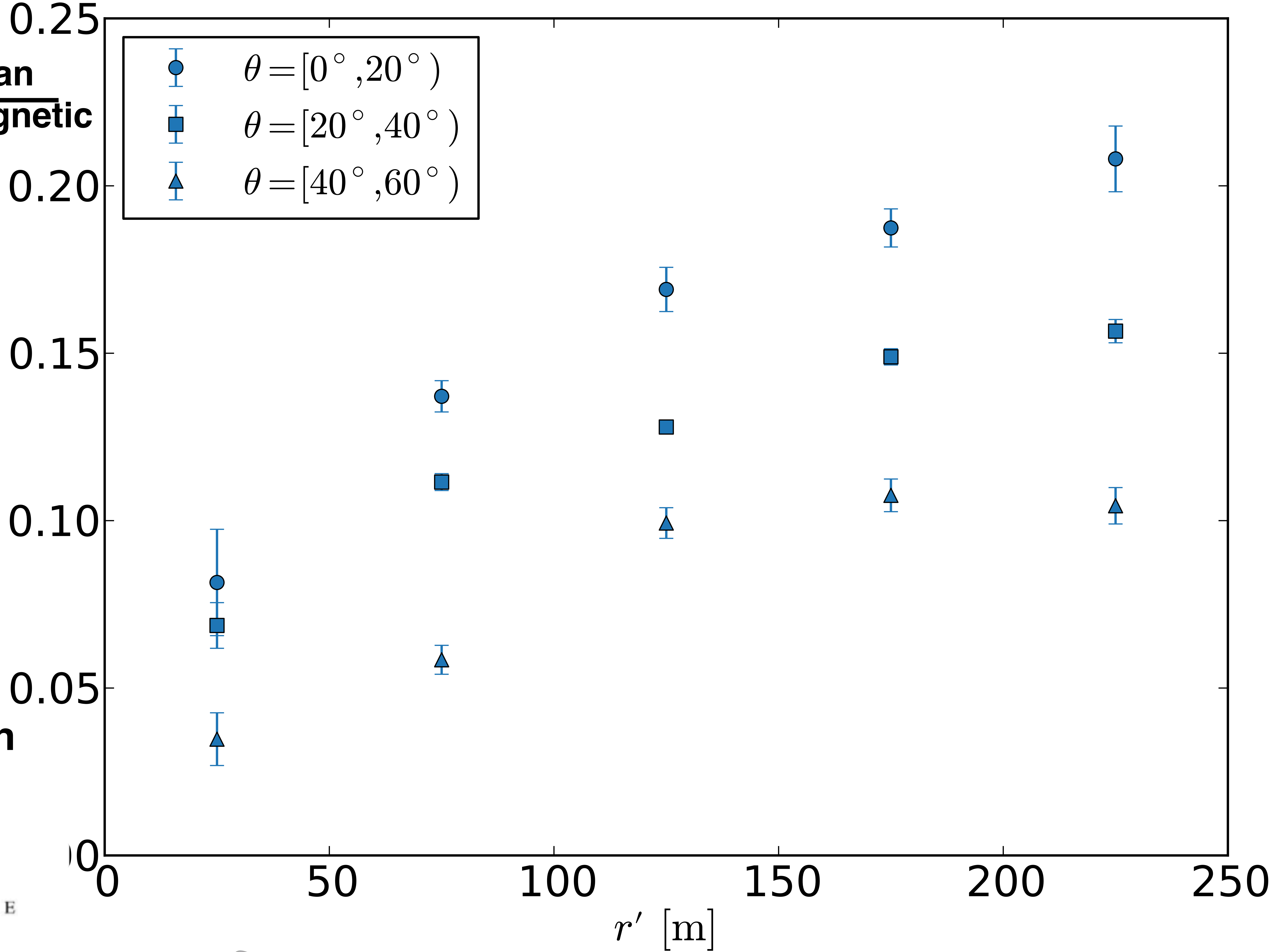
LOFAR

Charge excess fraction

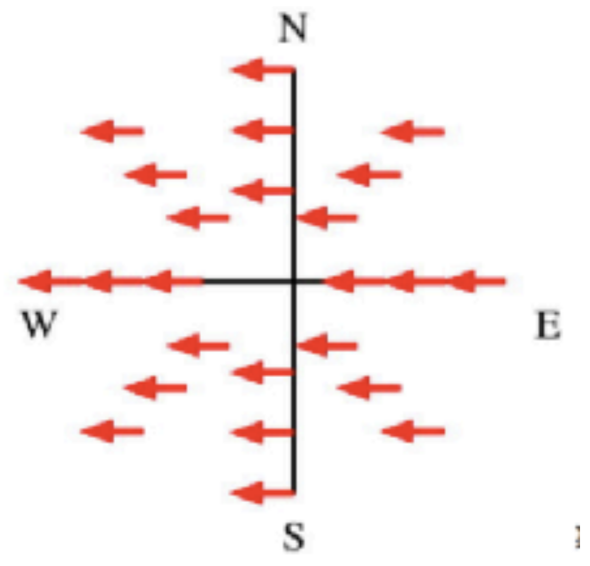


Askaryan

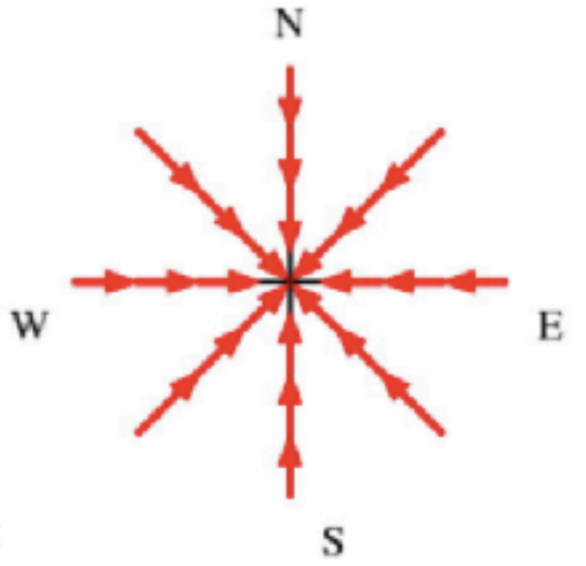
geomagnetic



geomagnetic

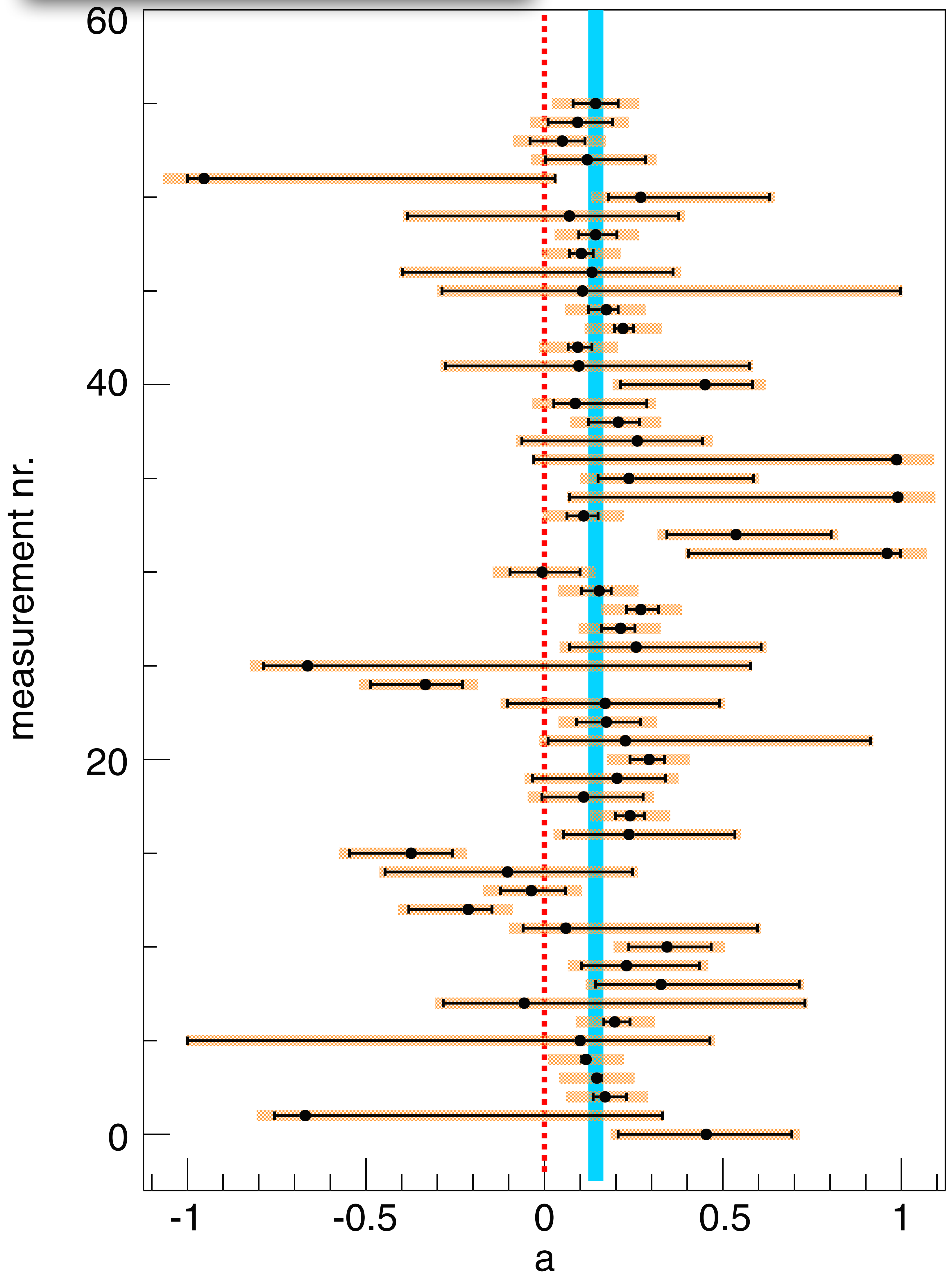


Askaryan

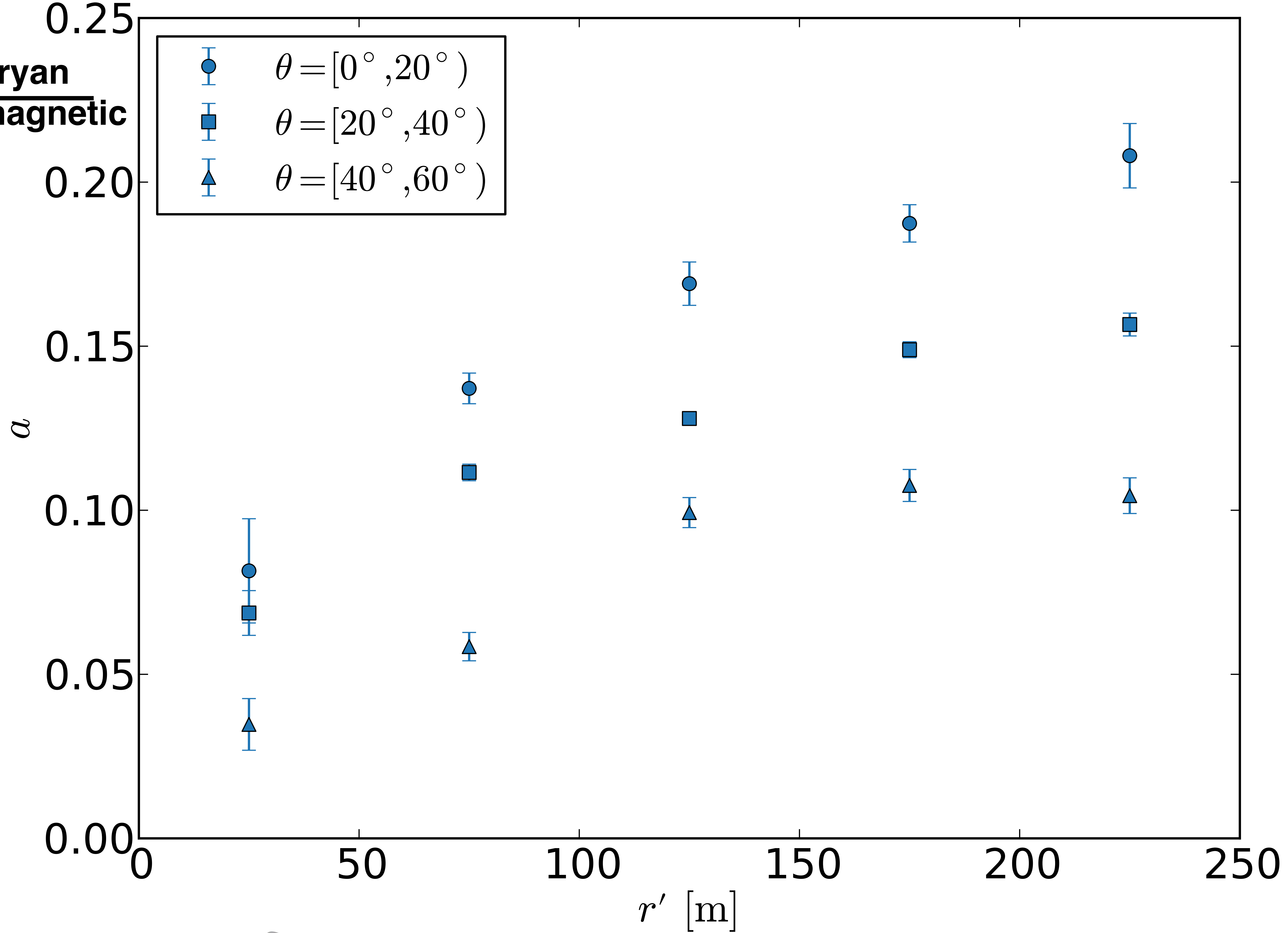


P. Schellart et al., JCAP 10 (2014) 014

Charge excess fraction

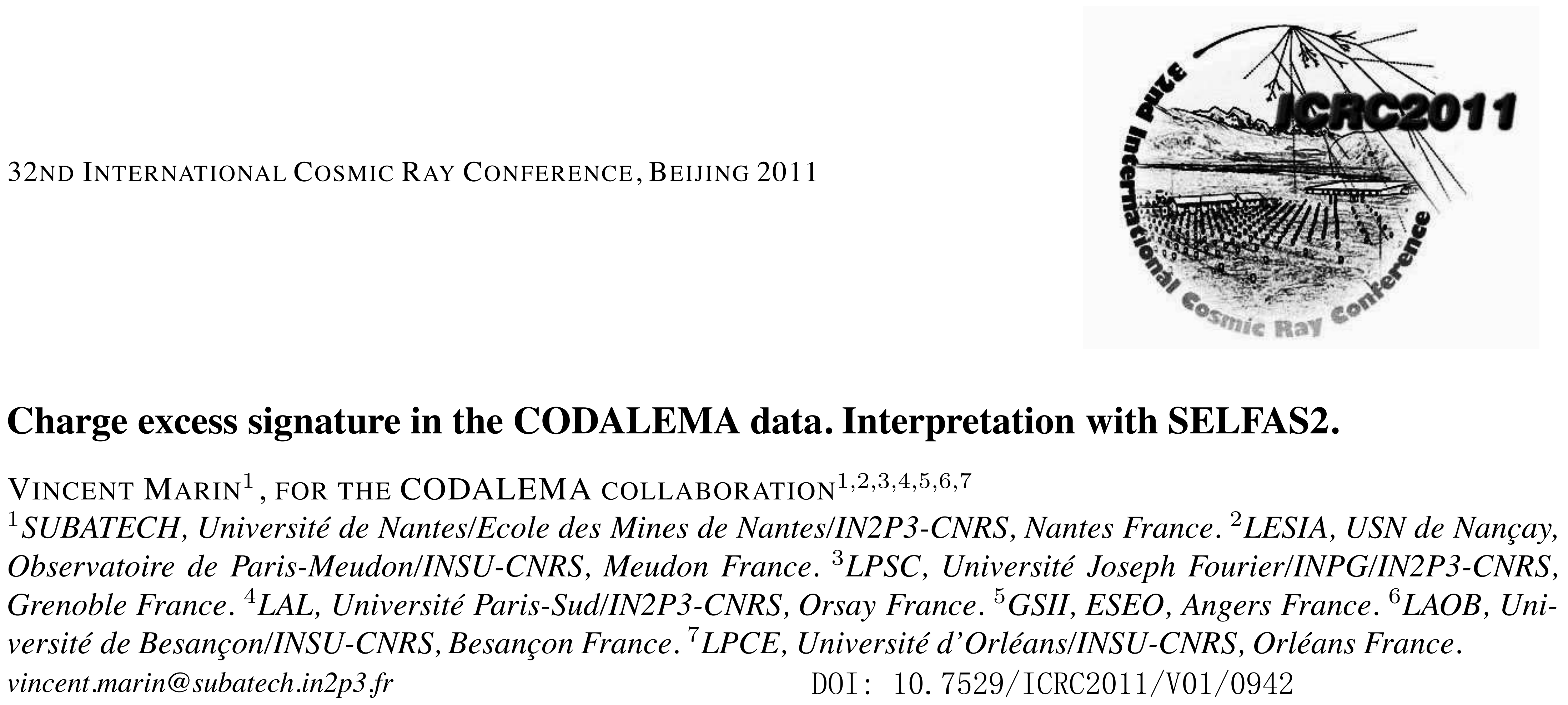


Askaryan
geomagnetic



A. Aab, PRD 89 (2014) 052002

P. Schellart et al., JCAP 10 (2014) 014



32ND INTERNATIONAL COSMIC RAY CONFERENCE, BEIJING 2011

Charge excess signature in the CODALEMA data. Interpretation with SELFAS2.

VINCENT MARIN[1], FOR THE CODALEMA COLLABORATION[1,2,3,4,5,6,7]
[1]*SUBATECH, Université de Nantes/Ecole des Mines de Nantes/IN2P3-CNRS, Nantes France.* [2]*LESIA, USN de Nançay, Observatoire de Paris-Meudon/INSU-CNRS, Meudon France.* [3]*LPSC, Université Joseph Fourier/INPG/IN2P3-CNRS, Grenoble France.* [4]*LAL, Université Paris-Sud/IN2P3-CNRS, Orsay France.* [5]*GSII, ESEO, Angers France.* [6]*LAOB, Université de Besançon/INSU-CNRS, Besançon France.* [7]*LPCE, Université d'Orléans/INSU-CNRS, Orléans France.*
vincent.marin@subatech.in2p3.fr

DOI: 10.7529/ICRC2011/V01/0942

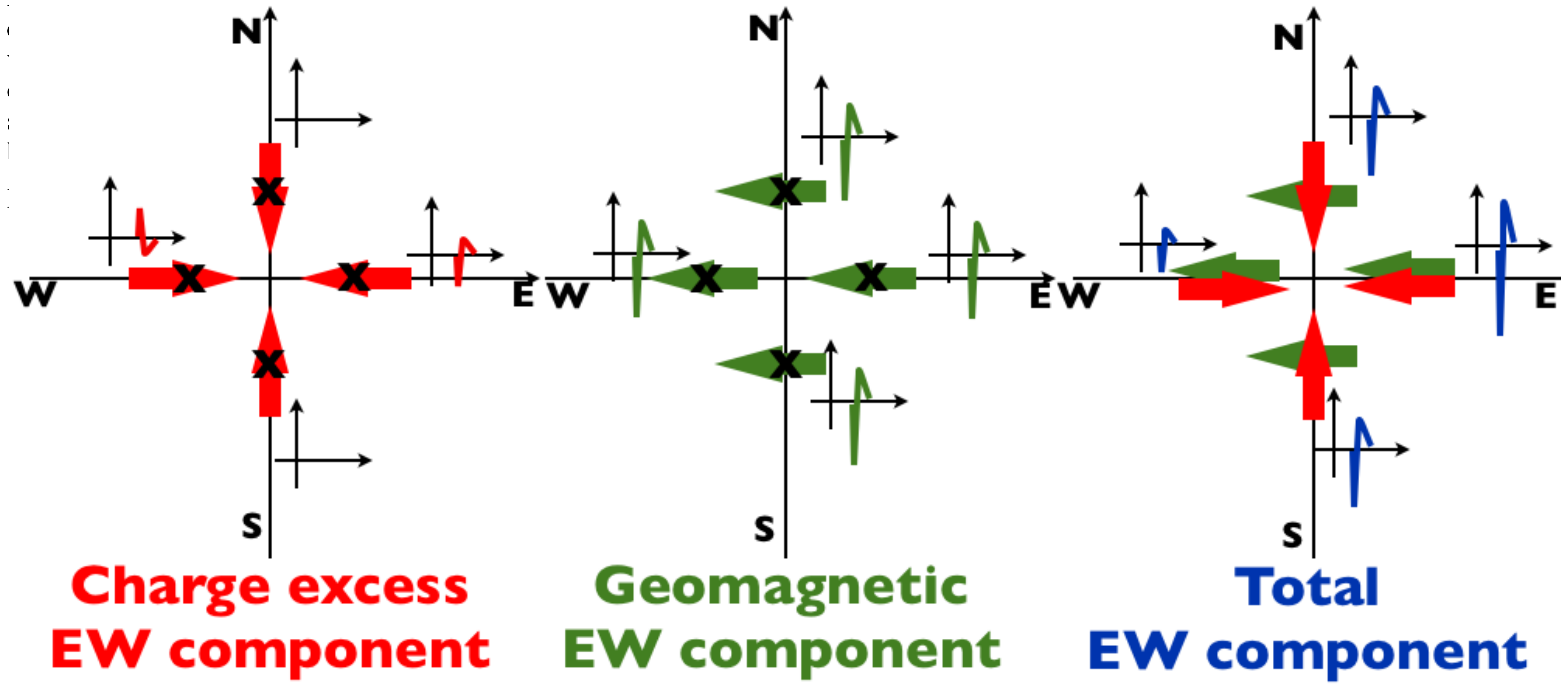


FIGURE 2 – Polarization vectors of the charge excess and transverse current contributions in the plane perpendicular to the shower axis. Due to the fact that the polarization vectors of these two contributions are not always oriented in the same direction, their combination can be constructive or destructive following the antenna position.

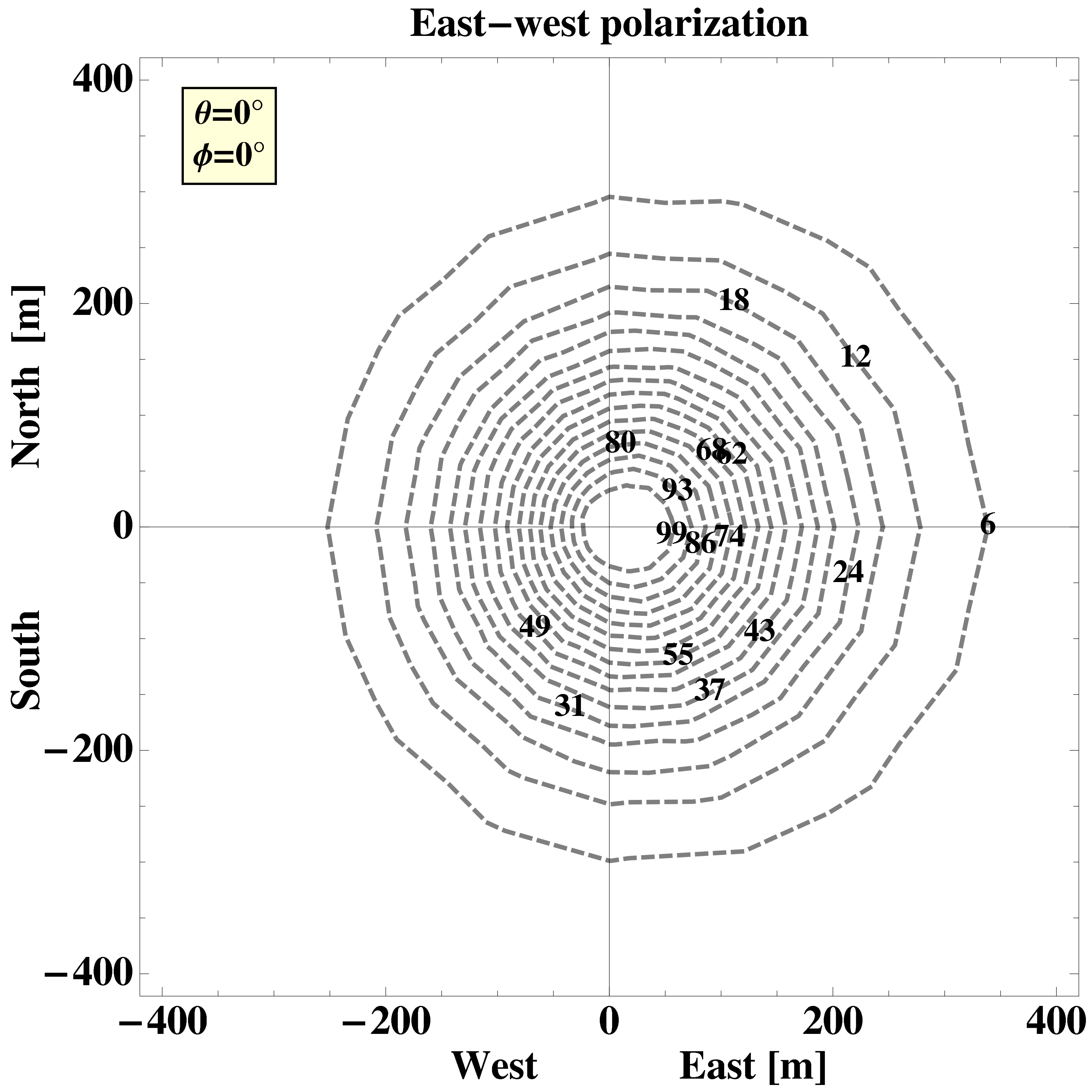
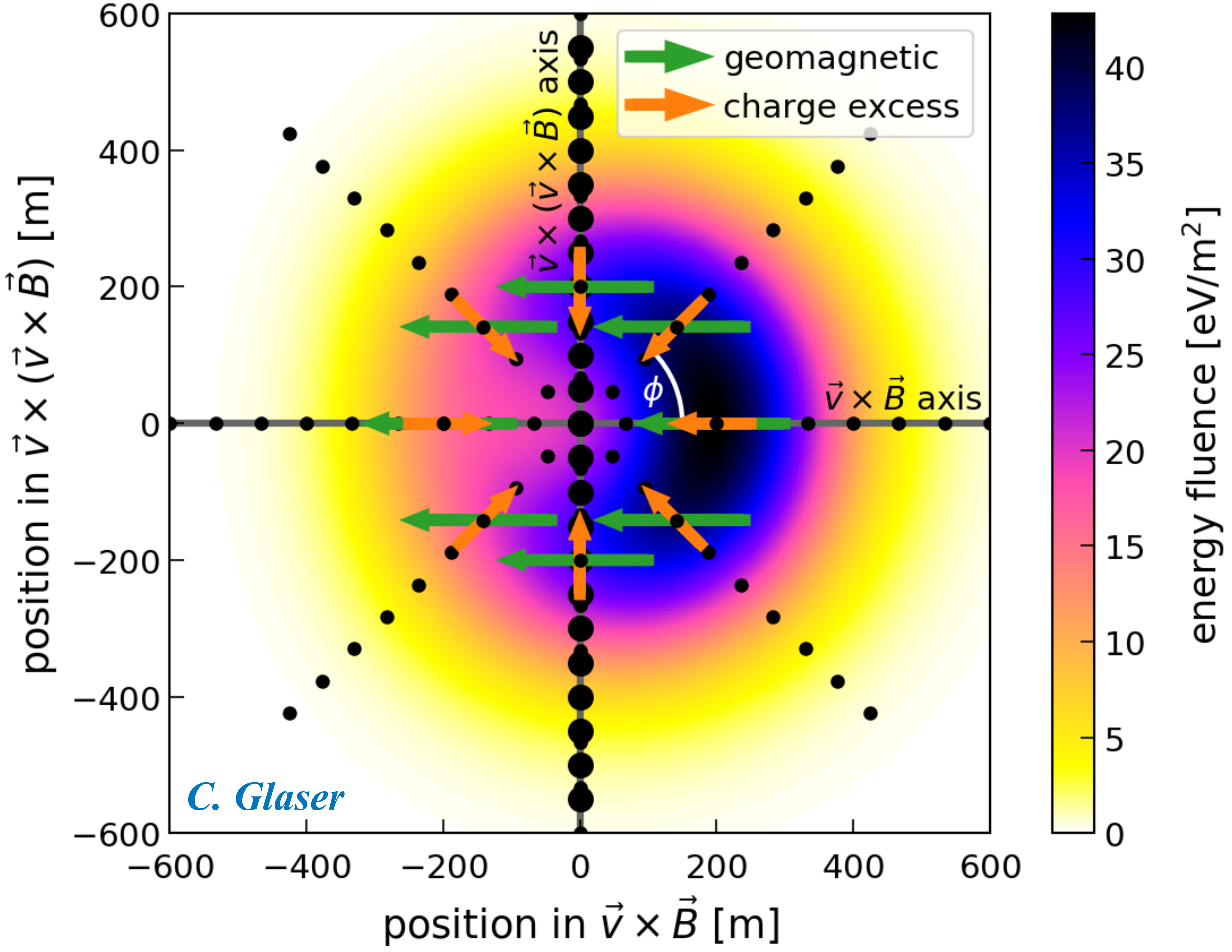
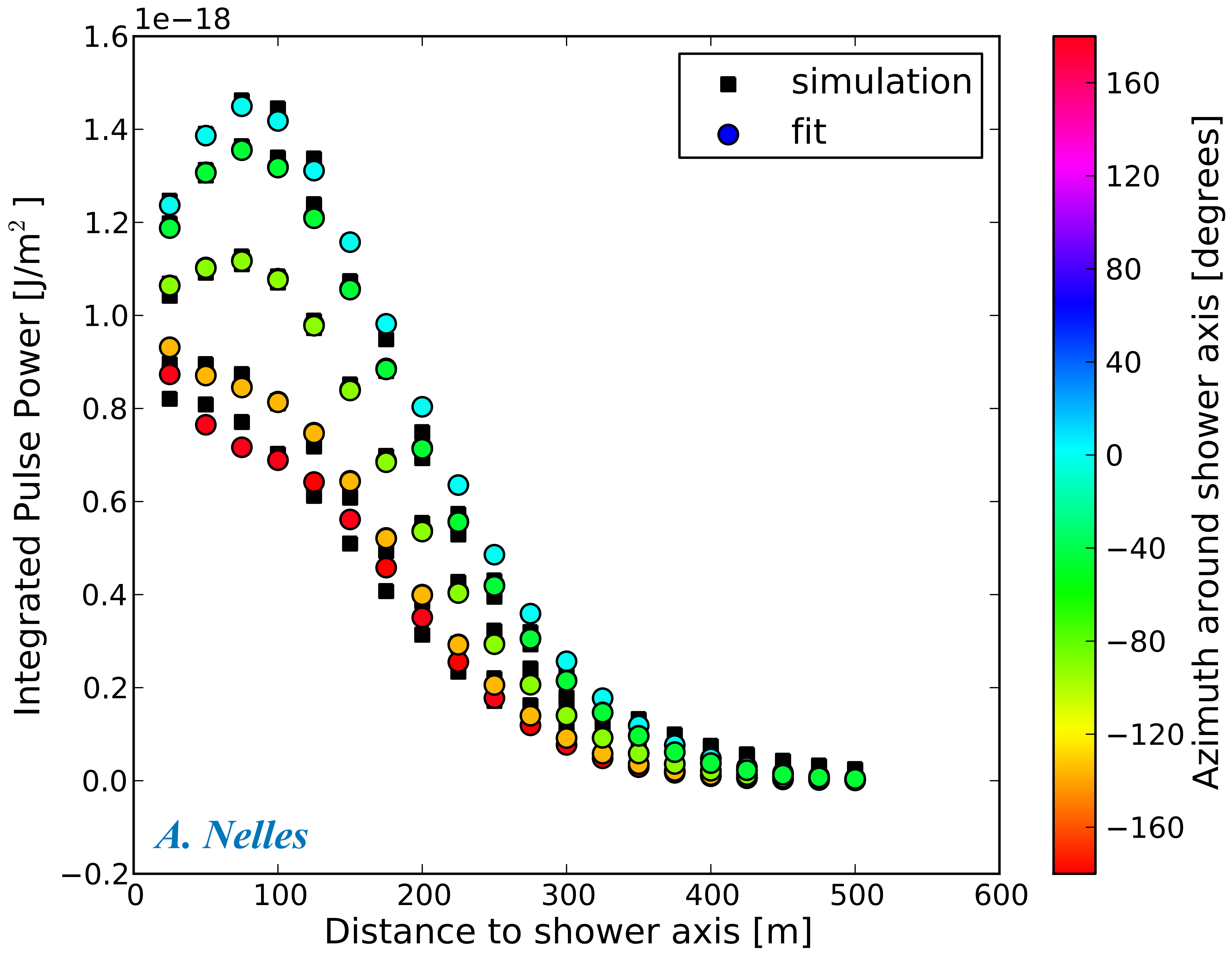


FIGURE 1 – Ground footprint of the signal deposited (absolute value) by a 10^{17} eV vertical EAS in the east-west polarization simulated with SELFAS2. The origin of the frame corresponds to the simulated ground particles shower core. The contour lines are in μV.m^{-1}, a 23-83 MHz numerical passband filter is applied on signal. The ground radio core is toward the east.

Footprint of radio emission on the ground



C. Glaser



A. Nelles

Footprint of radio emission on the ground

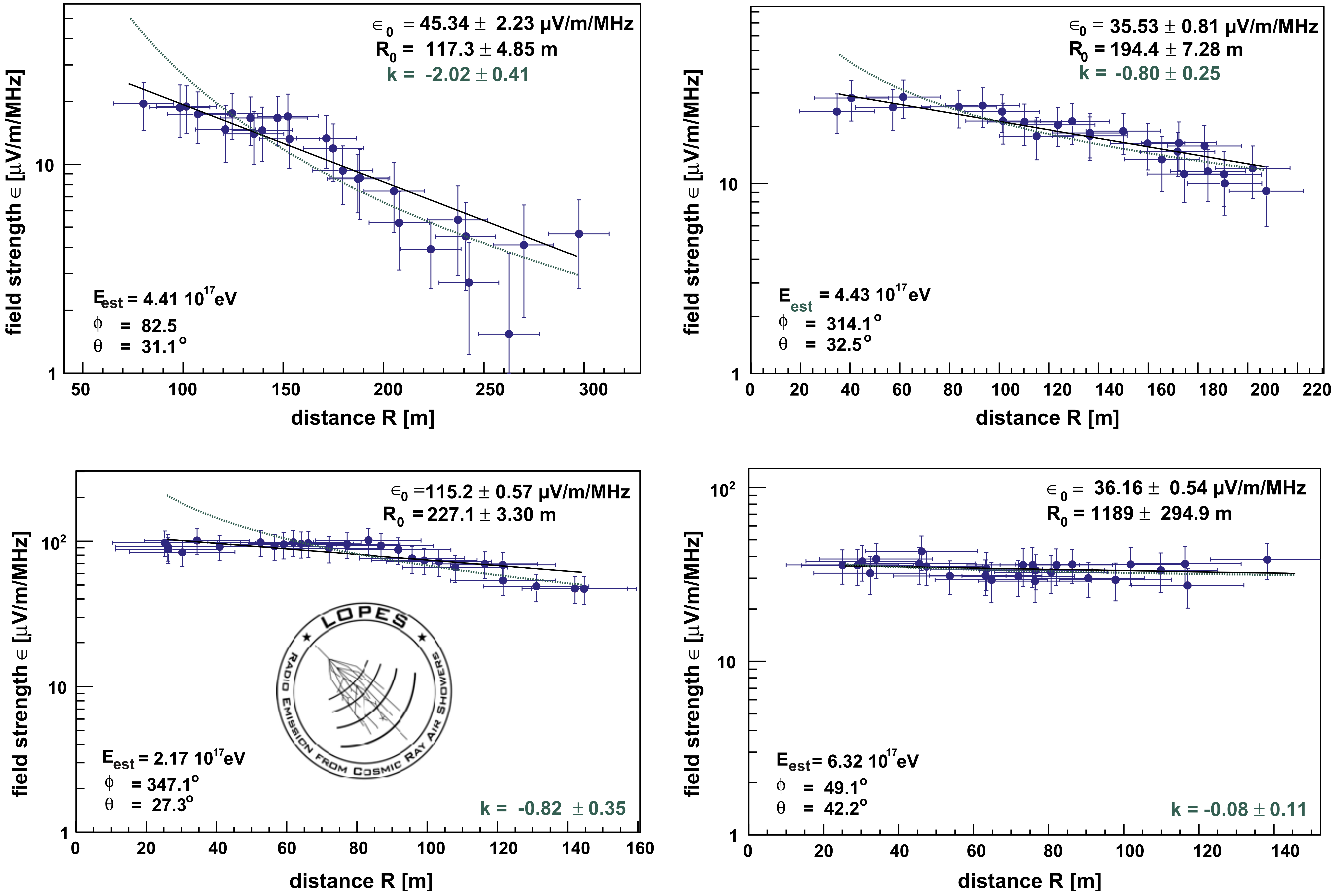
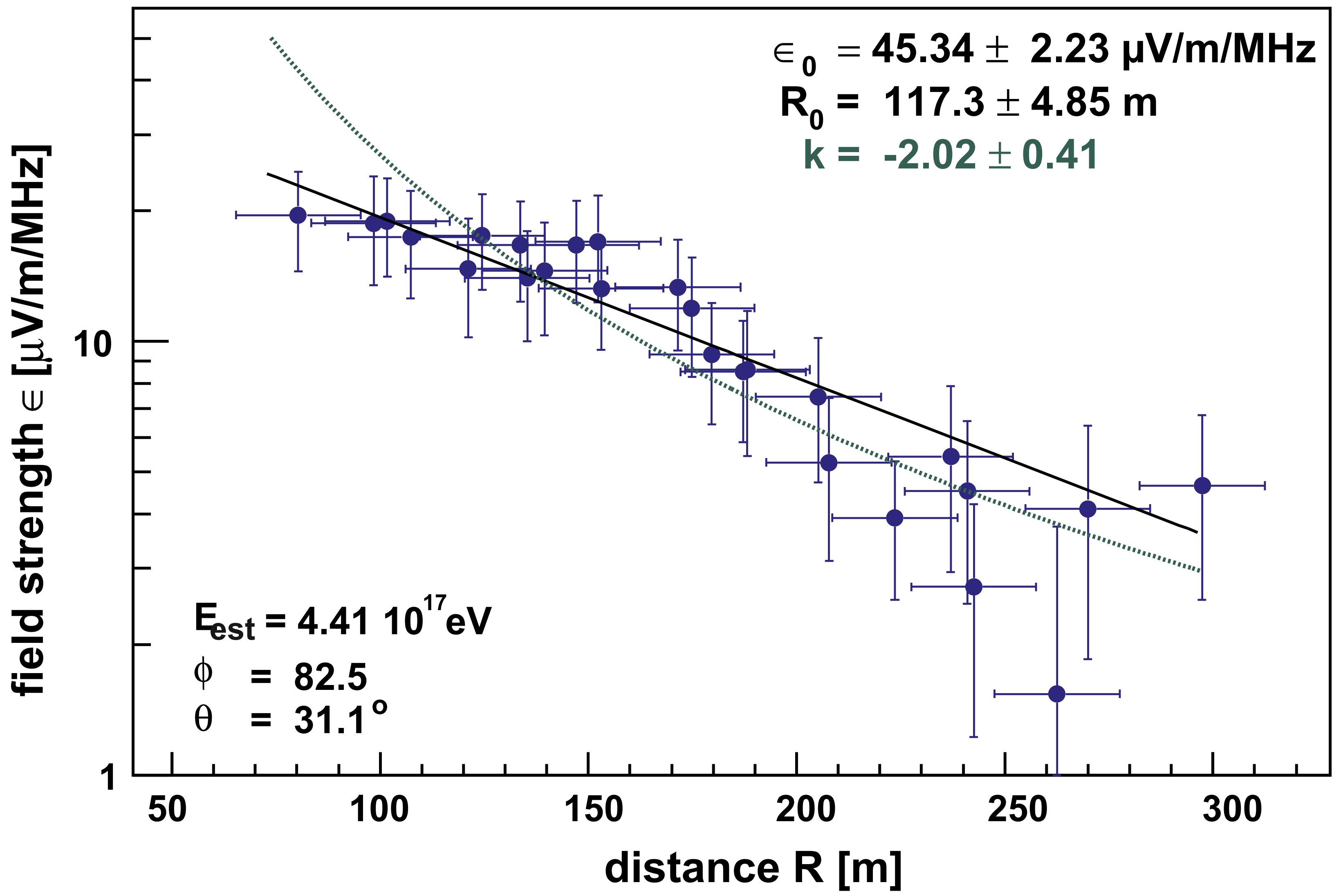
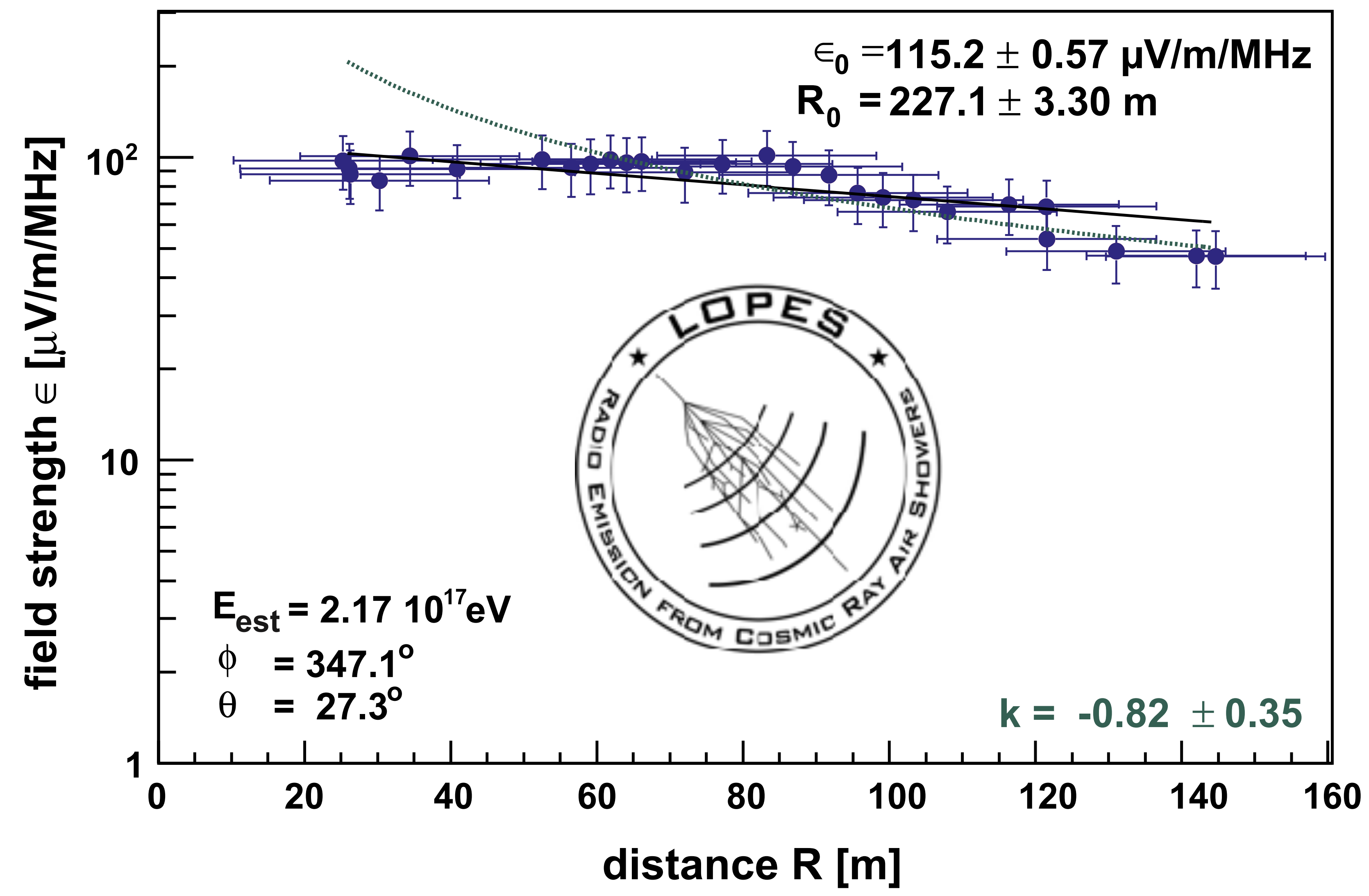


Fig. 6. Same as Fig. 5, but for four lateral distributions with unusual shapes. Discussion see text.

W.D. Apel et al., Astroparticle Physics 32 (2010) 294–303

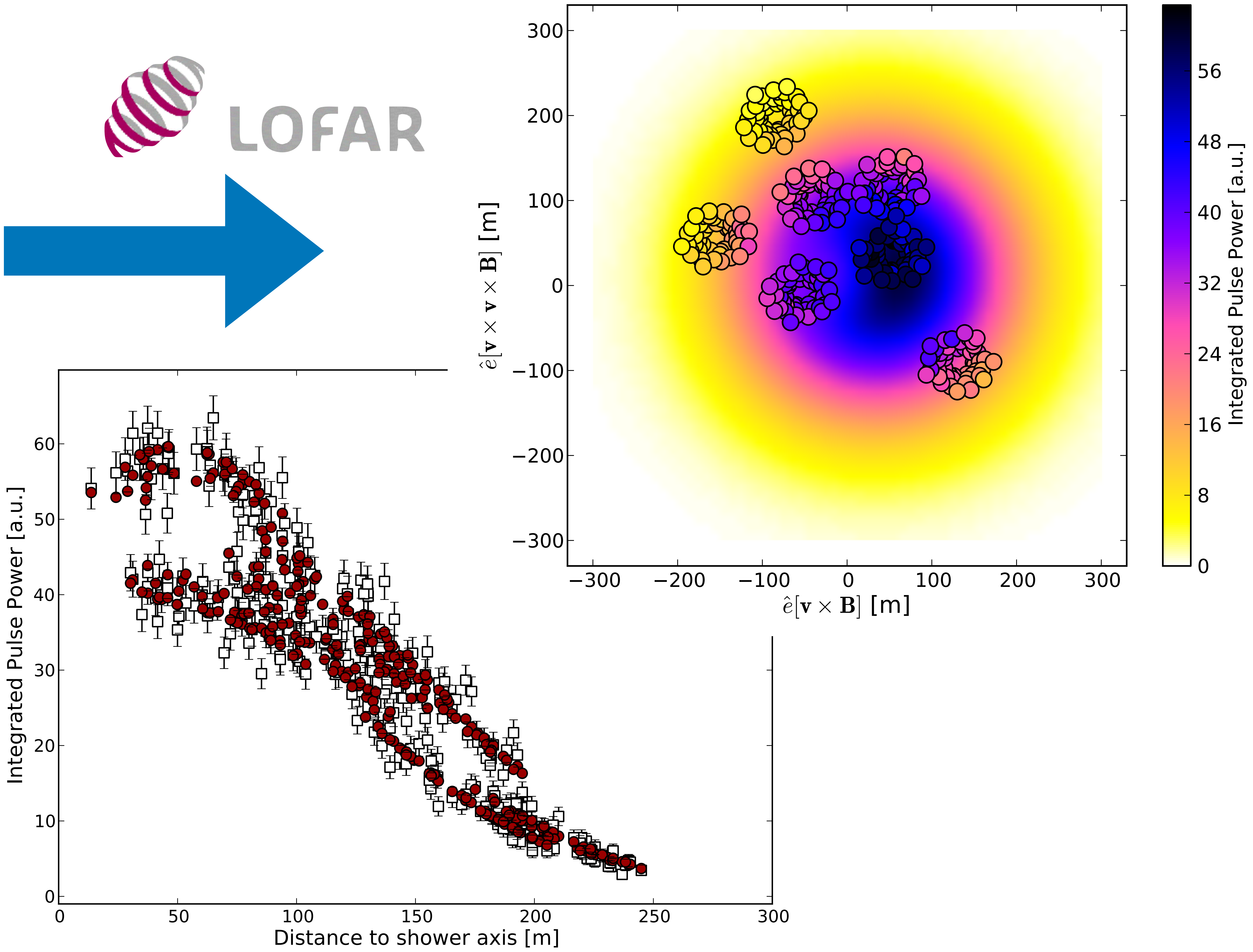
Footprint of radio emission on the ground





W.D. Apel et al. / Astroparticle Physics 32 (2010) 294–303

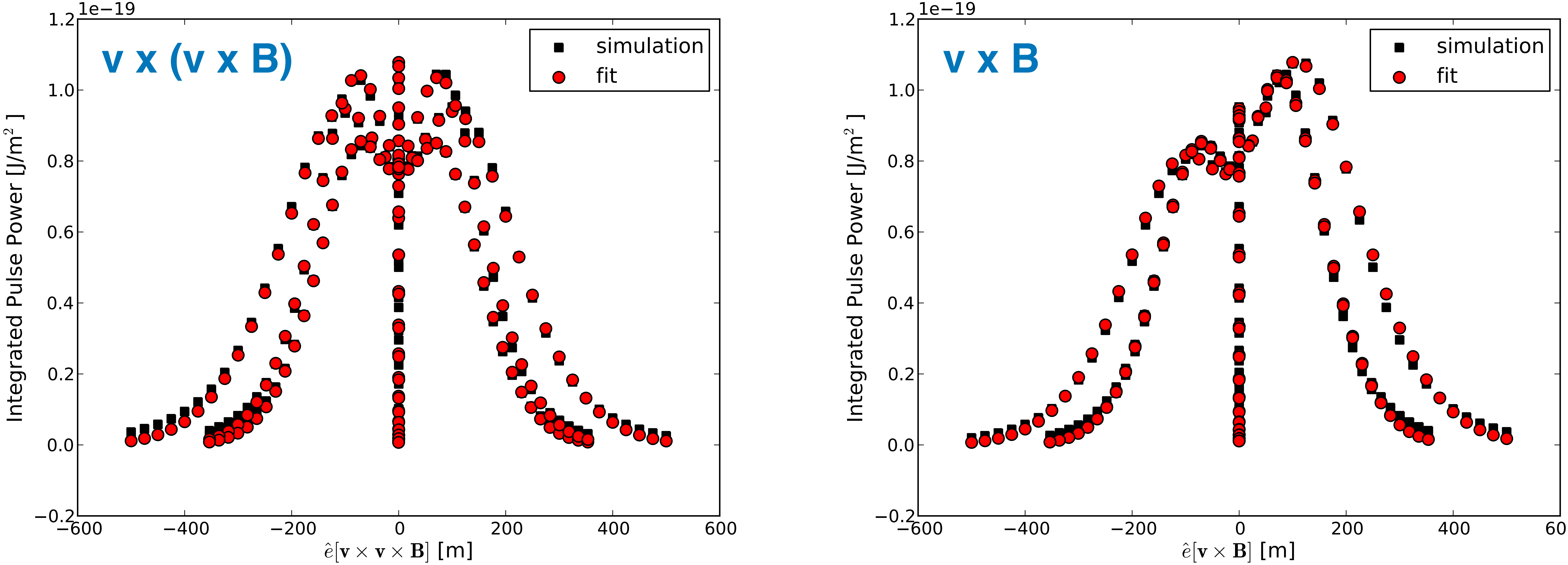
LOFAR



A. Nelles et al., Astropart. Phys. 60 (2015) 13

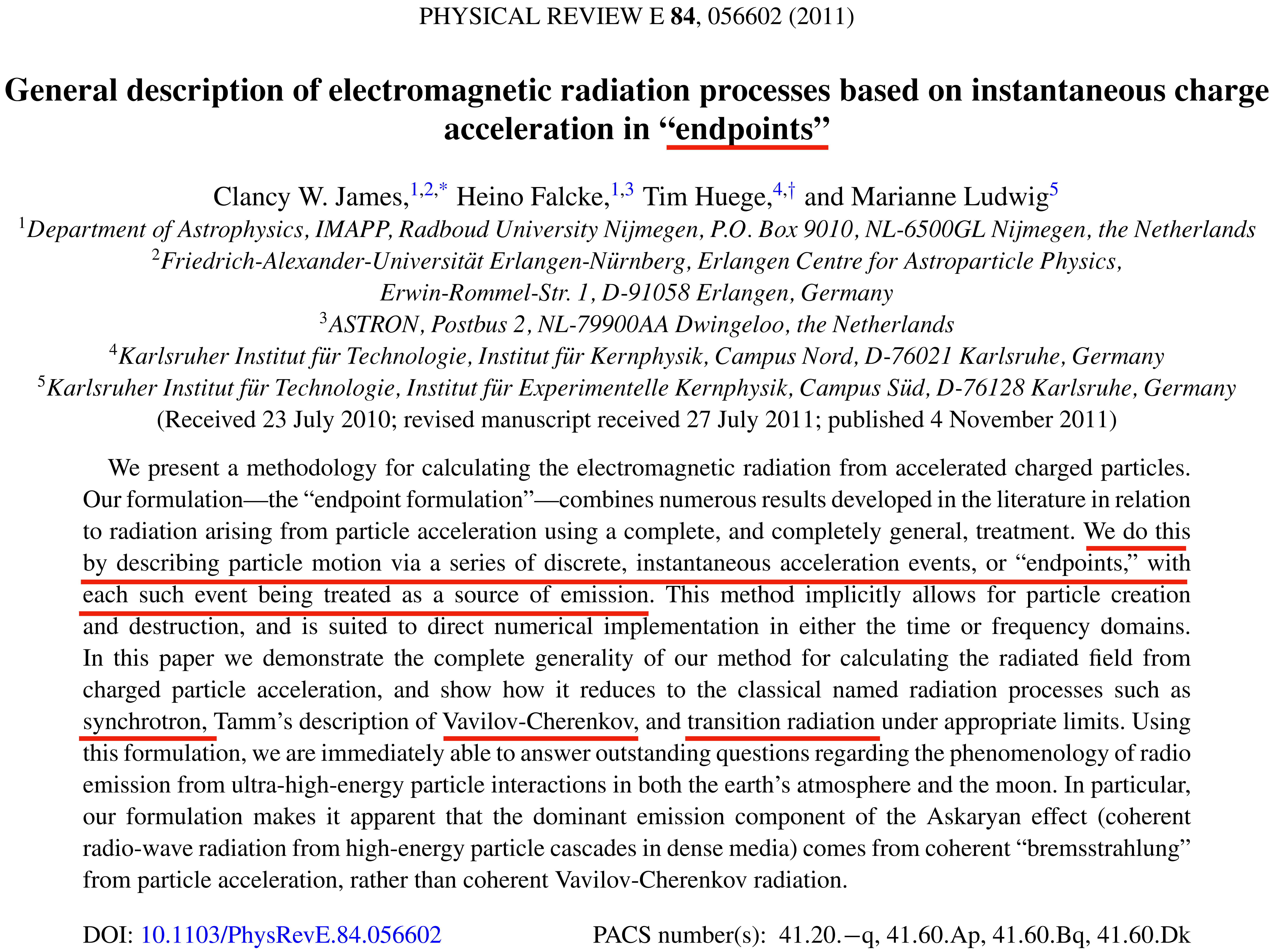
Lateral distribution of radio signals

not rotationally symmetric —> fit two Gaussian functions



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

A. Nelles et al., Astropart. Phys. 60 (2015) 13



PHYSICAL REVIEW E **84**, 056602 (2011)

General description of electromagnetic radiation processes based on instantaneous charge acceleration in “endpoints”

Clancy W. James,[1,2,*] Heino Falcke,[1,3] Tim Huege,[4,†] and Marianne Ludwig[5]
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(Received 23 July 2010; revised manuscript received 27 July 2011; published 4 November 2011)

We present a methodology for calculating the electromagnetic radiation from accelerated charged particles. Our formulation—the “endpoint formulation”—combines numerous results developed in the literature in relation to radiation arising from particle acceleration using a complete, and completely general, treatment. We do this by describing particle motion via a series of discrete, instantaneous acceleration events, or “endpoints,” with each such event being treated as a source of emission. This method implicitly allows for particle creation and destruction, and is suited to direct numerical implementation in either the time or frequency domains. In this paper we demonstrate the complete generality of our method for calculating the radiated field from charged particle acceleration, and show how it reduces to the classical named radiation processes such as synchrotron, Tamm’s description of Vavilov-Cherenkov, and transition radiation under appropriate limits. Using this formulation, we are immediately able to answer outstanding questions regarding the phenomenology of radio emission from ultra-high-energy particle interactions in both the earth’s atmosphere and the moon. In particular, our formulation makes it apparent that the dominant emission component of the Askaryan effect (coherent radio-wave radiation from high-energy particle cascades in dense media) comes from coherent “bremsstrahlung” from particle acceleration, rather than coherent Vavilov-Cherenkov radiation.

DOI: 10.1103/PhysRevE.84.056602 PACS number(s): 41.20.−q, 41.60.Ap, 41.60.Bq, 41.60.Dk

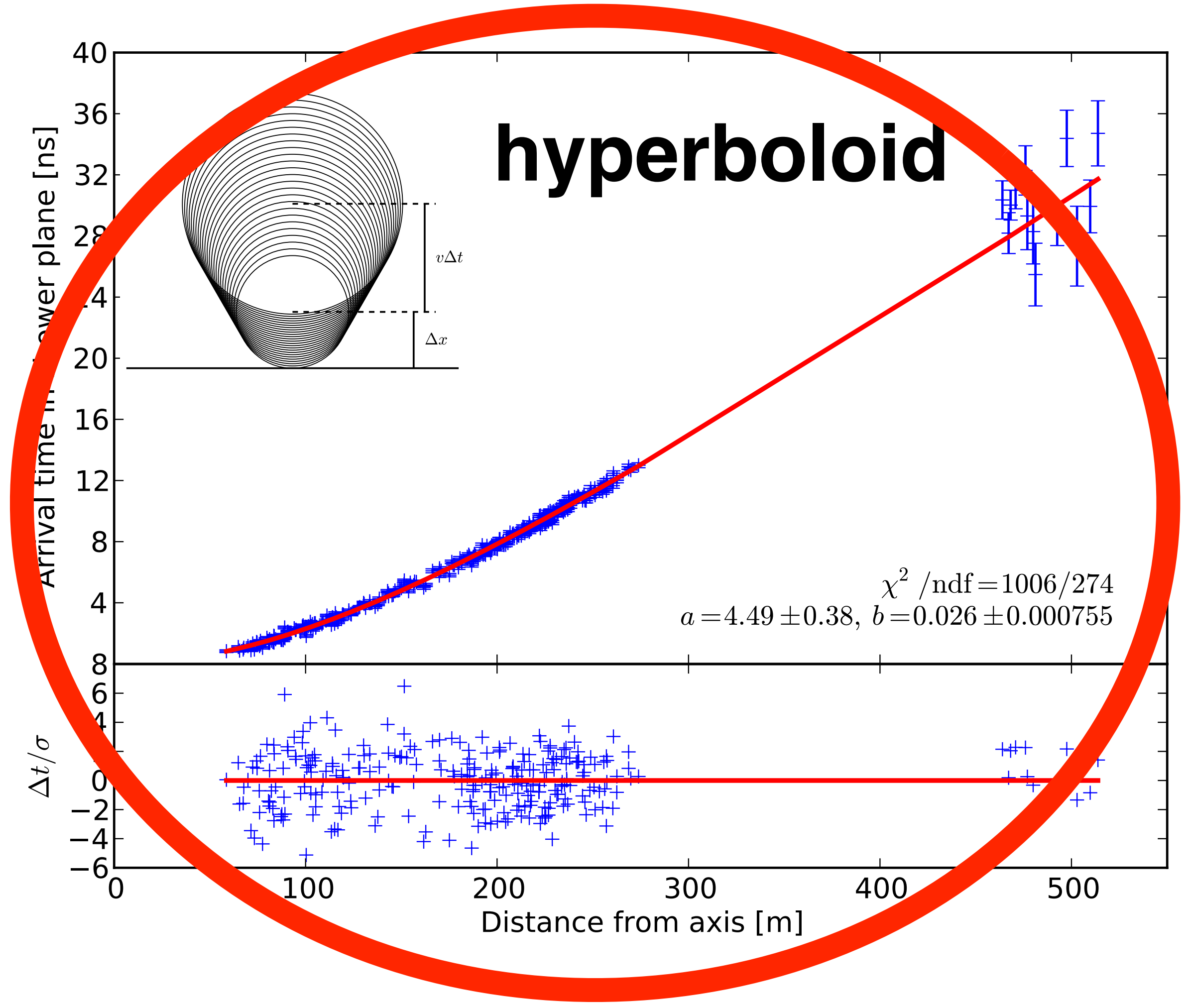
Properties of incoming cosmic ray

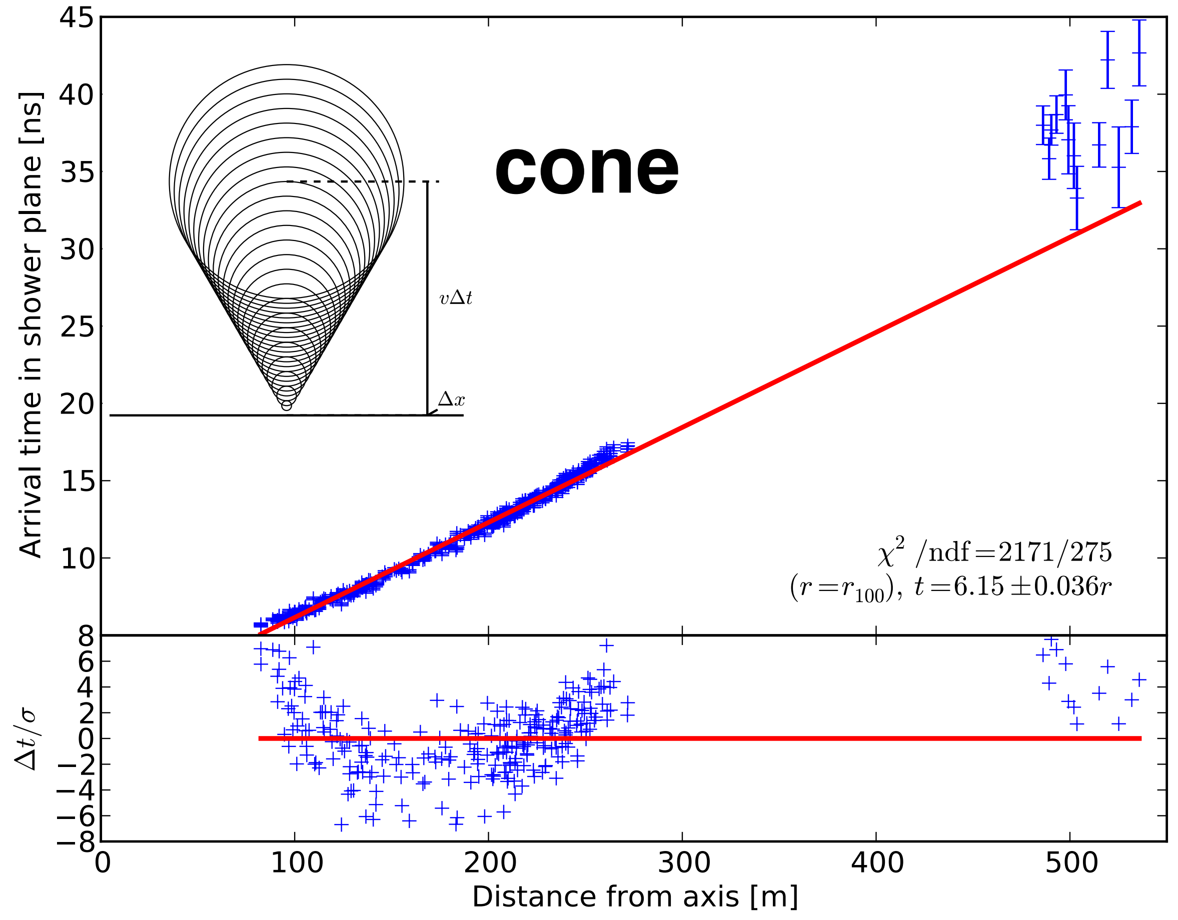
- direction
- energy
- type

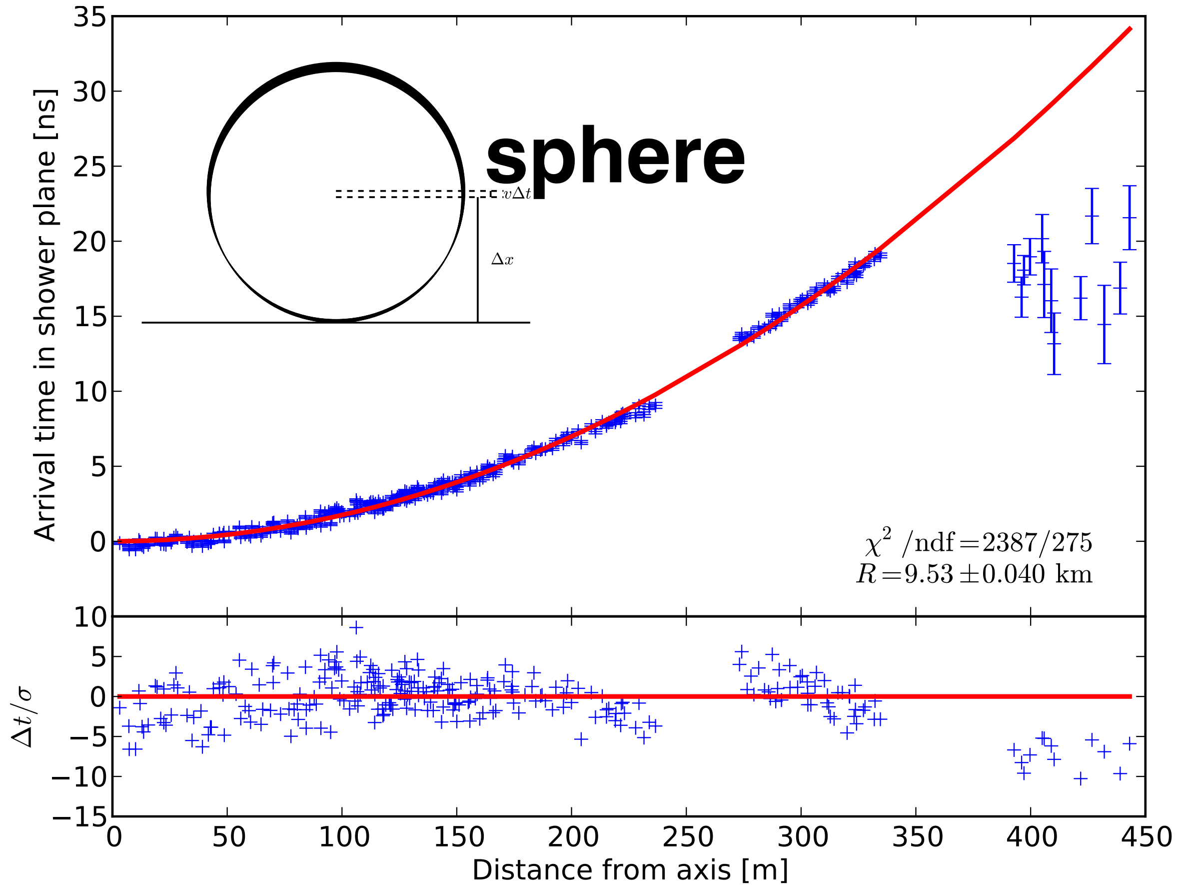
Direction

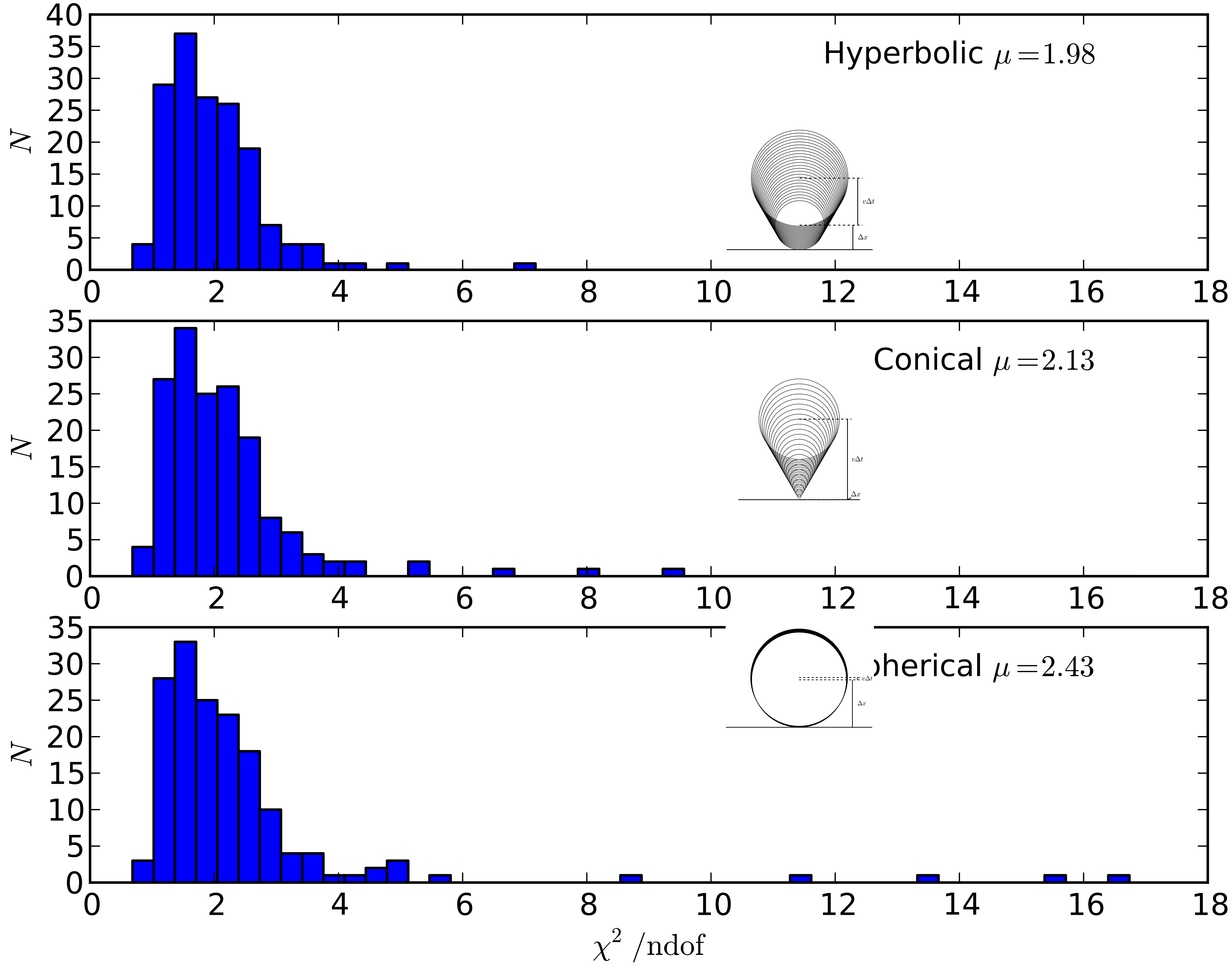
Shape of Shower Front

fit quality



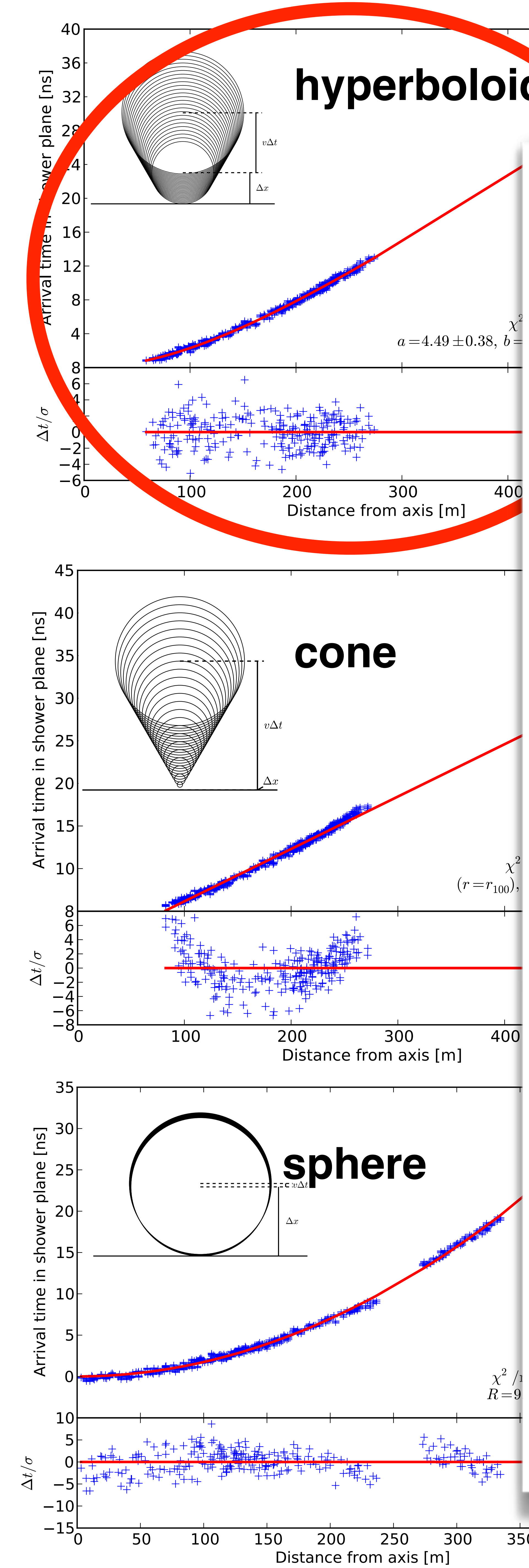


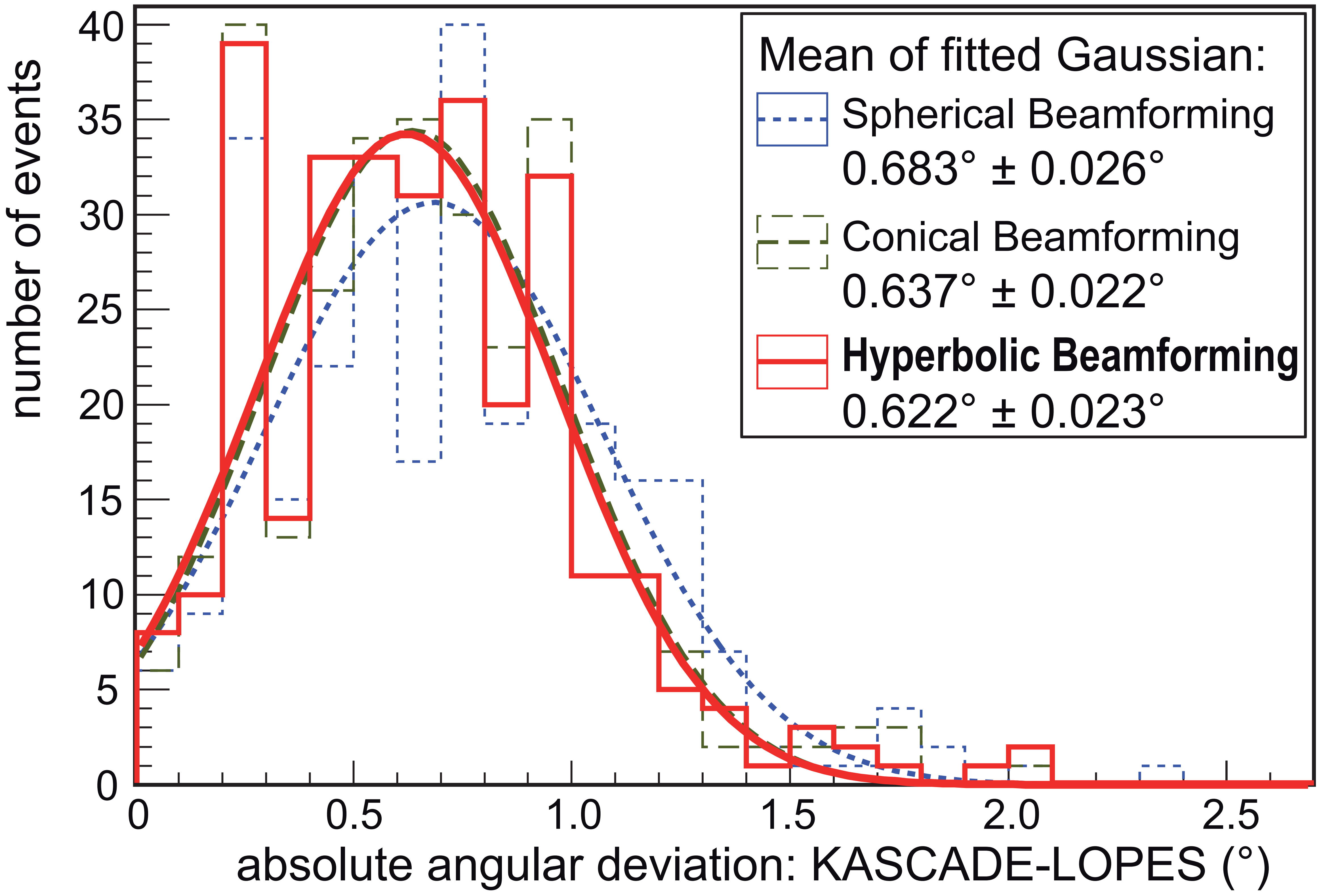




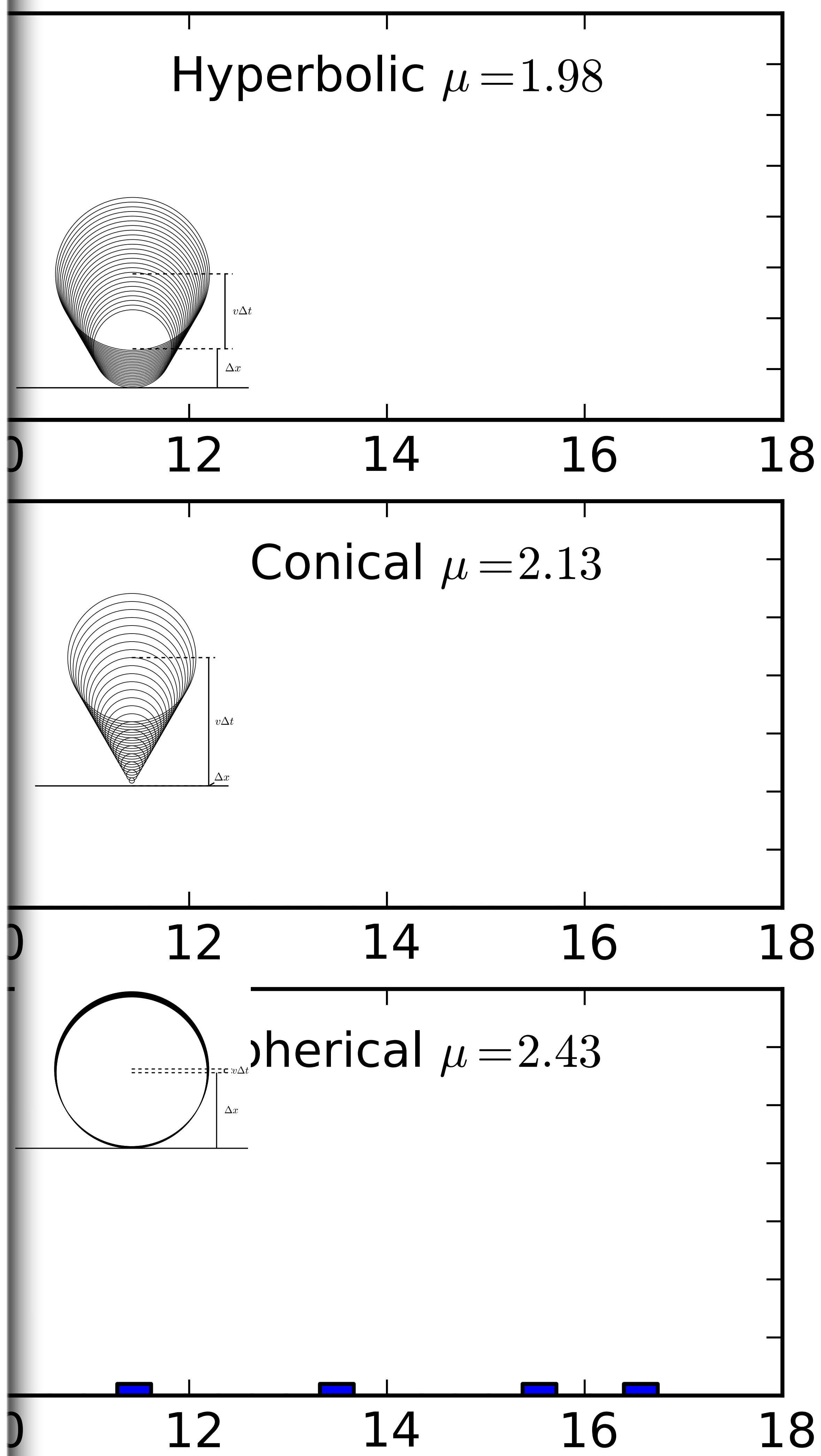
A. Corstanje et al., Astropart. Phys. 61 (2015) 22

Shape of Shower Front





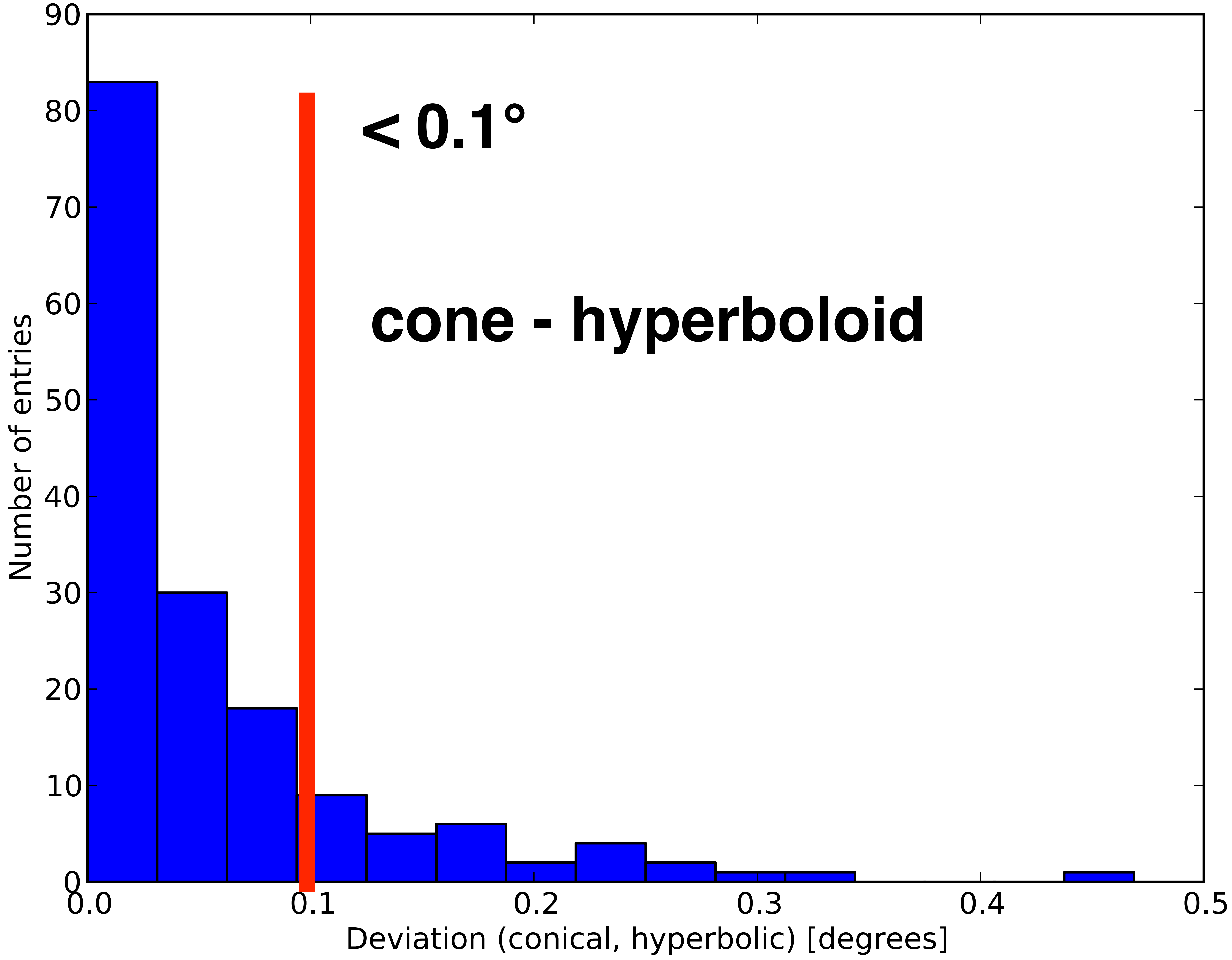
W.D. Apel et al., JCAP 1409 (2014) no.09, 025



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

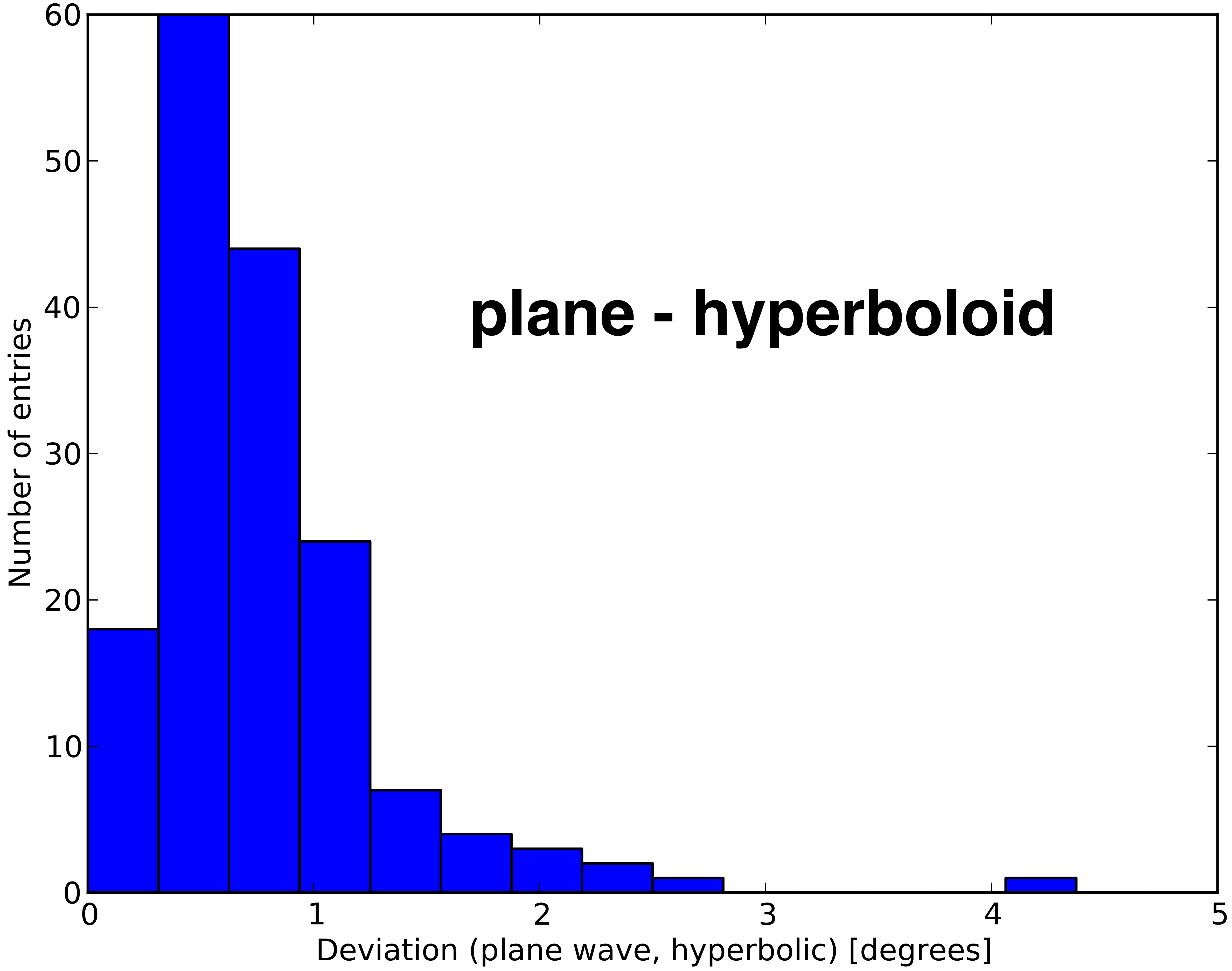
Accuracy of Shower Direction

angular difference between..



< 0.1°

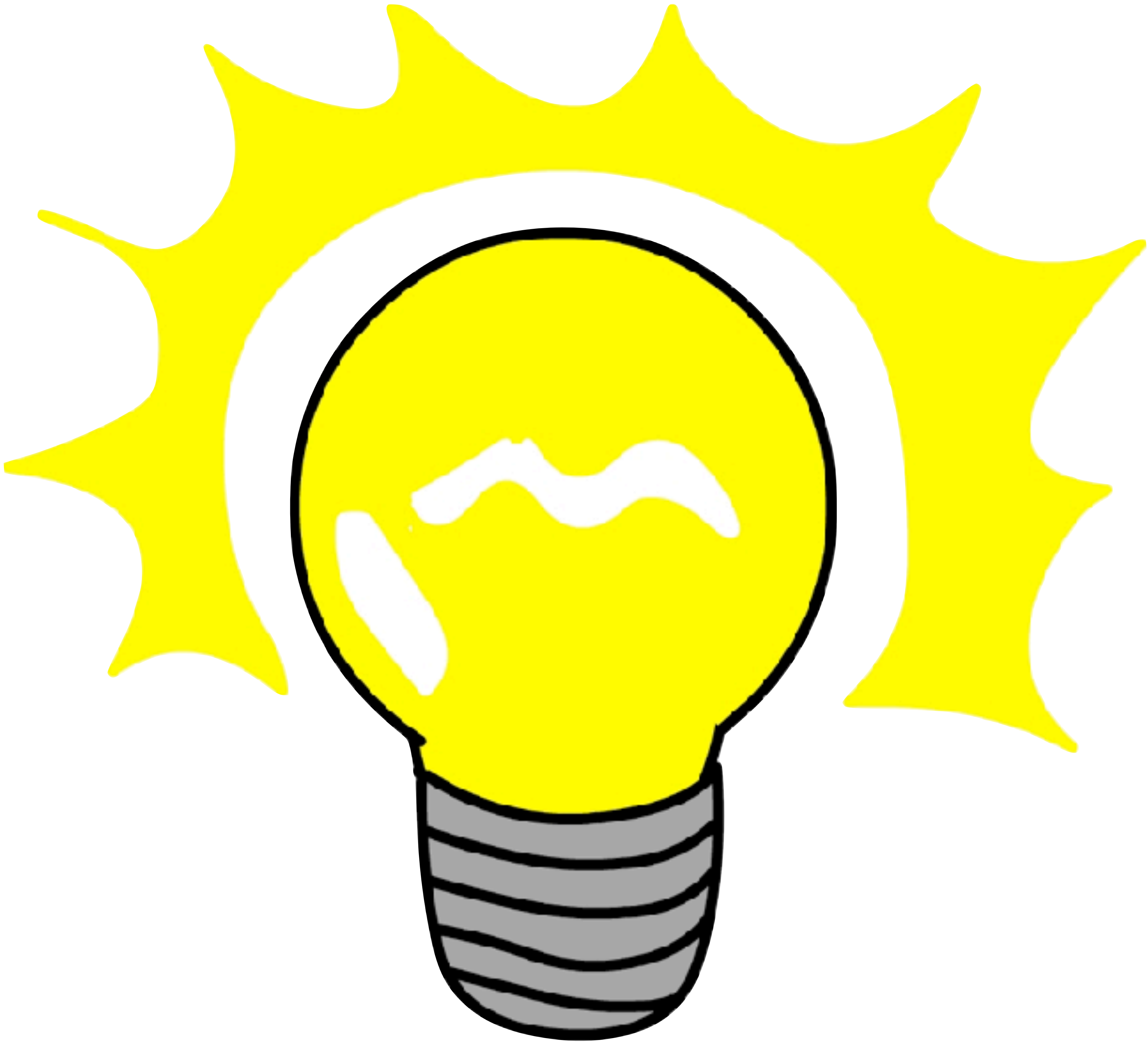
cone - hyperboloid



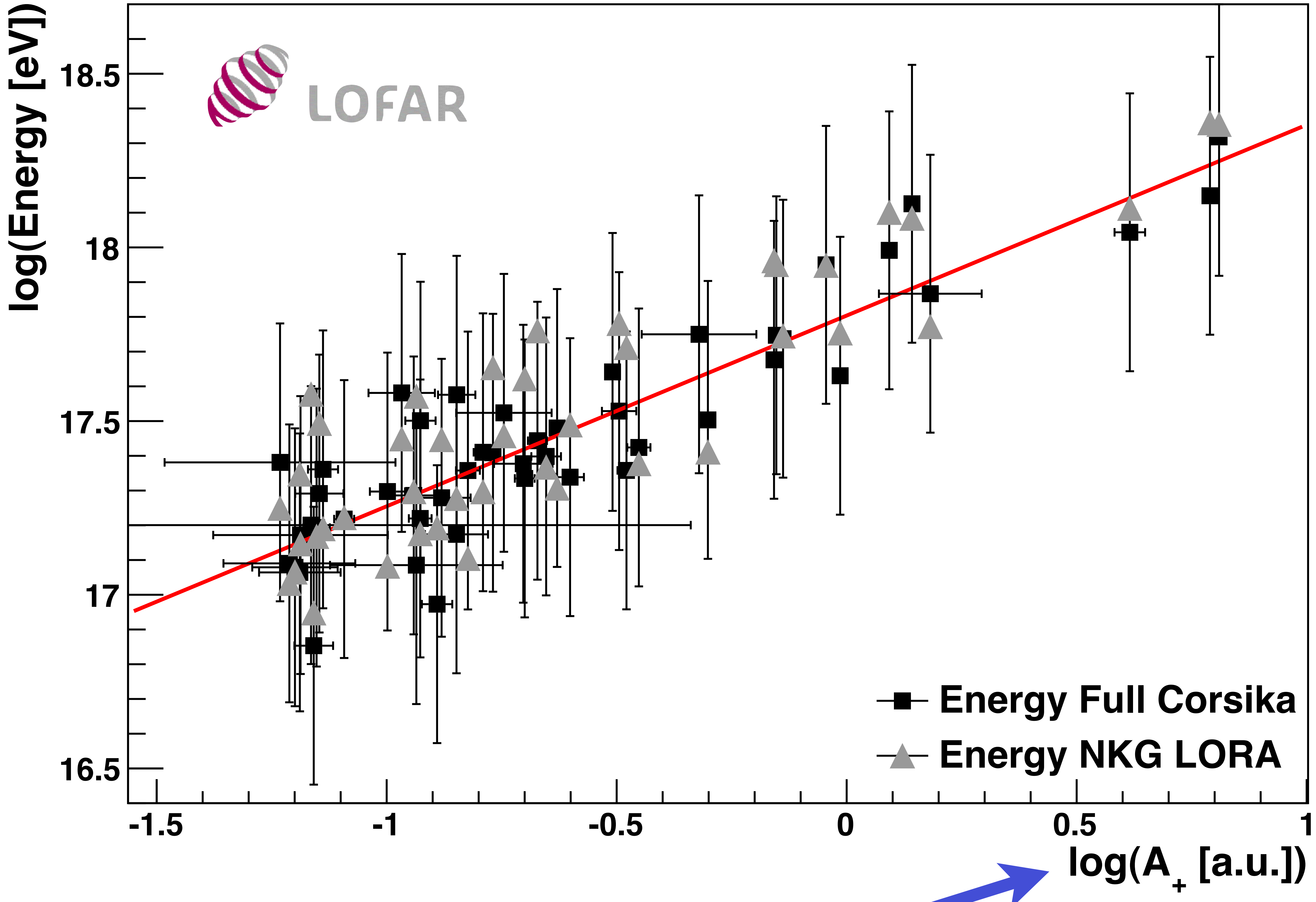
plane - hyperboloid

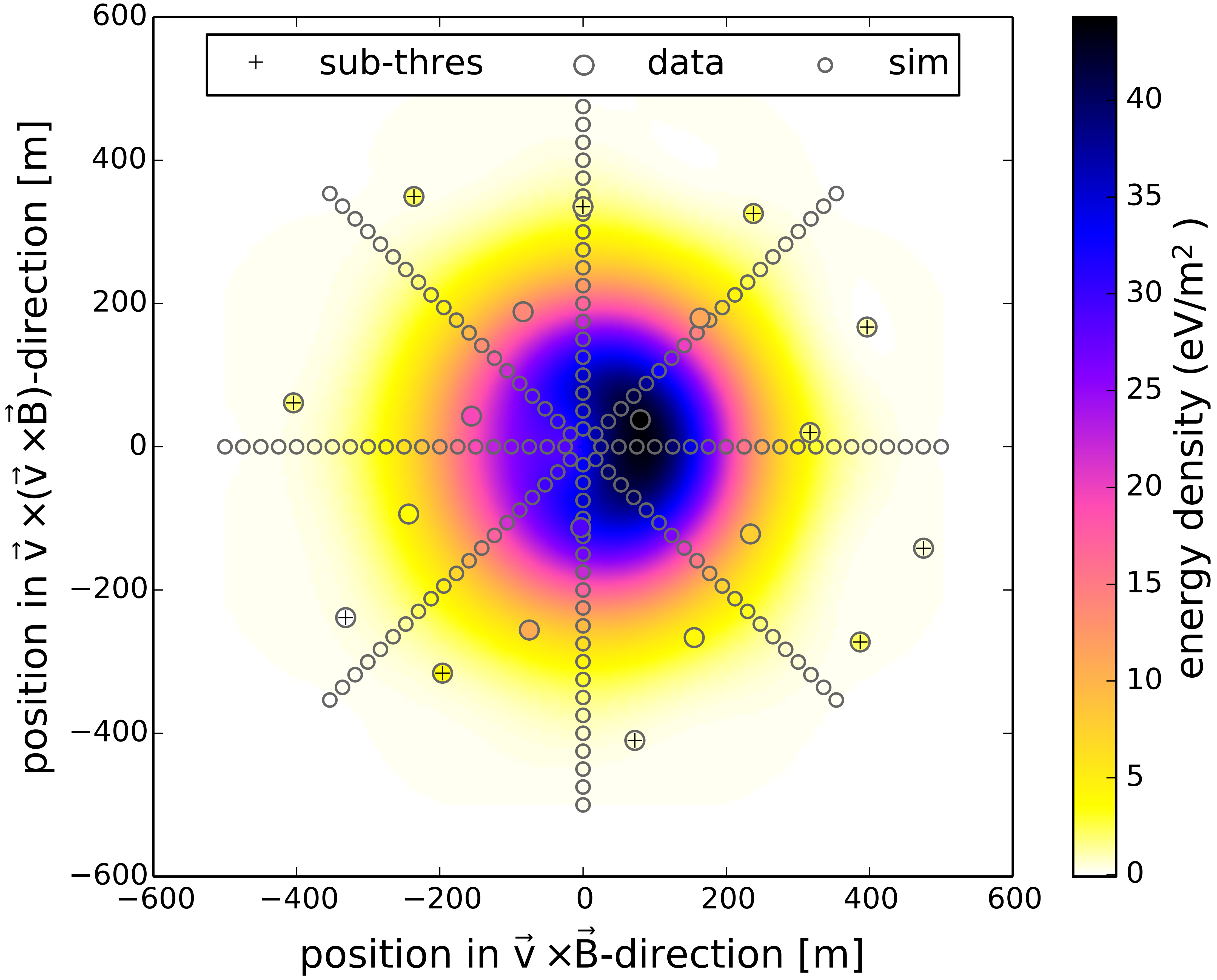
A. Corstanje et al., Astropart. Phys. 61 (2015) 22

Energy



Energy of primary particle





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

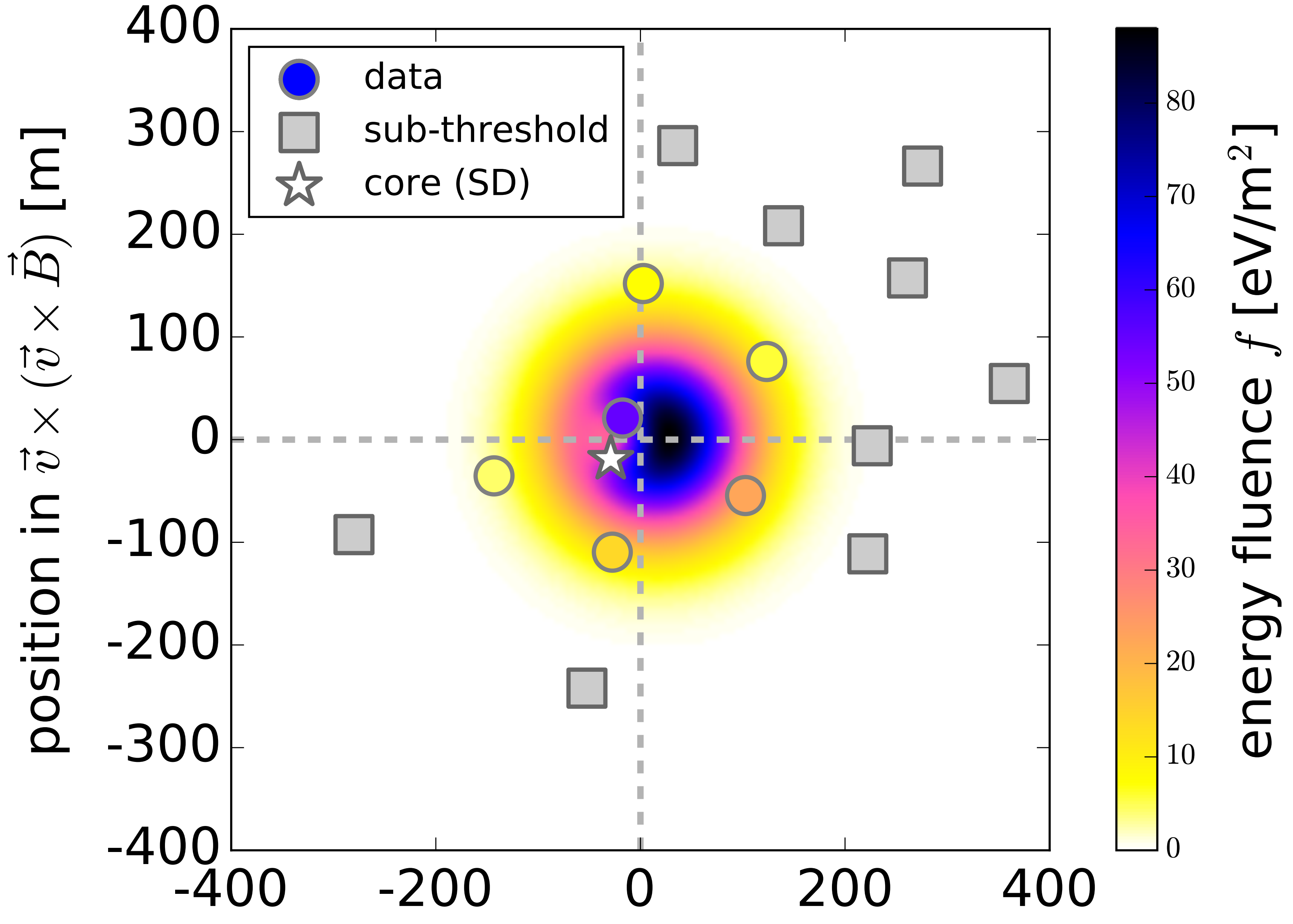
A. Nelles et al., JCAP 05 (2015) 018

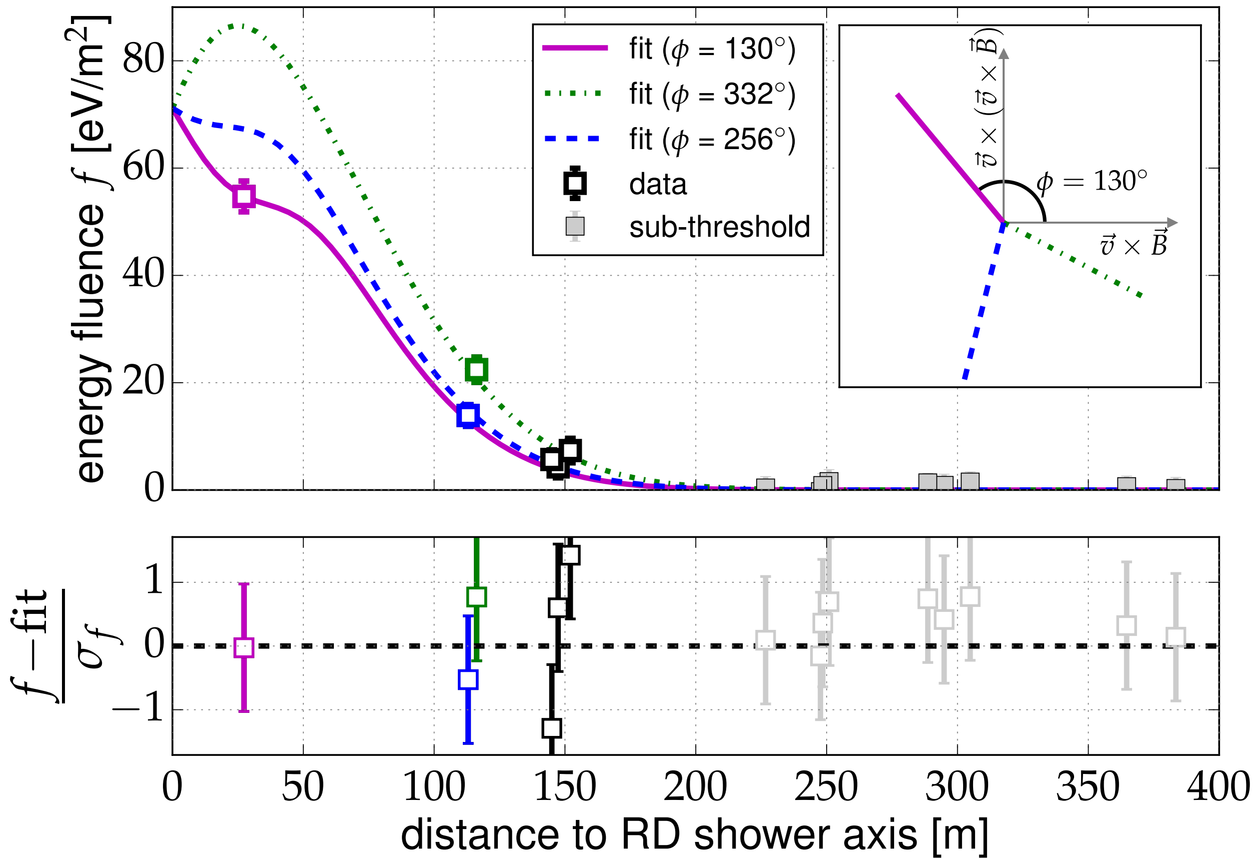
Measurement of the Radiation Energy in the Radio Signal of Extensive Air Showers as a Universal Estimator of Cosmic-Ray Energy

AERA
Auger Engineering Radio Array

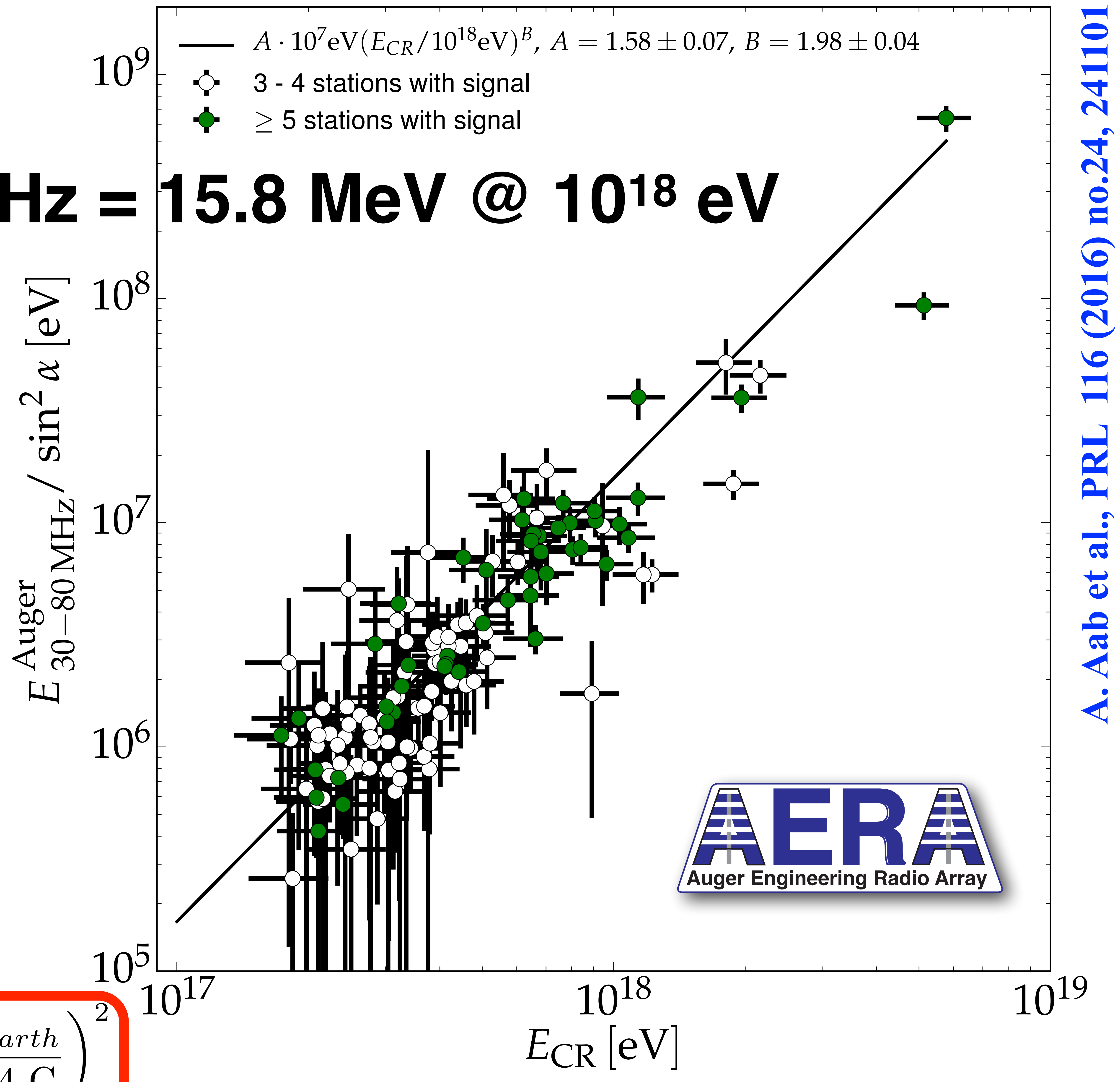
A. Aab et al., PRL 116 (2016) no.24, 241101

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

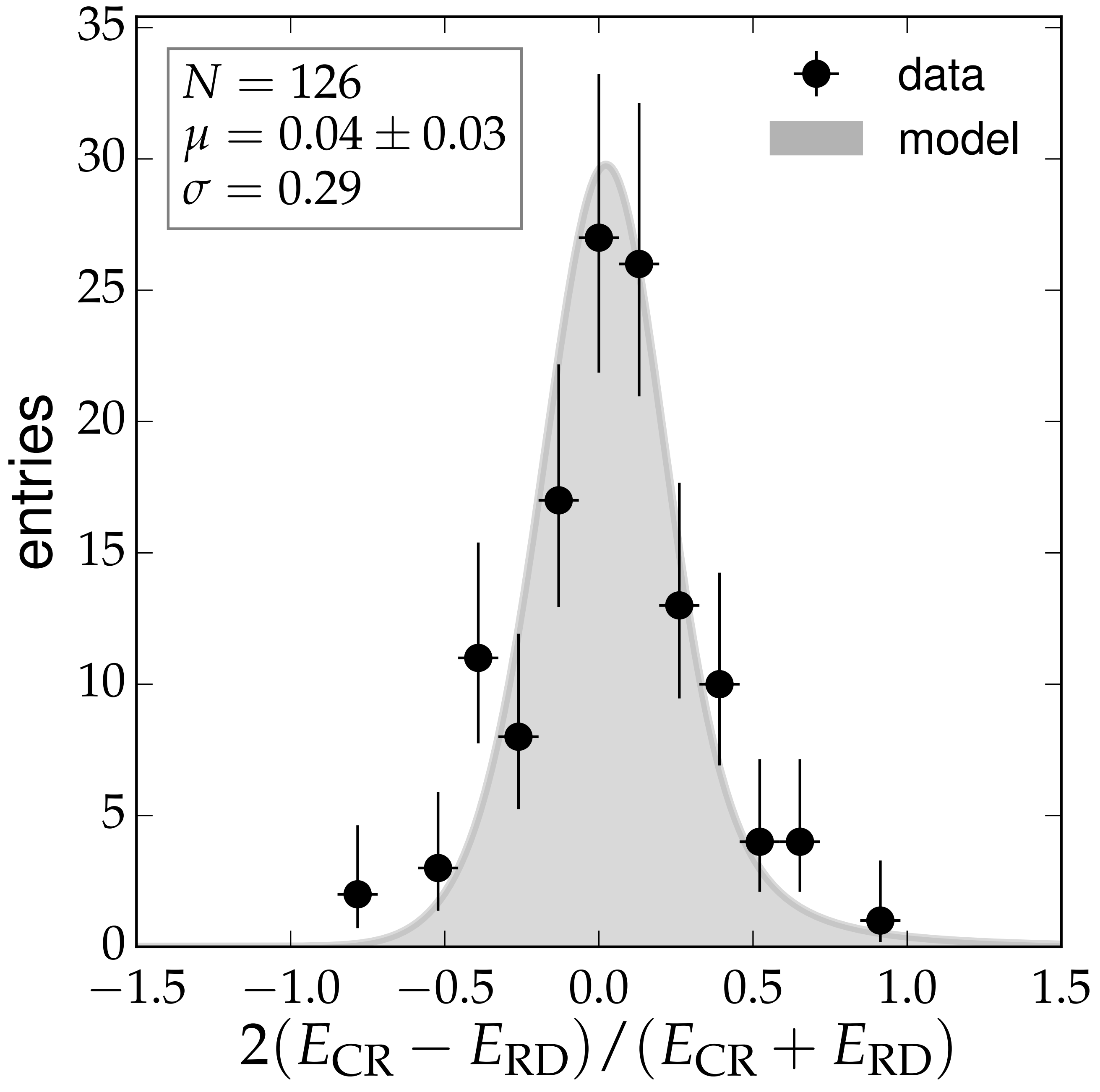


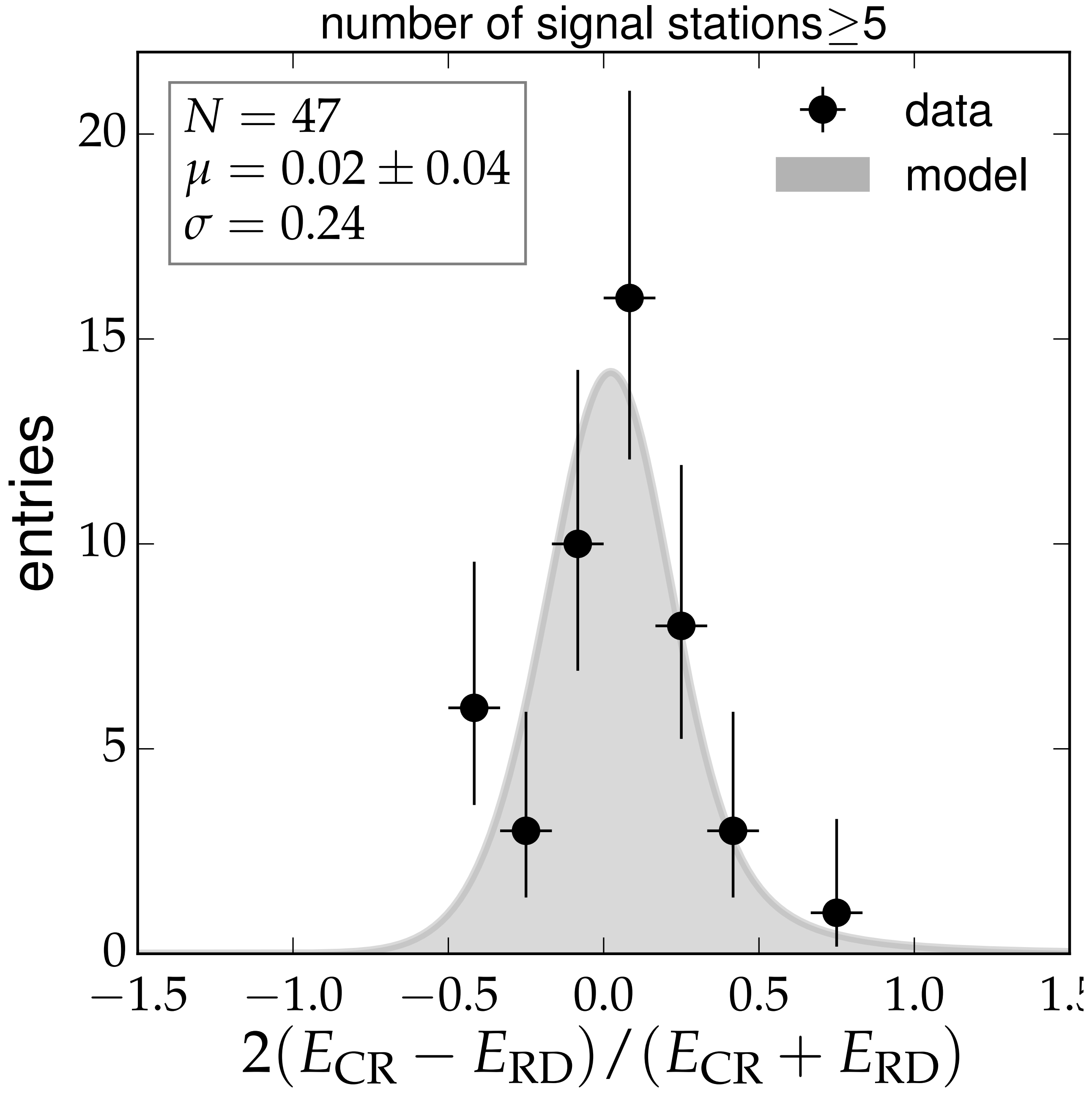
A. Aab et al., PRL 116 (2016) no.24, 241101

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

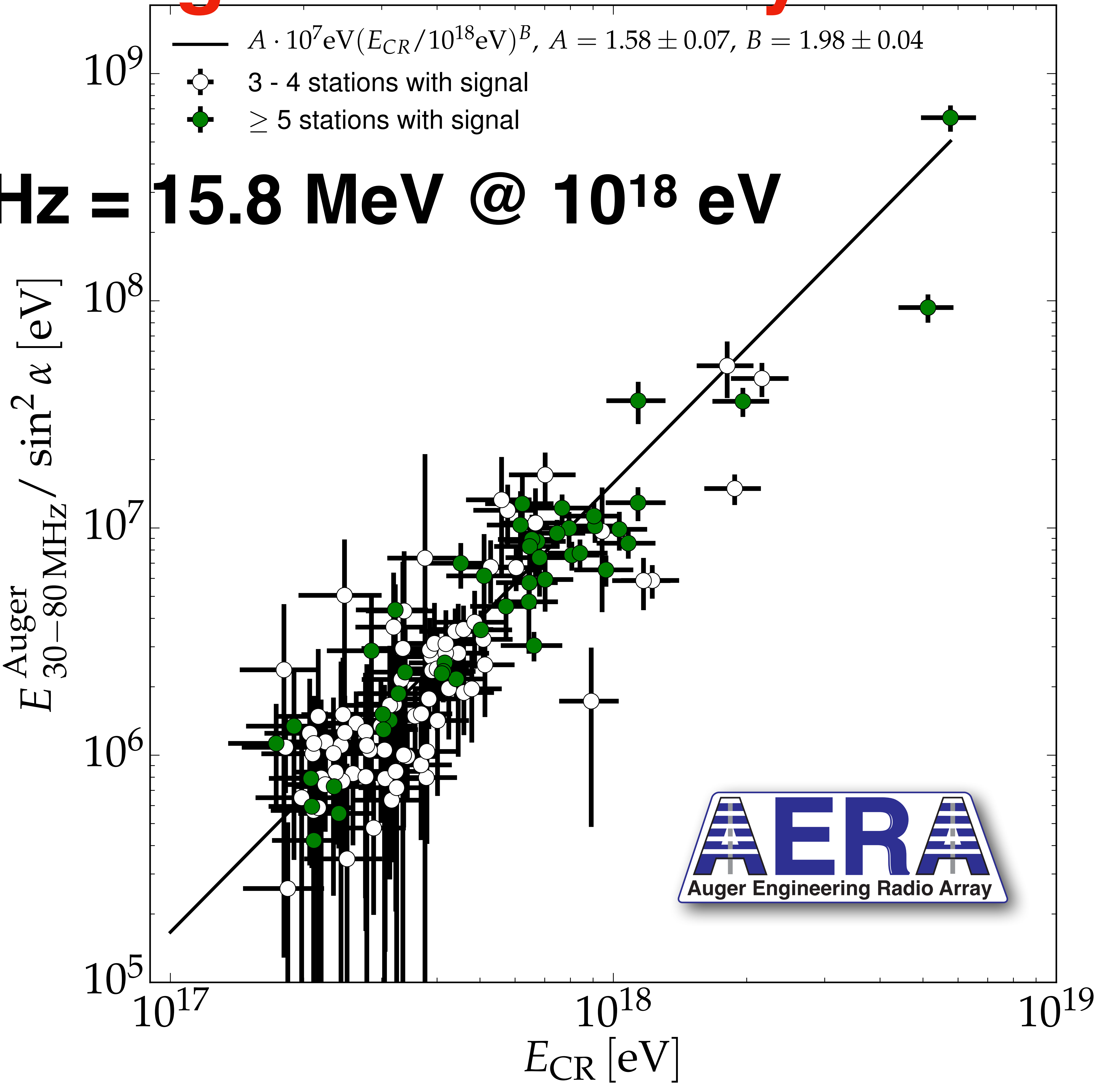
Energy Estimation of Cosmic Rays with the Engineering Radio Array of the Pierre Auger Observatory

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





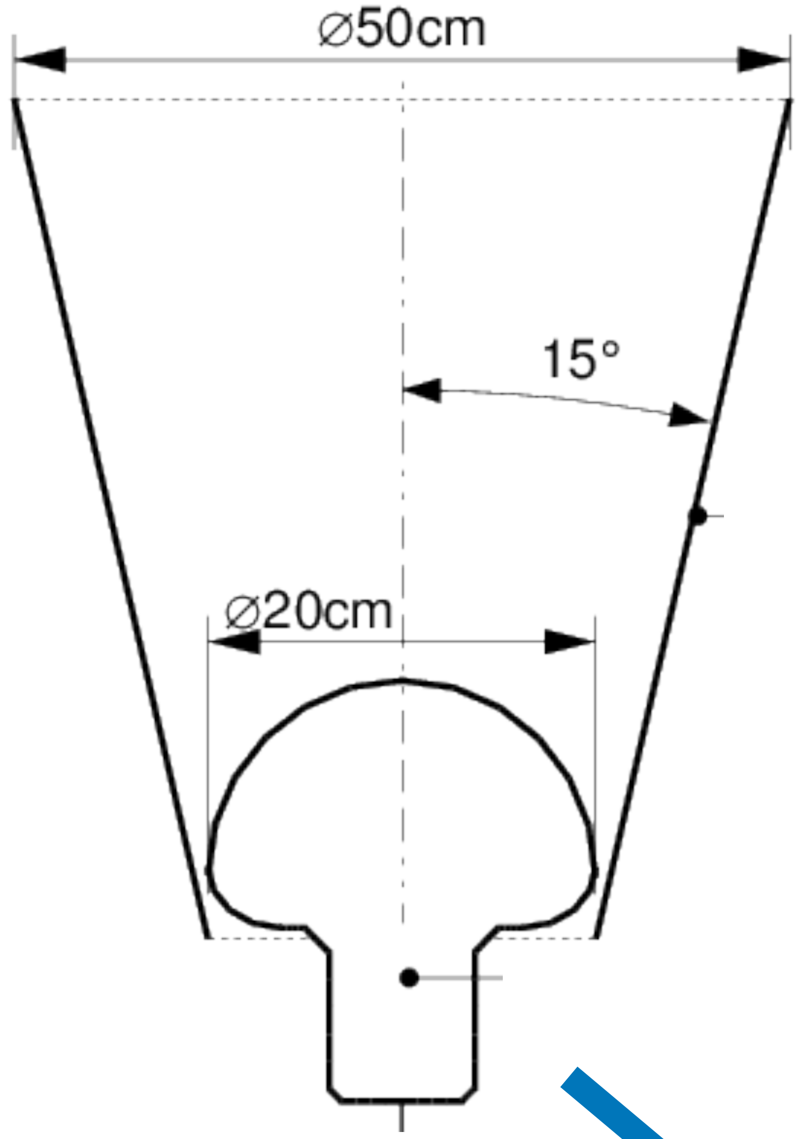
$$\sigma \approx 24\%$$

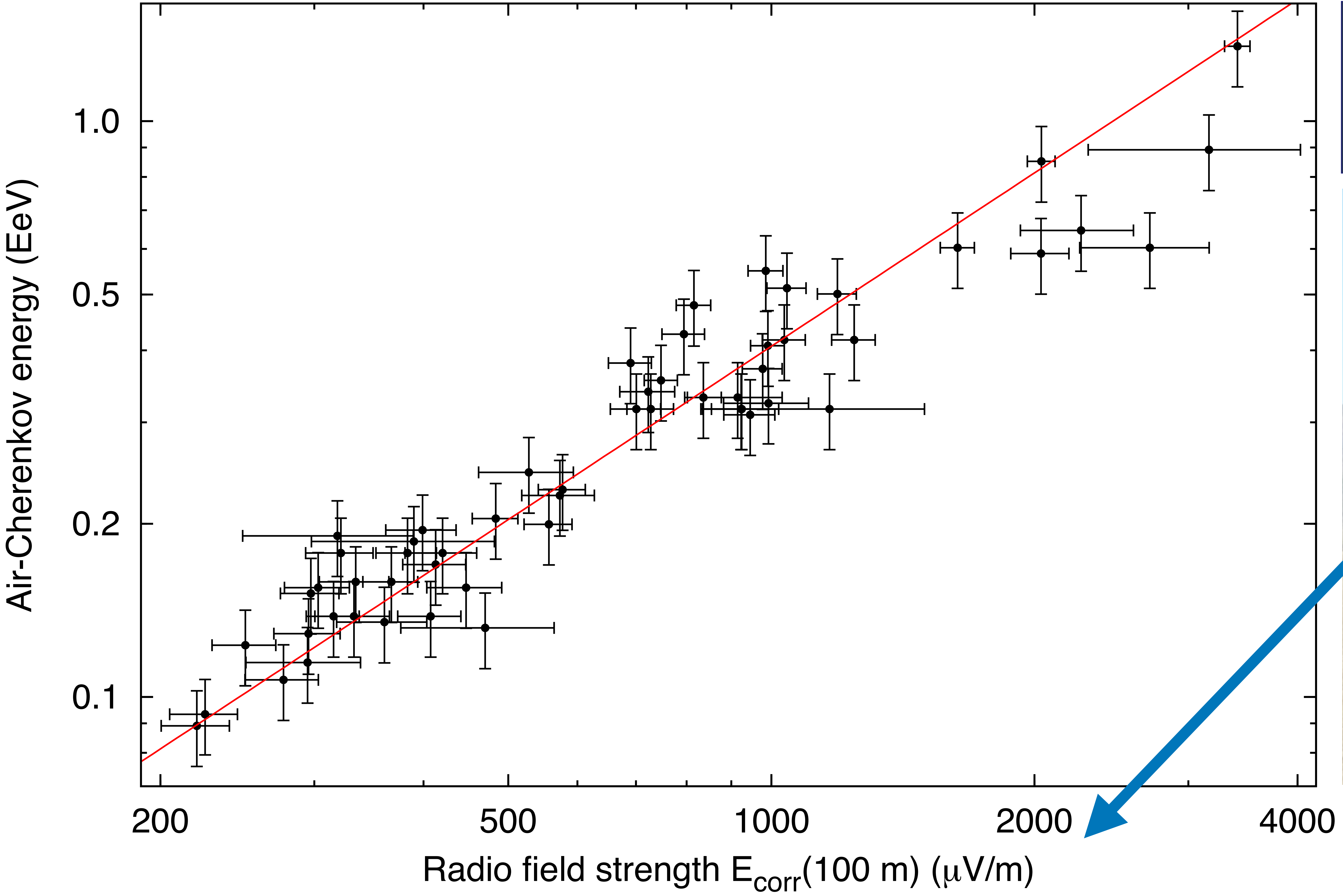


A. Aab et al., PRL 116 (2016) no.24, 241101

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

Cosmic-ray energy (Cherenkov) vs radio signal





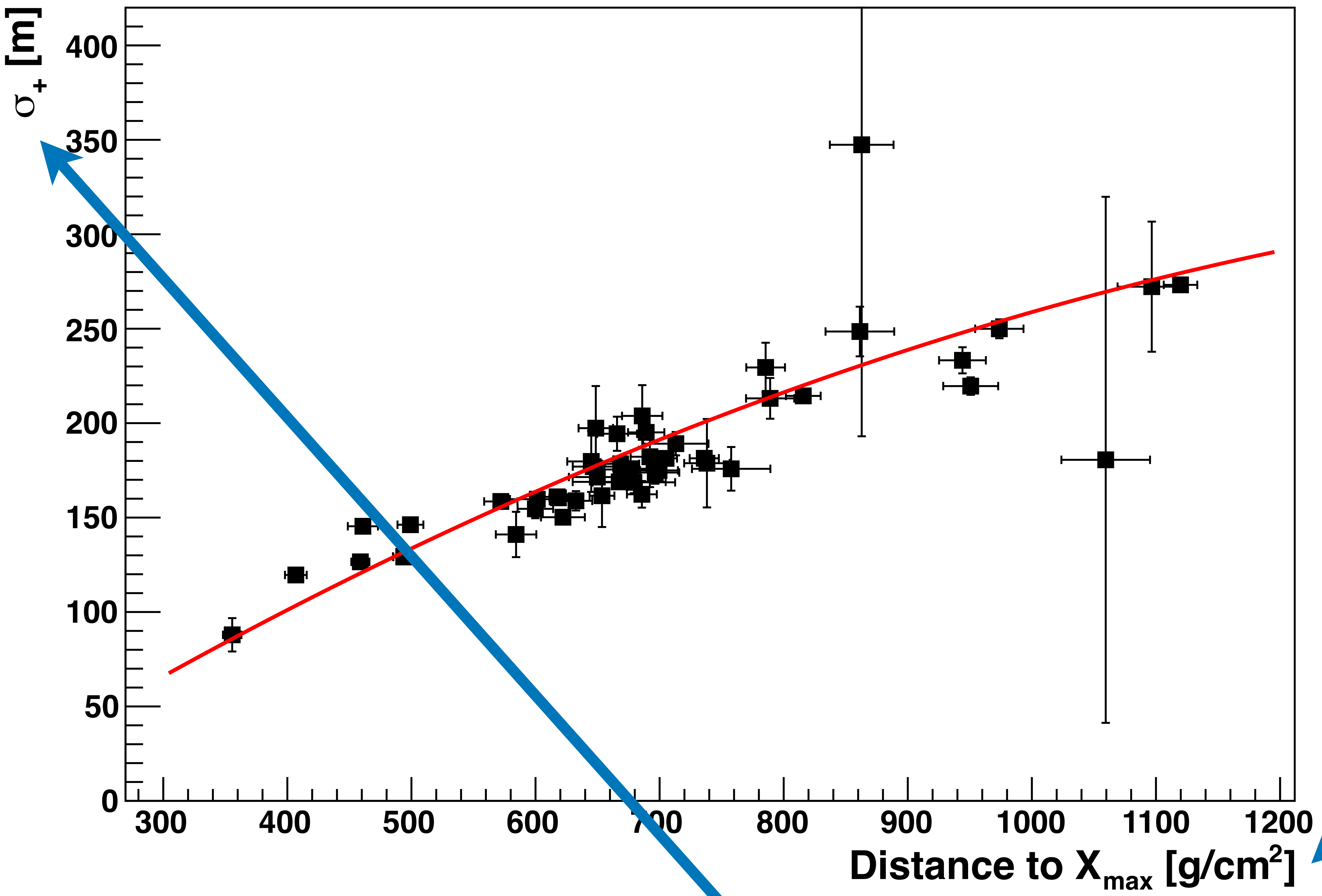
Tunka-Rex

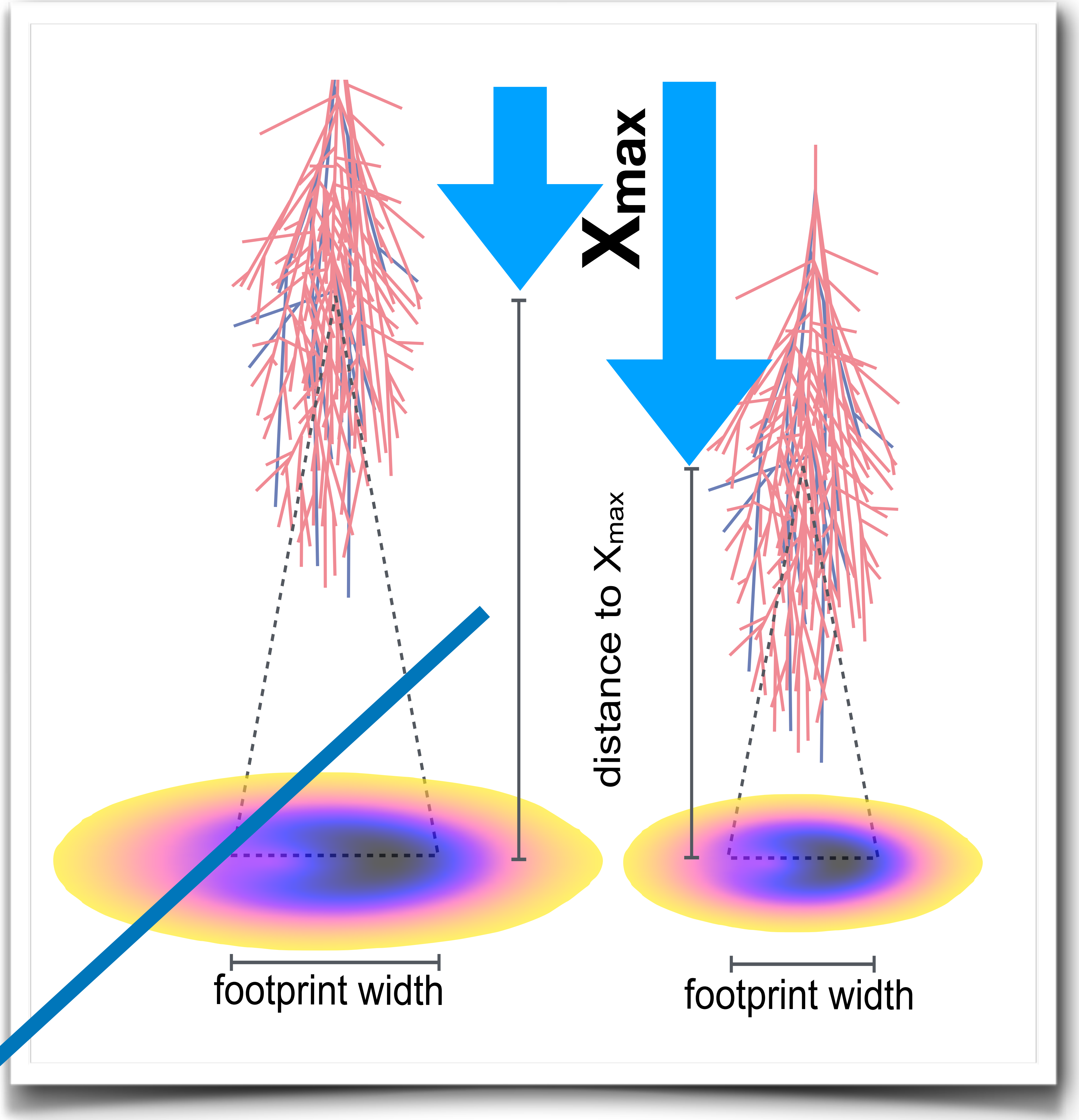
Fig. 3. Correlation of the energy measured with the air-Cherenkov array and an energy estimator based on the radio amplitude at 100 m measured with Tunka-Rex. The line indicates a linear correlation.

F.G. Schröder et al., JPS Conf. Proc. 9 (2016) 010008

Particle type
Mass

Distance to Xmax





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

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

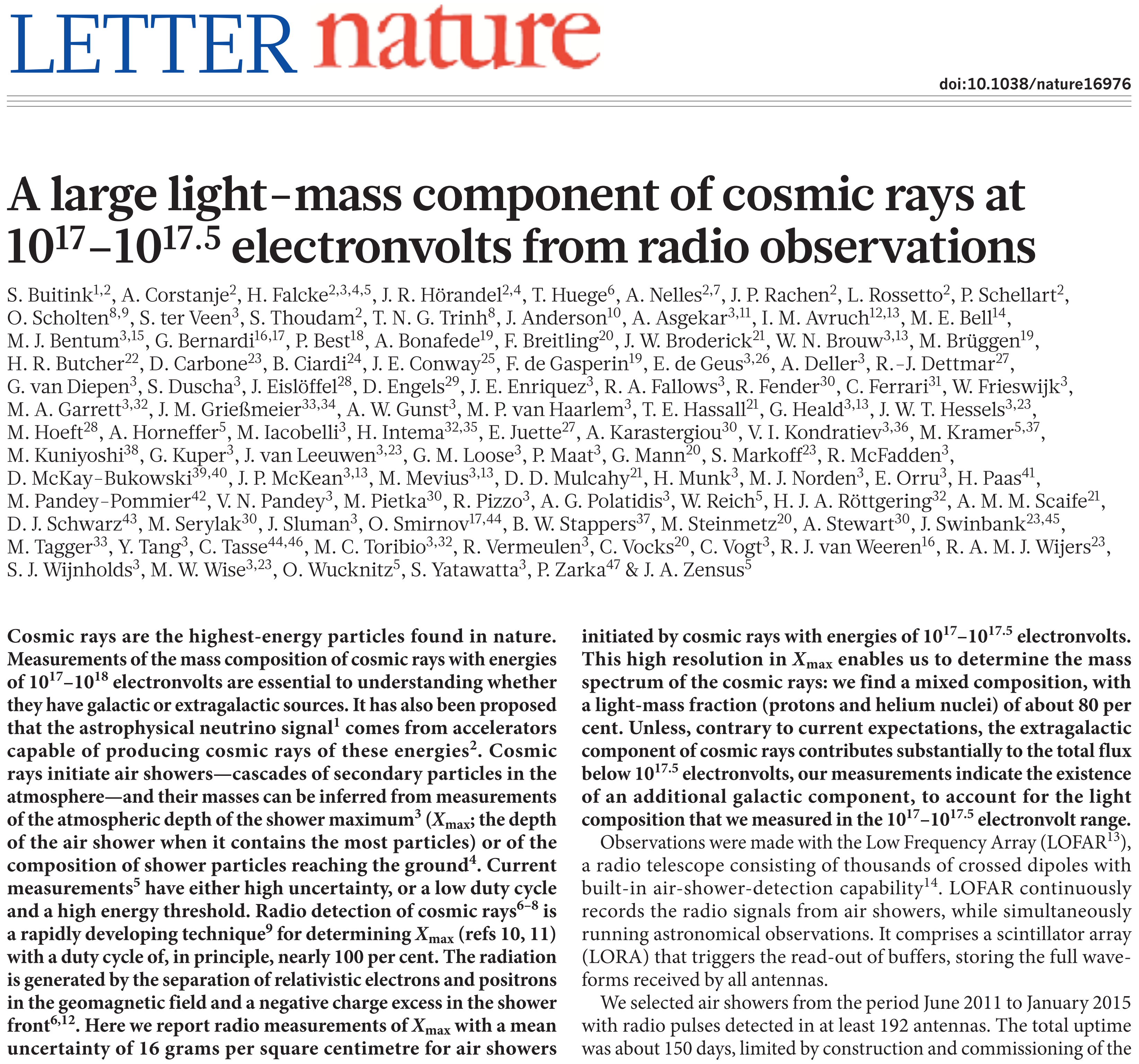
Measurement of particle mass

$\sigma_E \approx 32\%$

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

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

Depth of the shower maximum



LETTER nature

doi:10.1038/nature16976

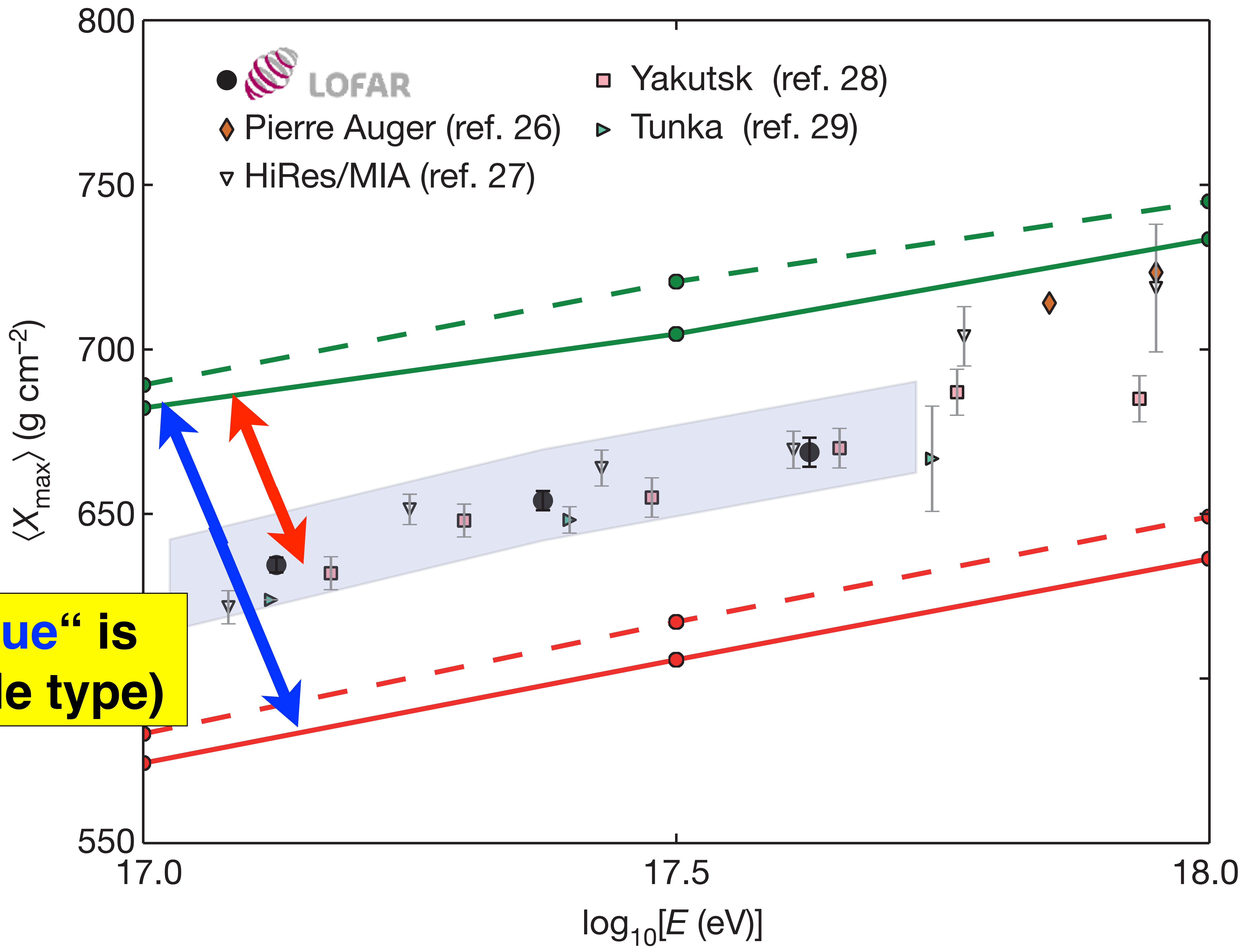
A large light-mass component of cosmic rays at 10^{17}–$10^{17.5}$ electronvolts from radio observations

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

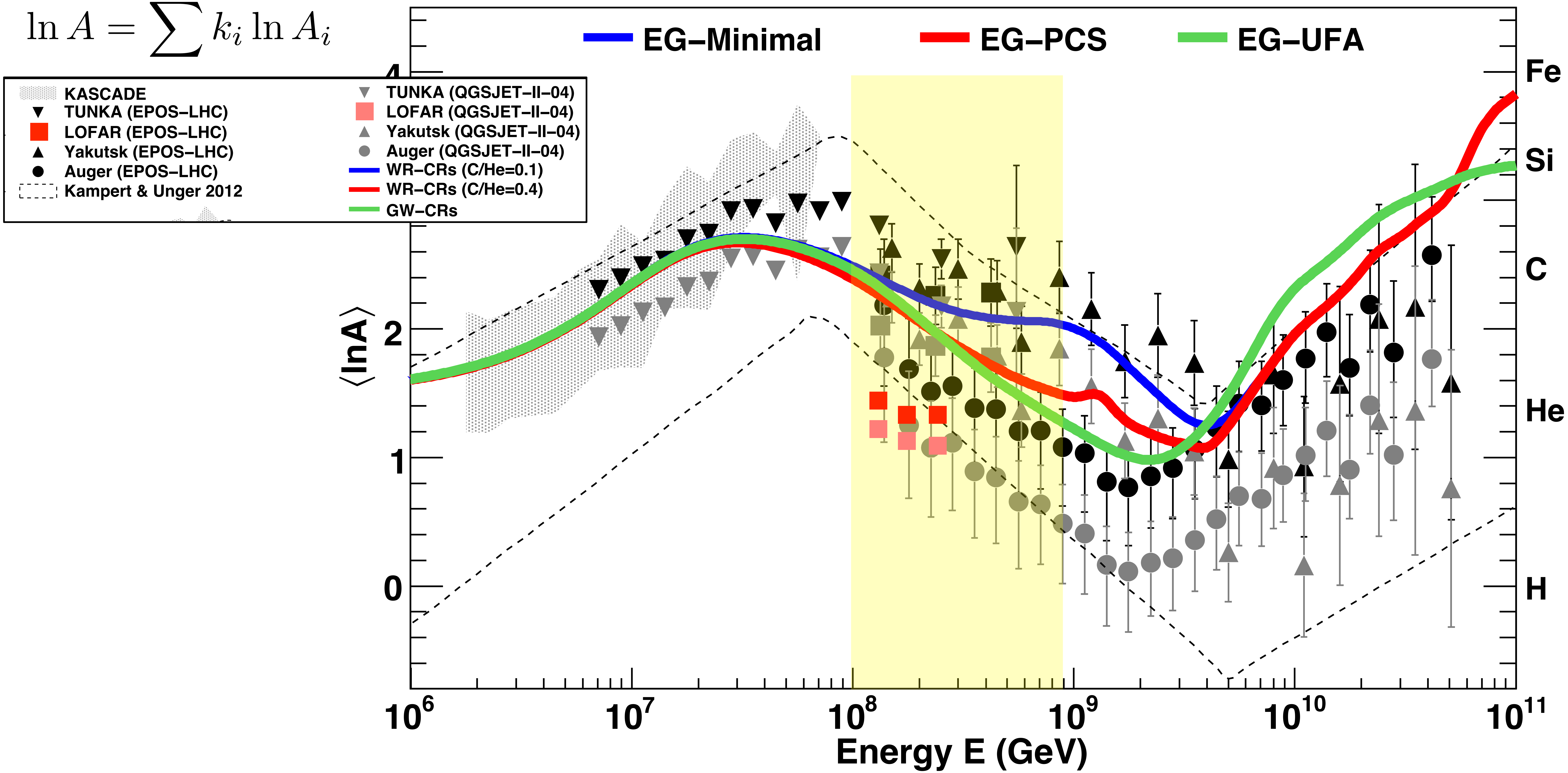


relative distance "red/blue" is measure for ln A (particle type)

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

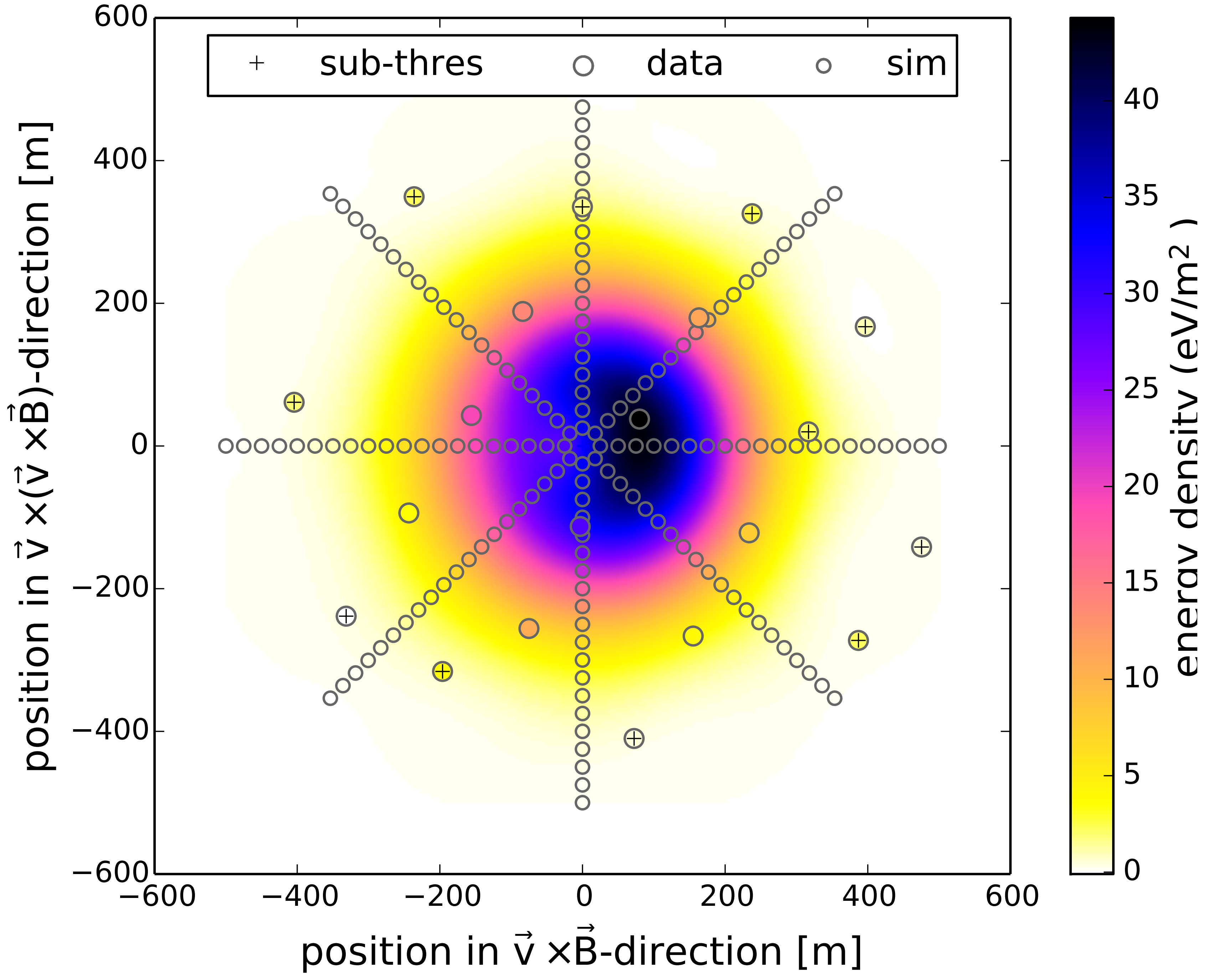
Mean logarithmic mass

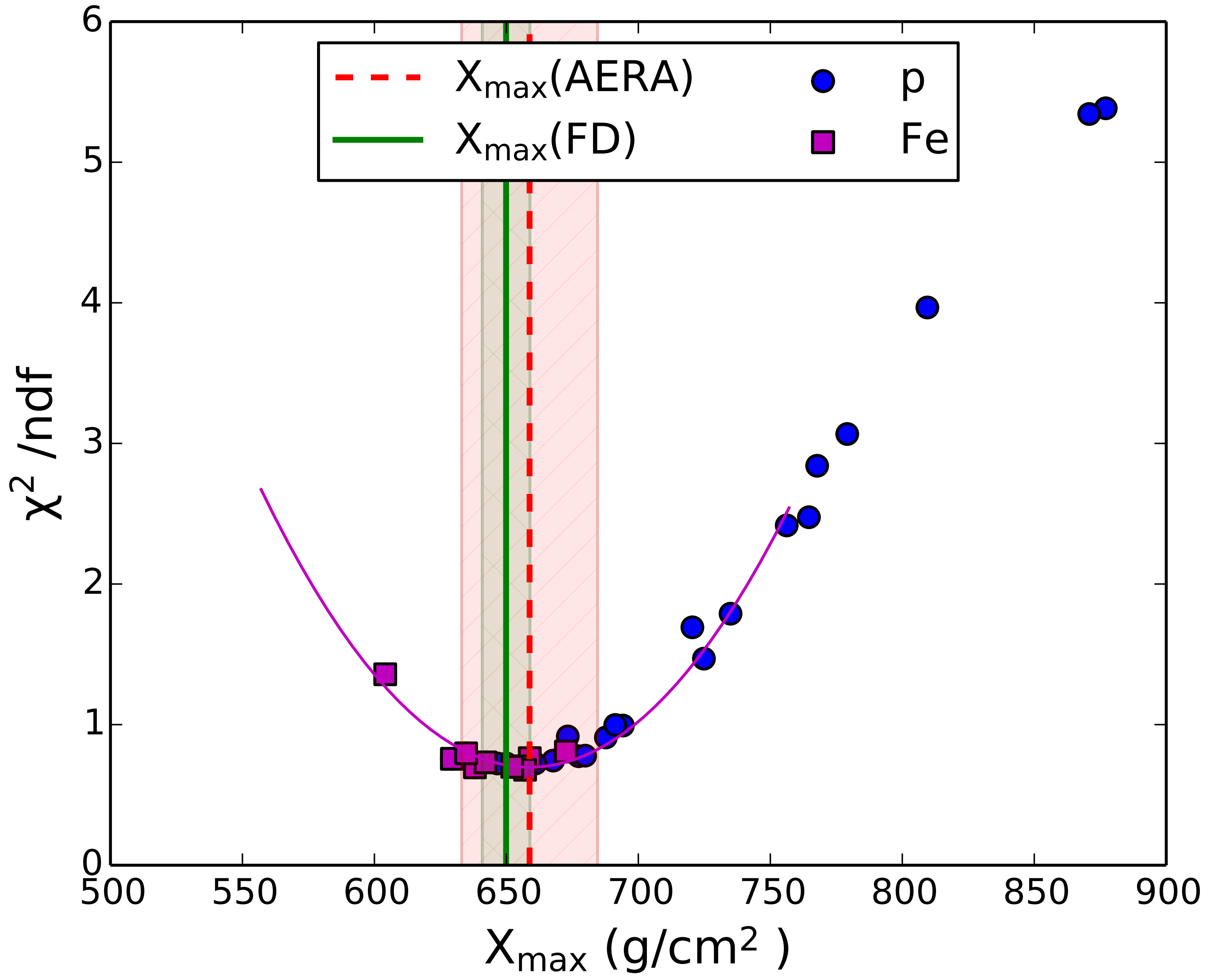
$$\ln A = \sum k_i \ln A_i$$

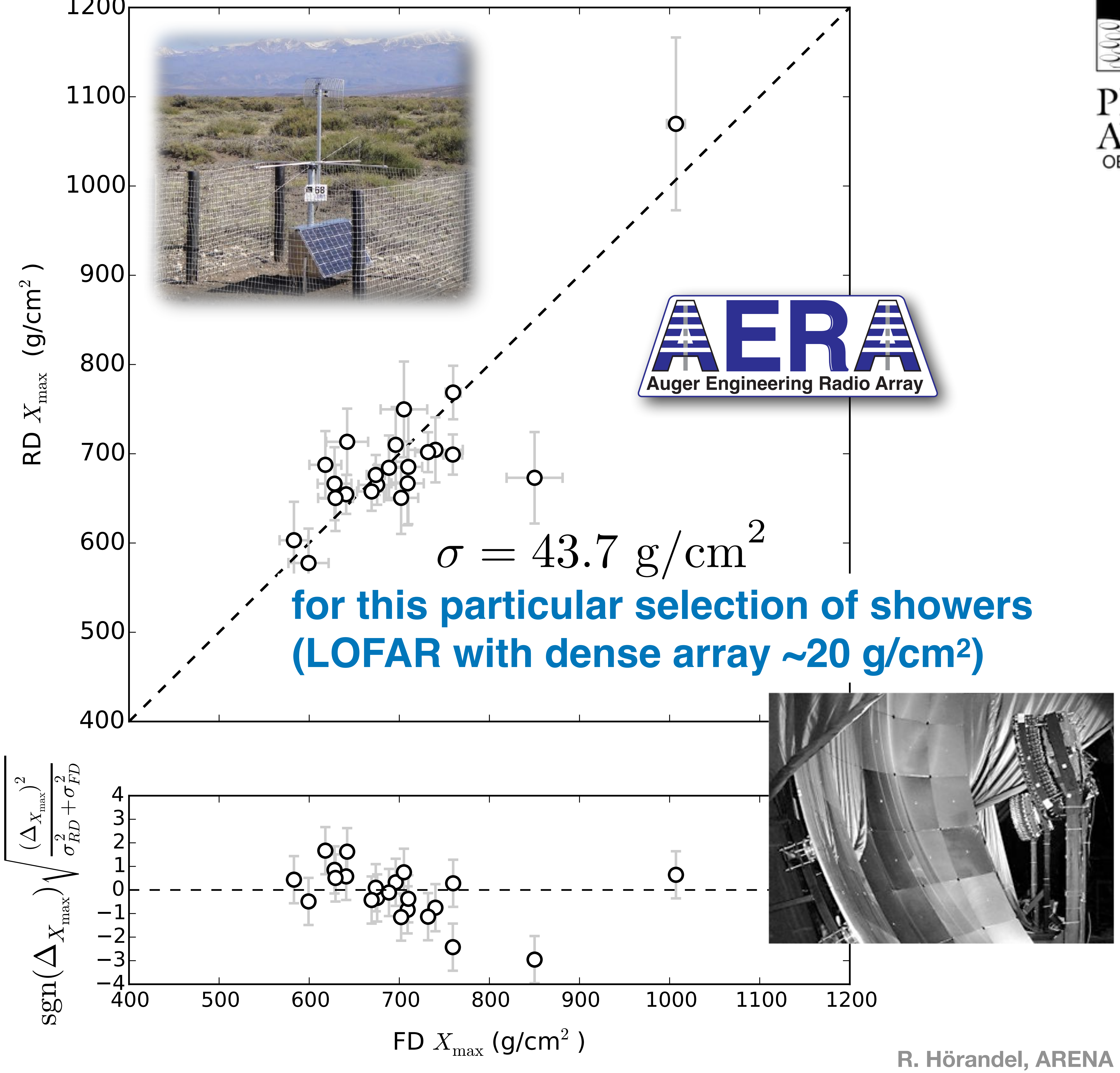


S. Thoudam et al., A&A 595 (2016) A33

Xmax radio vs fluorescence







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

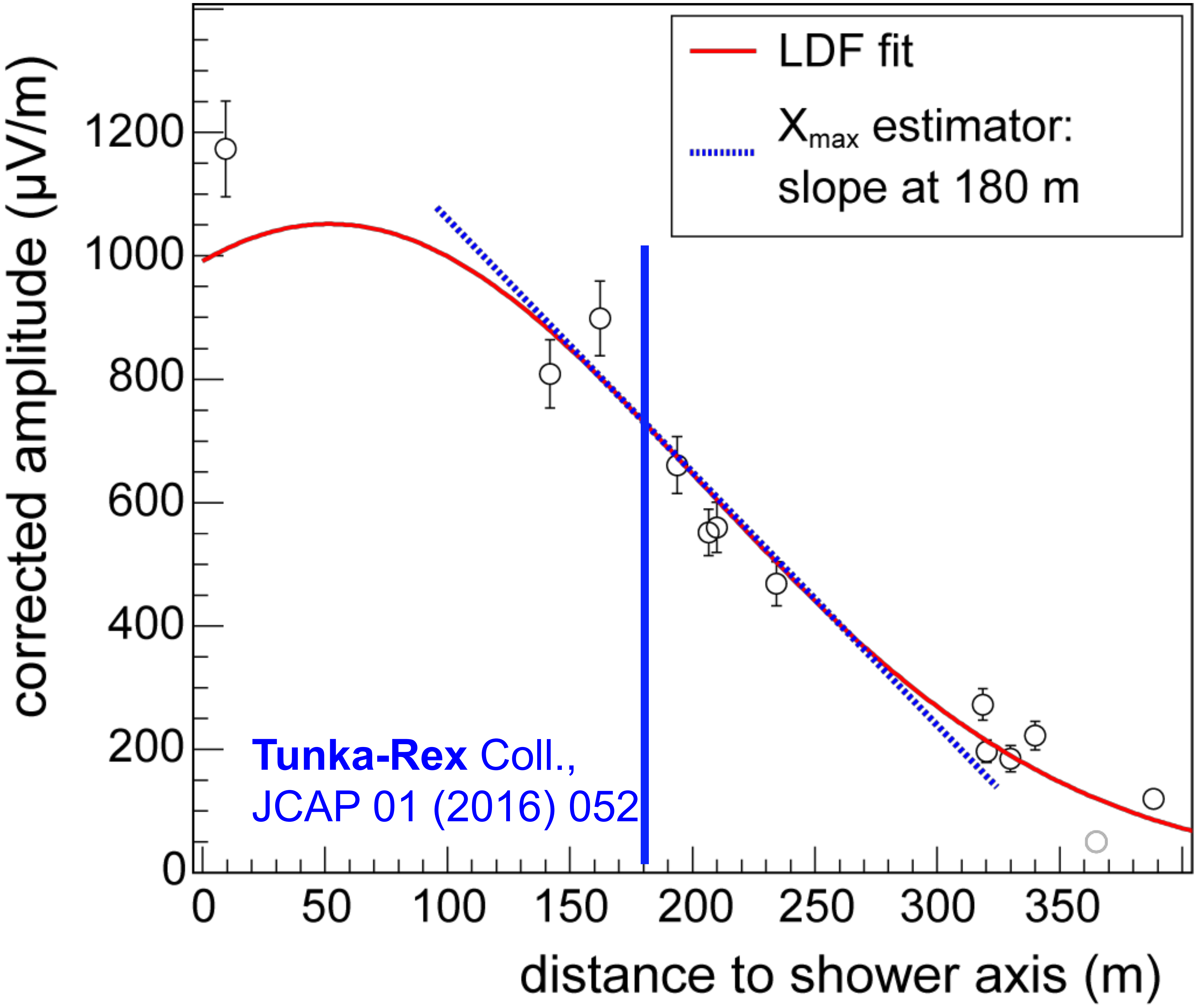
for this particular selection of showers
(LOFAR with dense array ~20 g/cm²)

PIERRE
AUGER
OBSERVATORY

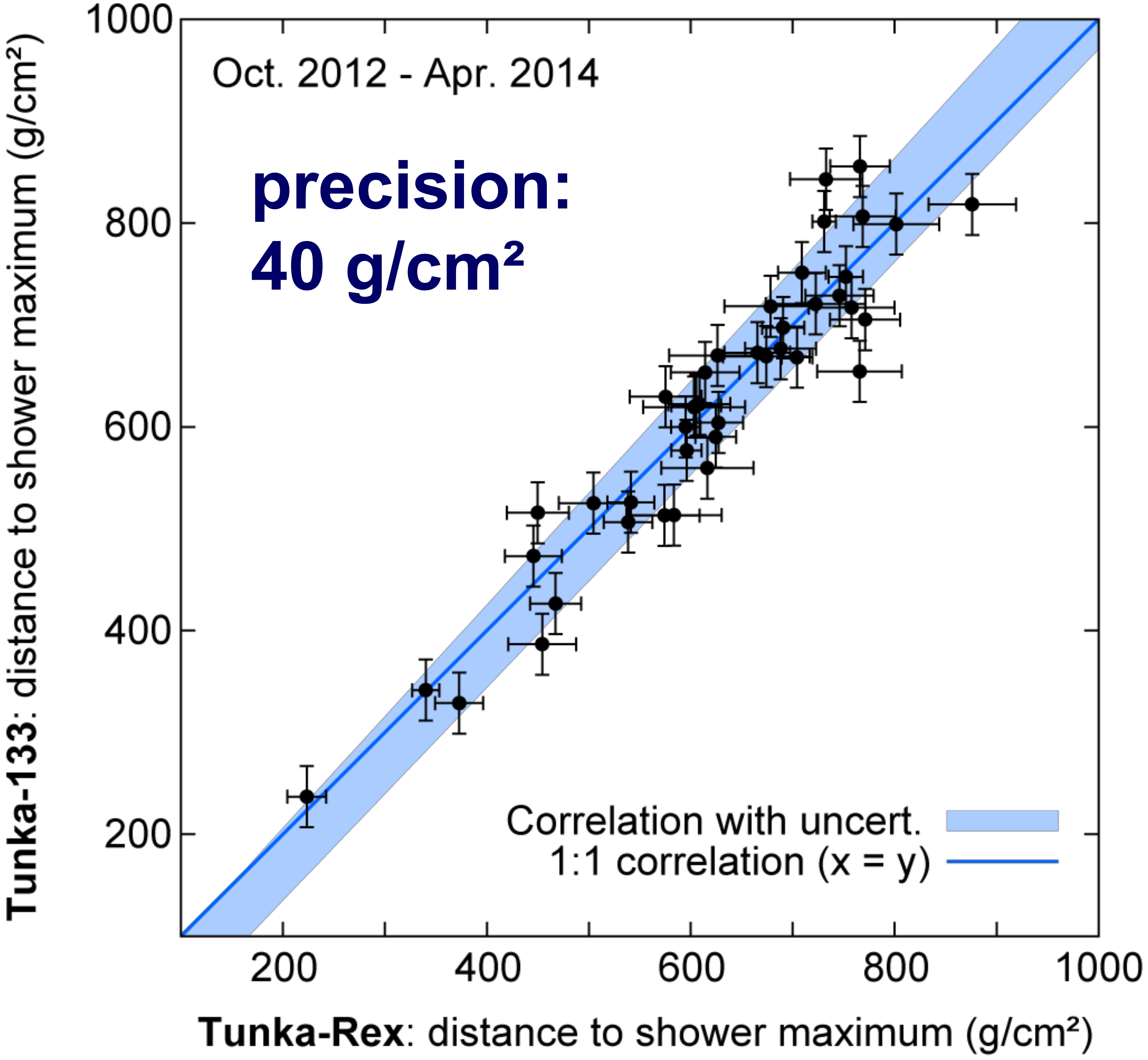
J. Schulz, PhD thesis RU Nijmegen (2016)

Shower maximum: proof by Tunka-Rex

- One of several methods: slope of lateral distribution



Tunka-Rex Coll., JCAP 01 (2016) 052



precision: 40 g/cm²

Determine the properties of the incoming particle with the radio technique

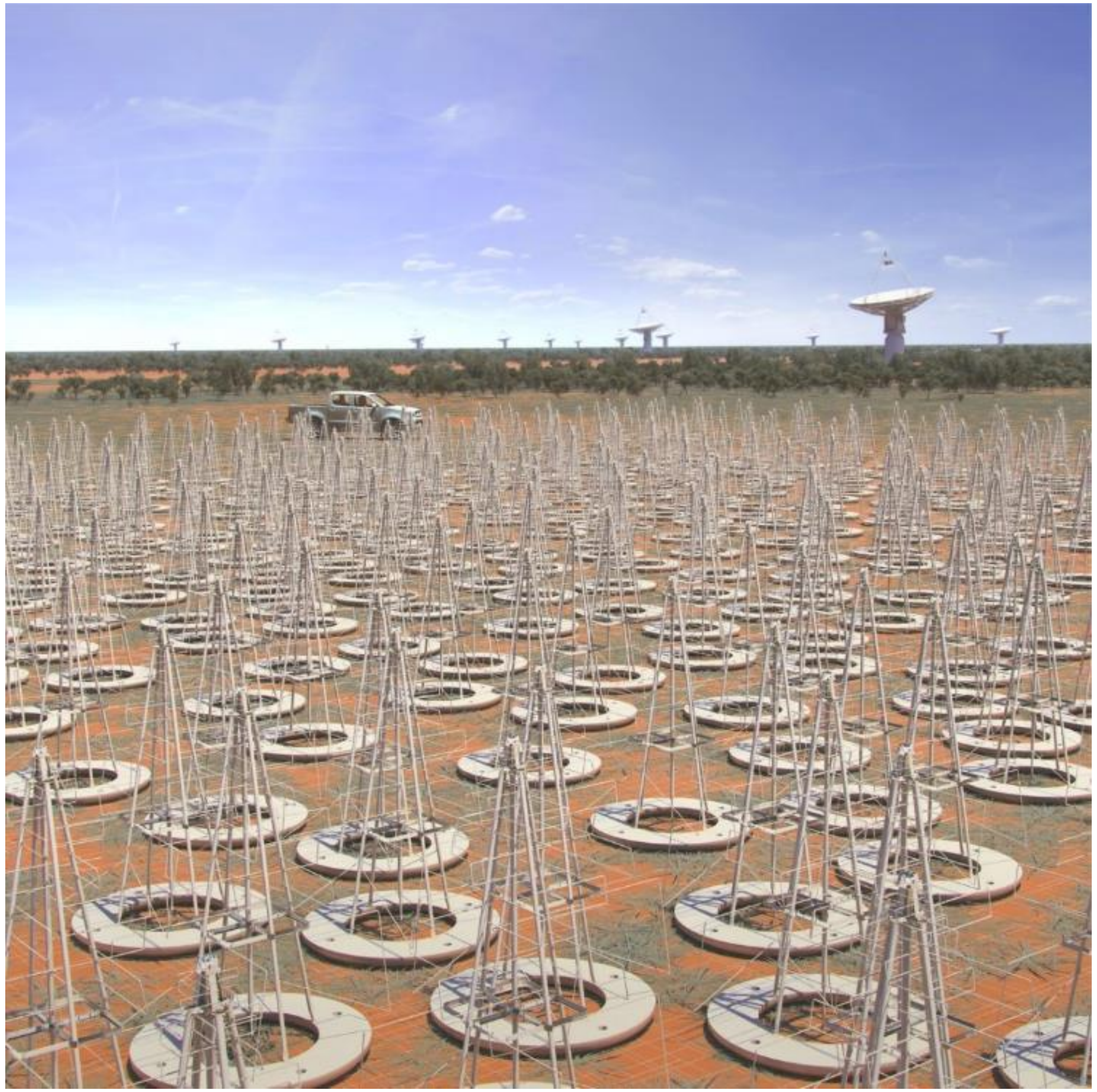
- direction ~ 0.1° - 0.5°
- energy ~ 20% - 30%
- type (X_{max}) ~ 20 - 40 g/cm^2

(depending on detector spacing)

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


The Future
NEXT EXIT

Square Kilometer Array (SKA) - dense array

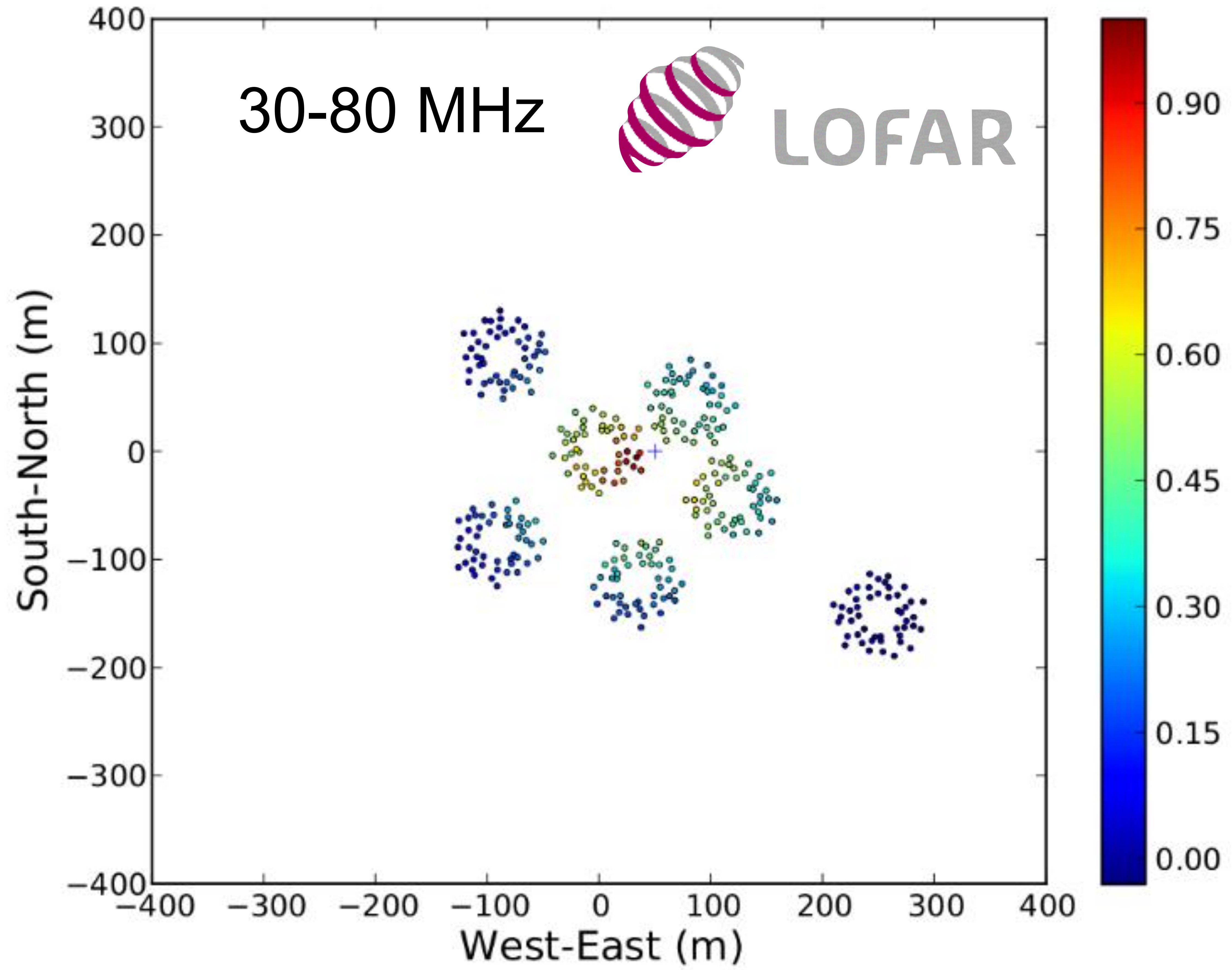


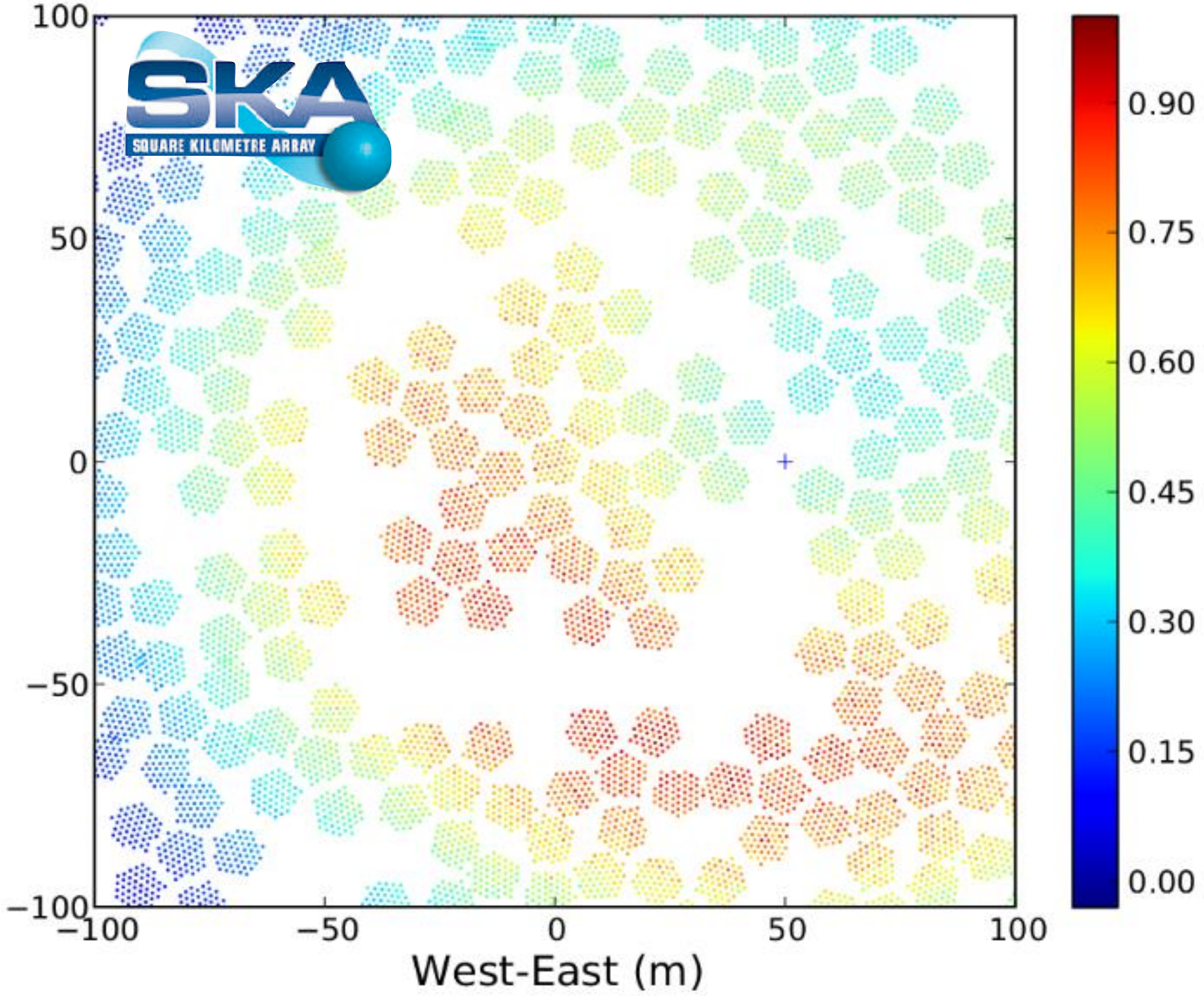
- in the final design stages
- to be built in western Australia
- first science 2020
- planned completion 2023
- >60,000 dual-polarized antennas within 750 m diameter
- bandwidth 50-350 MHz
- can be used for air shower detection with minor additions
- precision measurements in energy range of ~$10^{16.5}$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

TH et al., ARENA2016 conference, arXiv:1608.08869

Square Kilometer Array (SKA) - dense array

precision measurements of radio emission

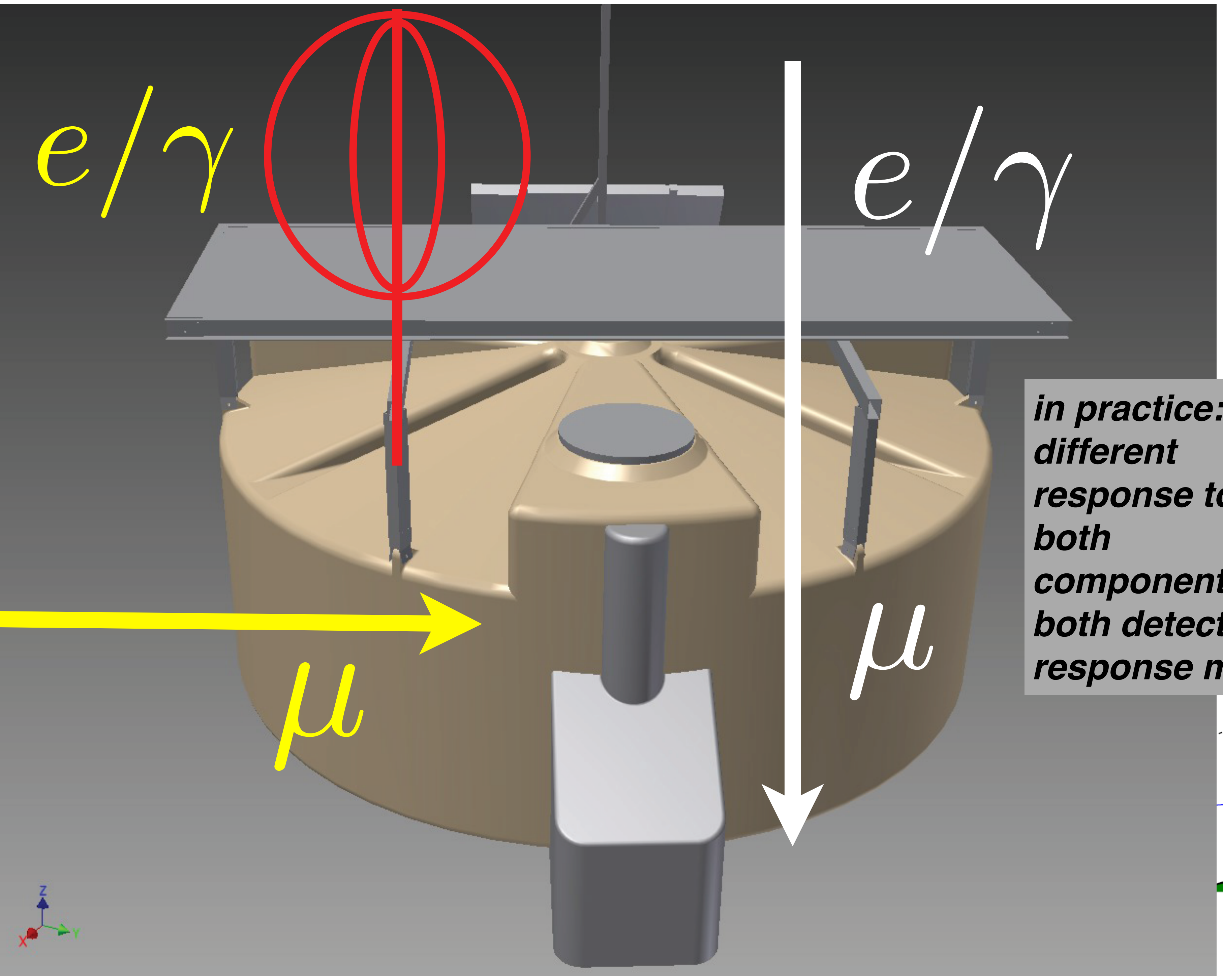




- **Xmax determination with well below 10 g/cm^2 resolution predicted by simulation study based on LOFAR reconstruction approaches**

A. Zilles et al., ARENA2016 conference

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



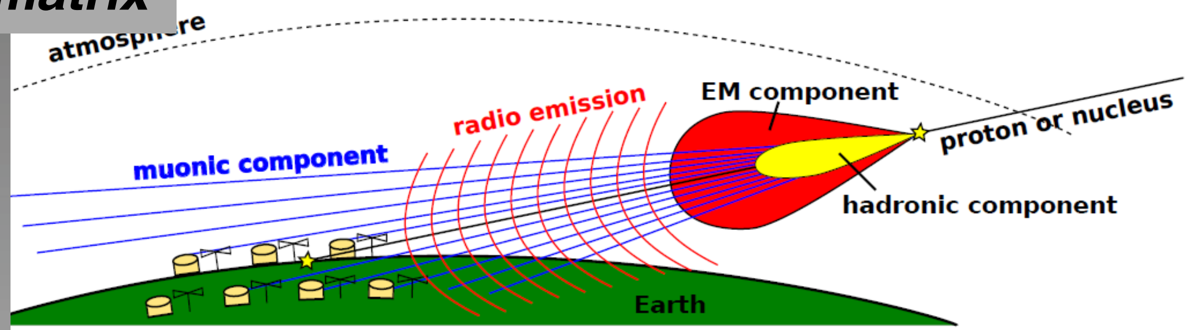
in practice: different response to both components in both detectors: response matrix

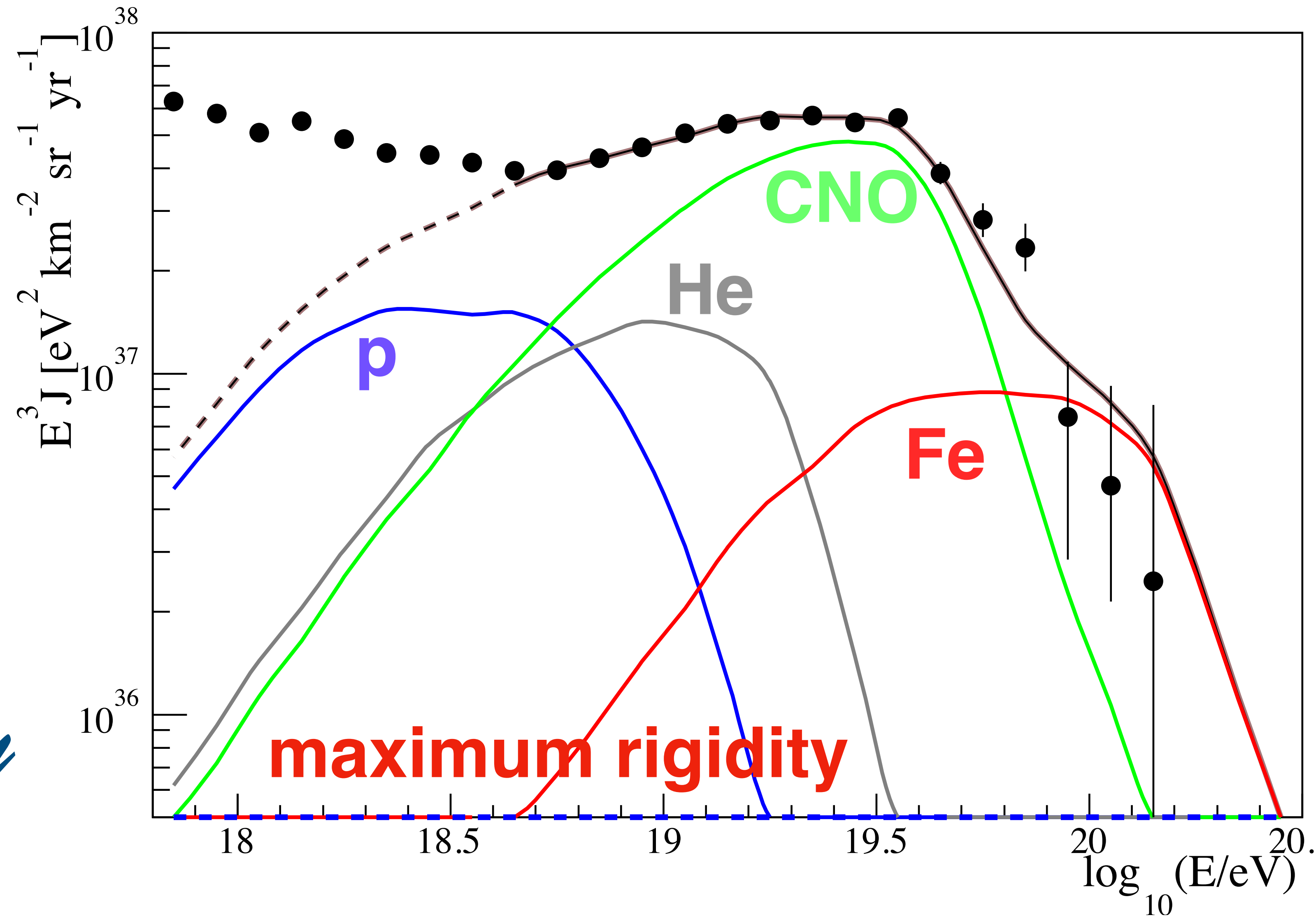
upgrade PAO

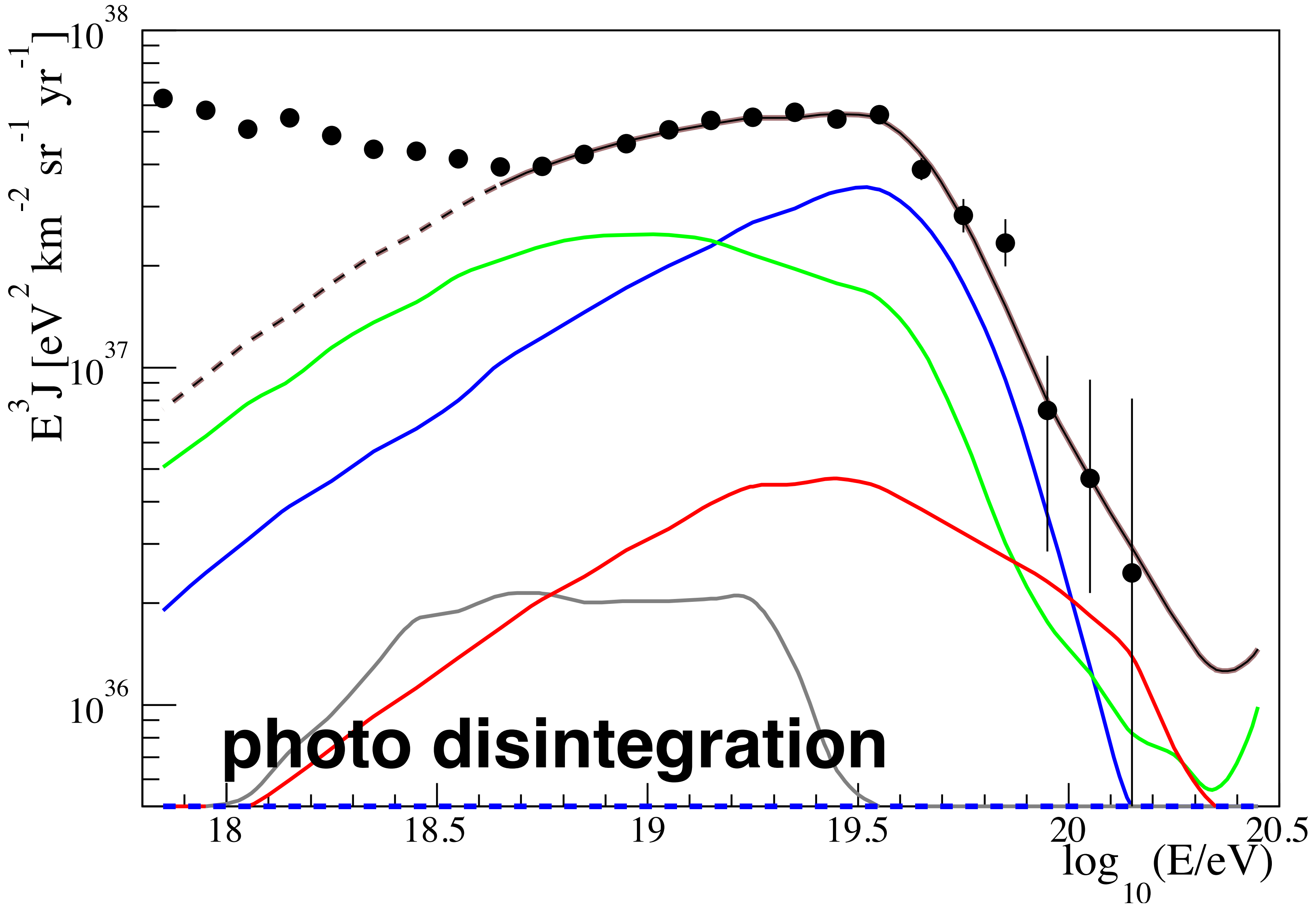
- electronics
- scintillator layer
- radio detector

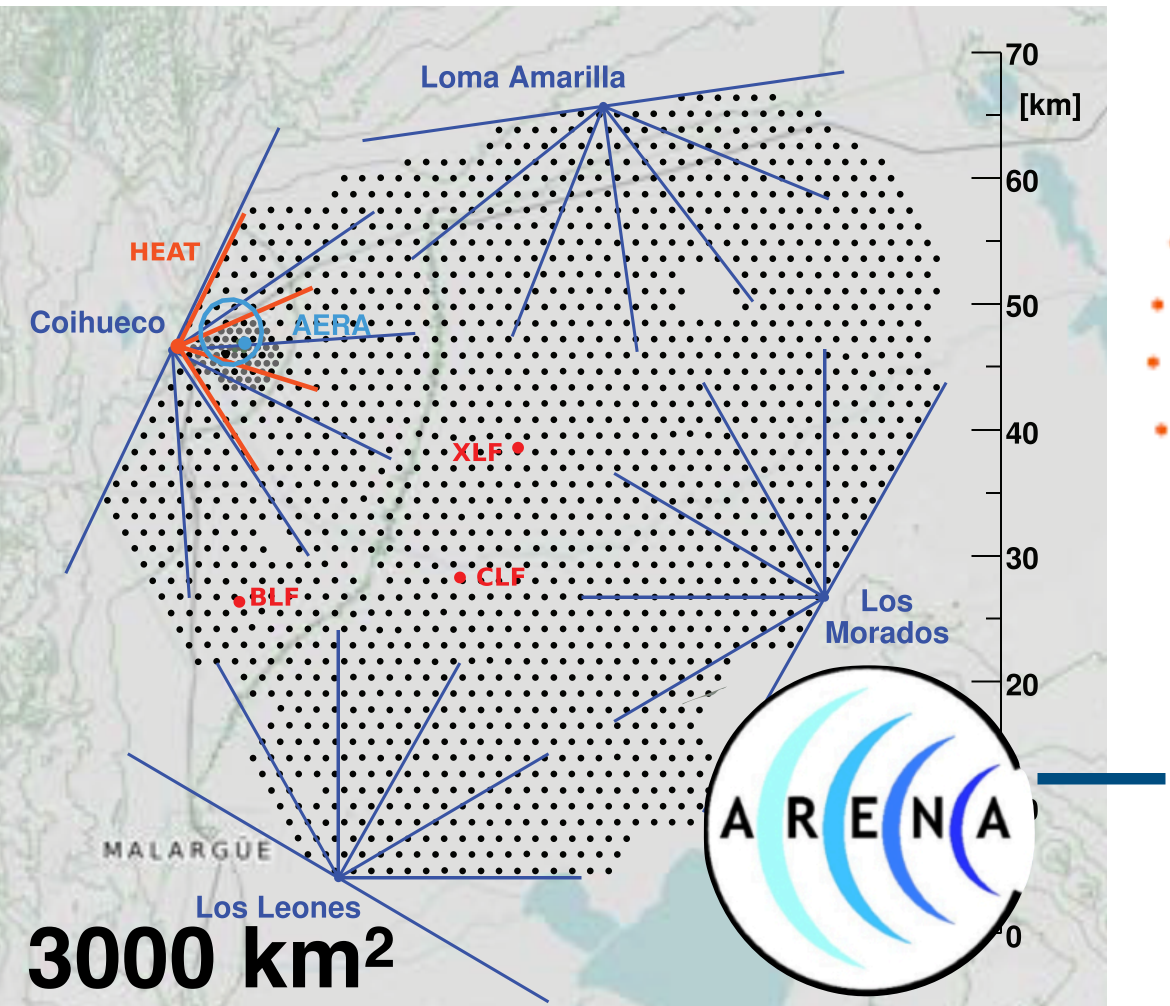
Key science questions

- 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?







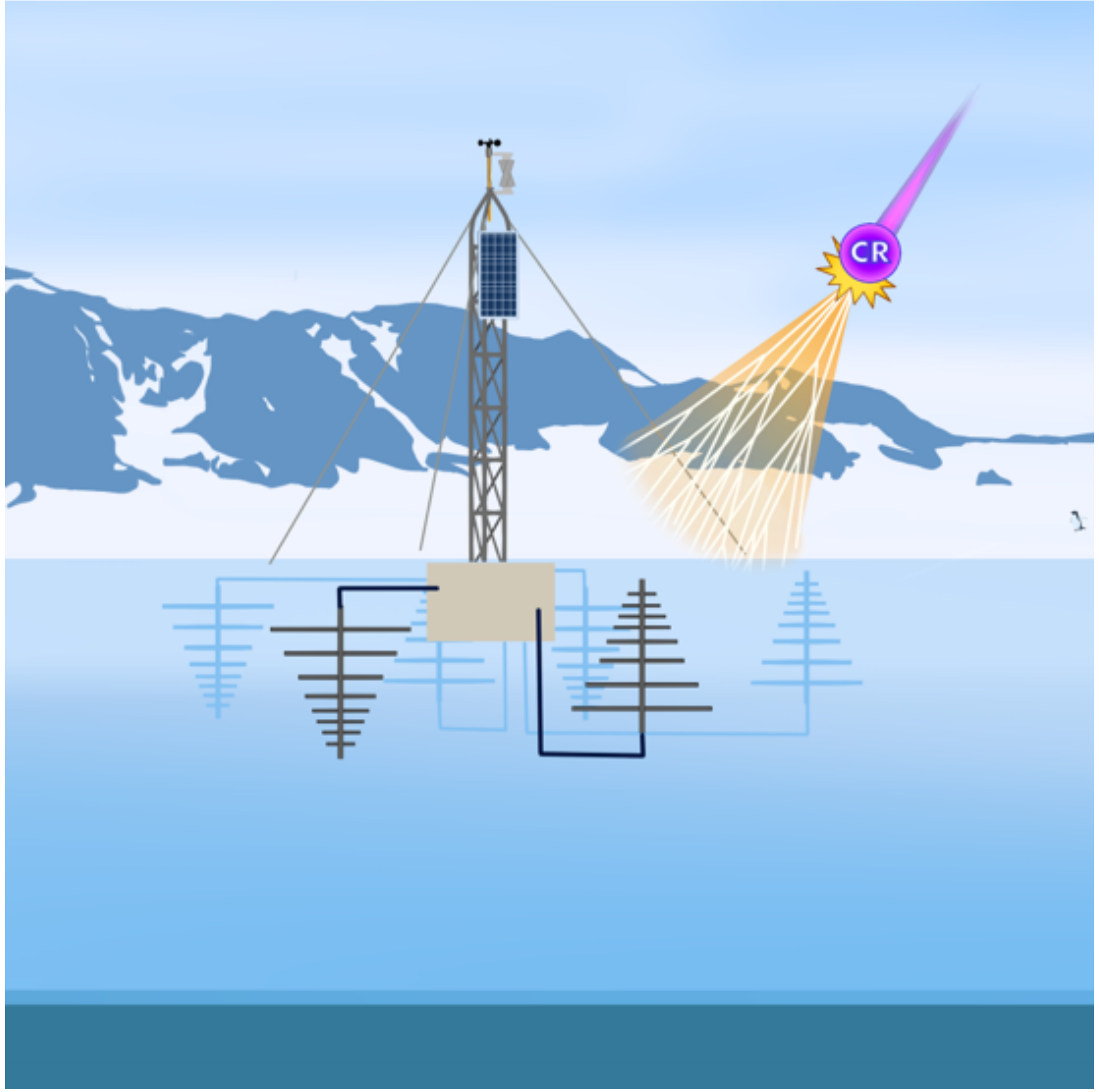


3000 km²

→ see talk by Hörandel

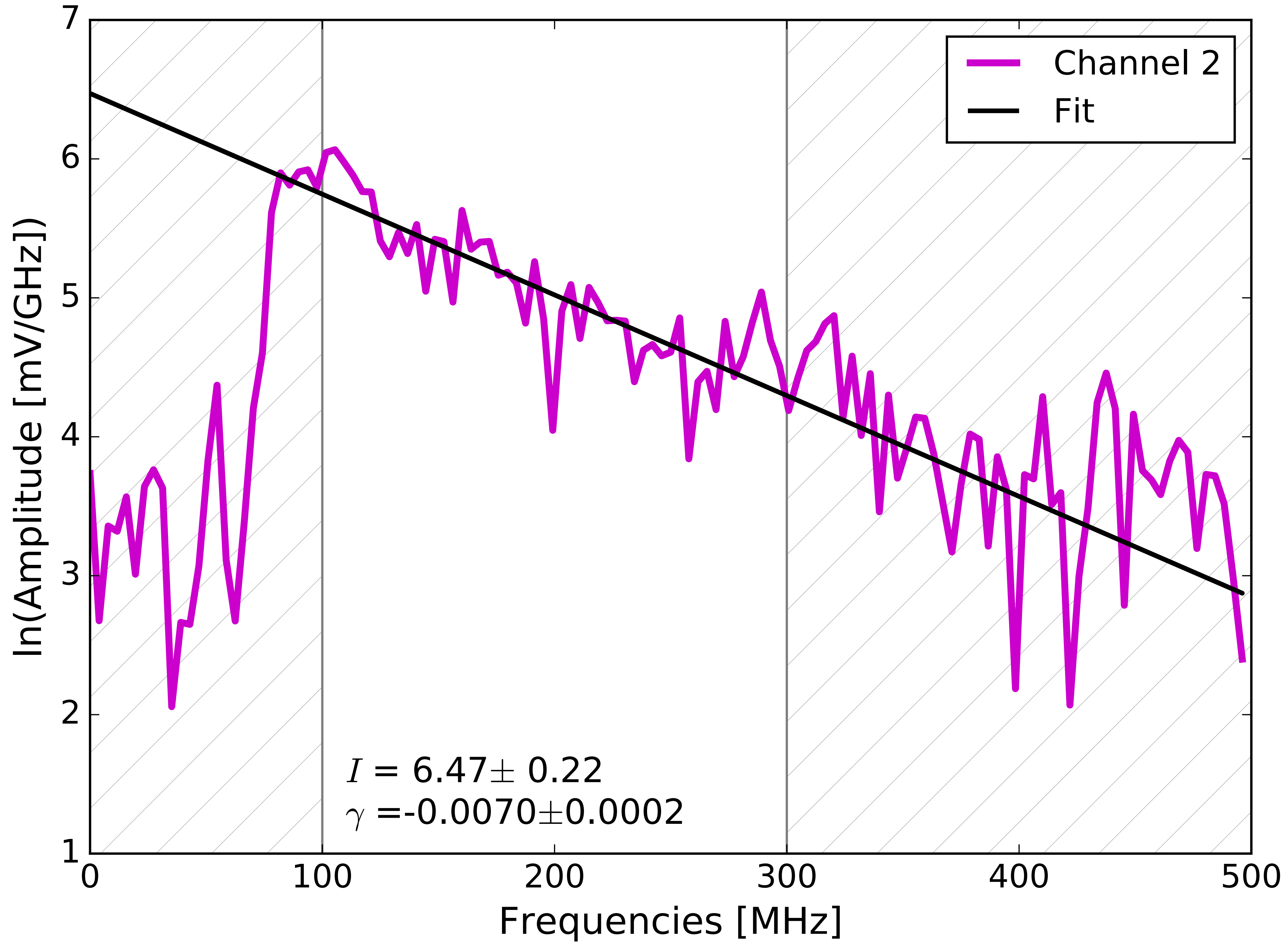
Concept of ARIANNA

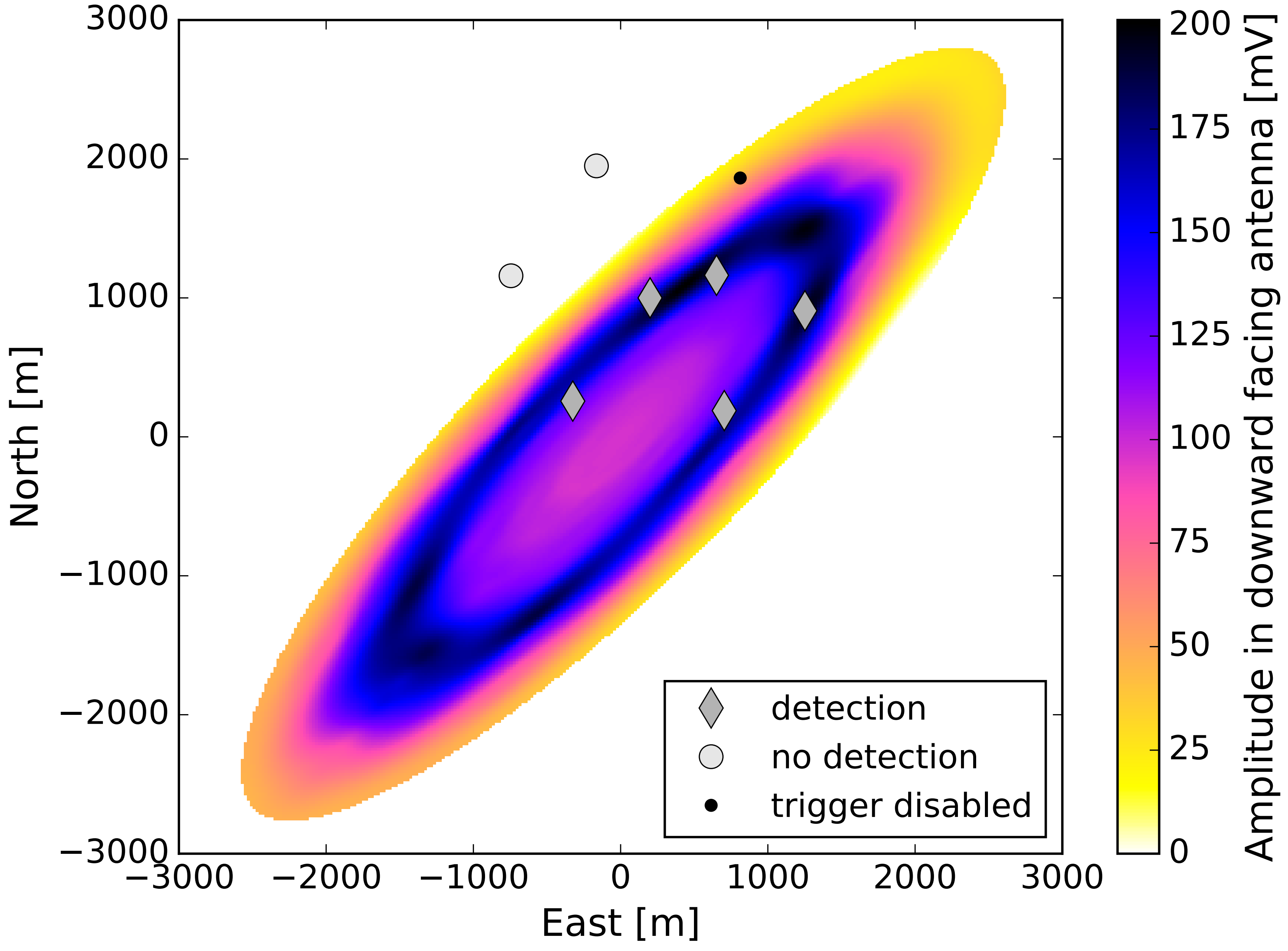
- On ice-shelf: **Ice-water boundary** almost perfect reflector for radio emission
- **Independent antenna stations** can be installed at low costs on the surface
- **Real-time data transfer** via satellite
- Solar and wind power possible
- **High gain antennas** (50 - 1000 MHz) can be used to instrument a large volume
- Array of about 1000 antennas needed



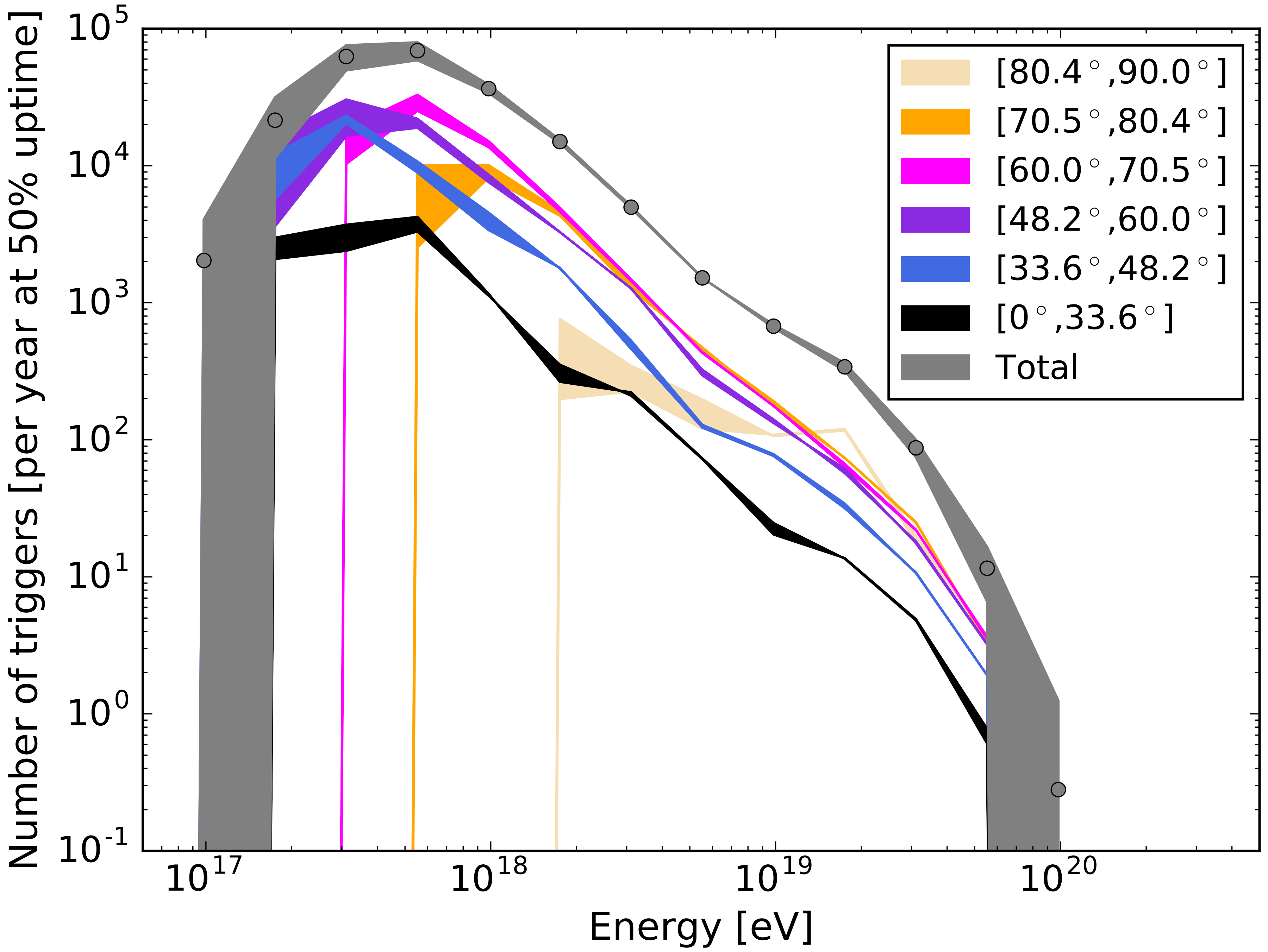
S.W. Barwick et al., Astropart.Phys. 90 (2017) 50

ARIANNA





use slope of measured frequency spectrum to derive energy and other shower parameters



full ARIANNA
36 km² x 36 km²
1296 km²

S.W. Barwick et al., Astropart.Phys. 90 (2017) 50

Cosmogenic neutrinos

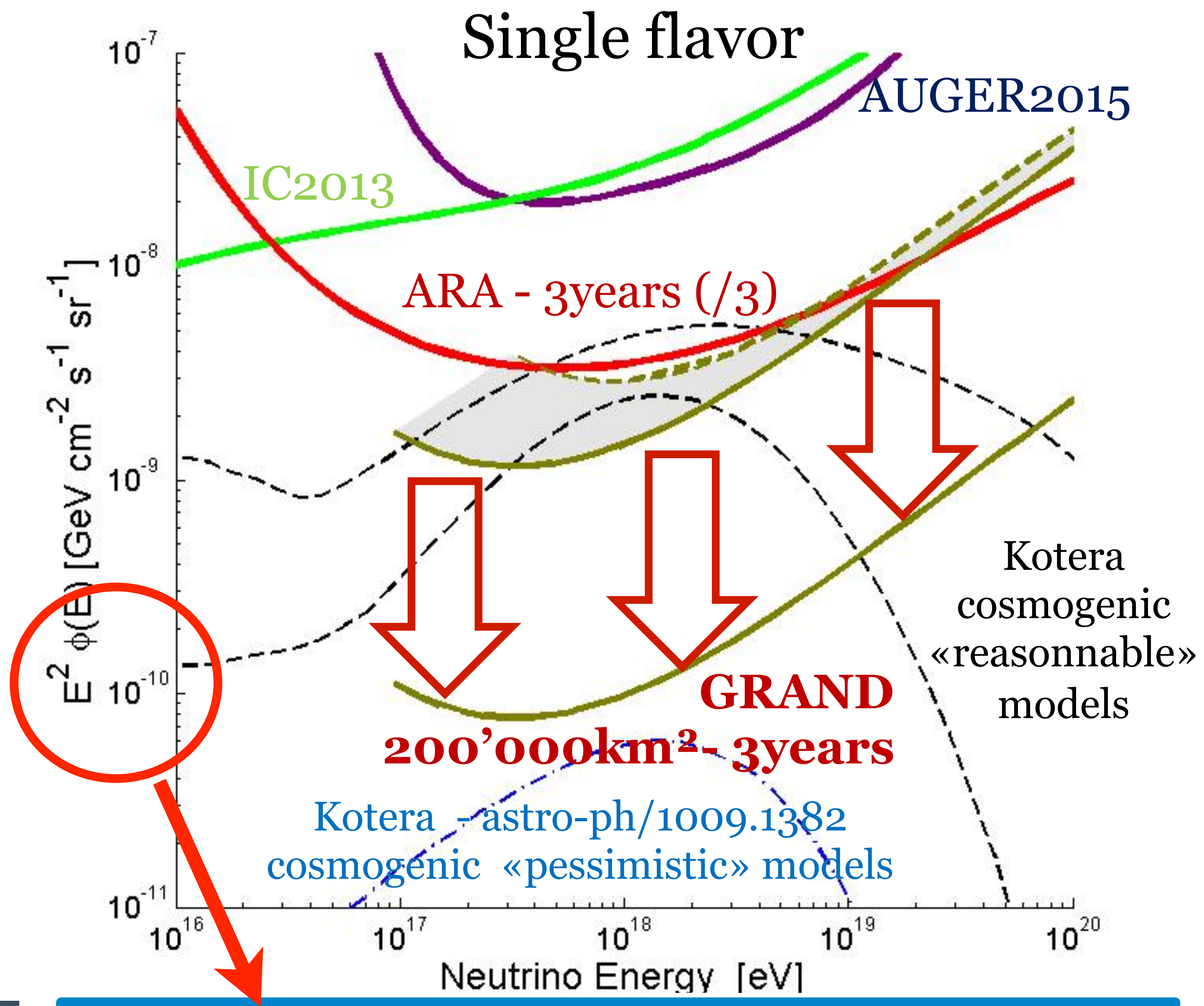
- GZK neutrinos above $10^{19.5}$eV:

$p+\gamma_{CMB} \longrightarrow \Delta^+ \longrightarrow \pi^+ + n$

$\pi^+ \longrightarrow l + \nu_l$

Guaranteed flux.

Great tool to study UHECRs.

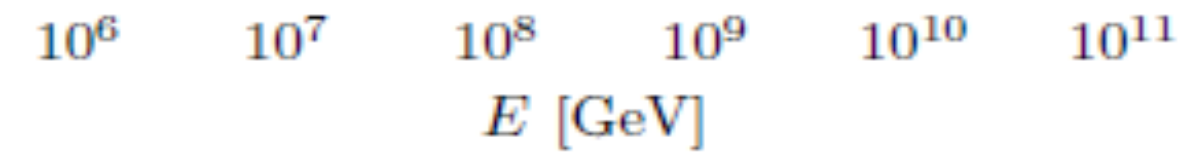


$\sim 10^{-10}$ GeV cm^{-2} s^{-1} sr^{-1}

Output of GRAND 1st workshop (LPNHE, Feb. 2015):

GRAND should GUARANTEE detection of cosmogenic neutrinos (and rate of several tens/year for reasonnable models)

a GIANT array may be technically & financialy feasable!
... How well would it perform?



Next-generation cosmic-ray experiment

if upgraded PAO finds p-fraction >10%

--> source hunting

Key science questions

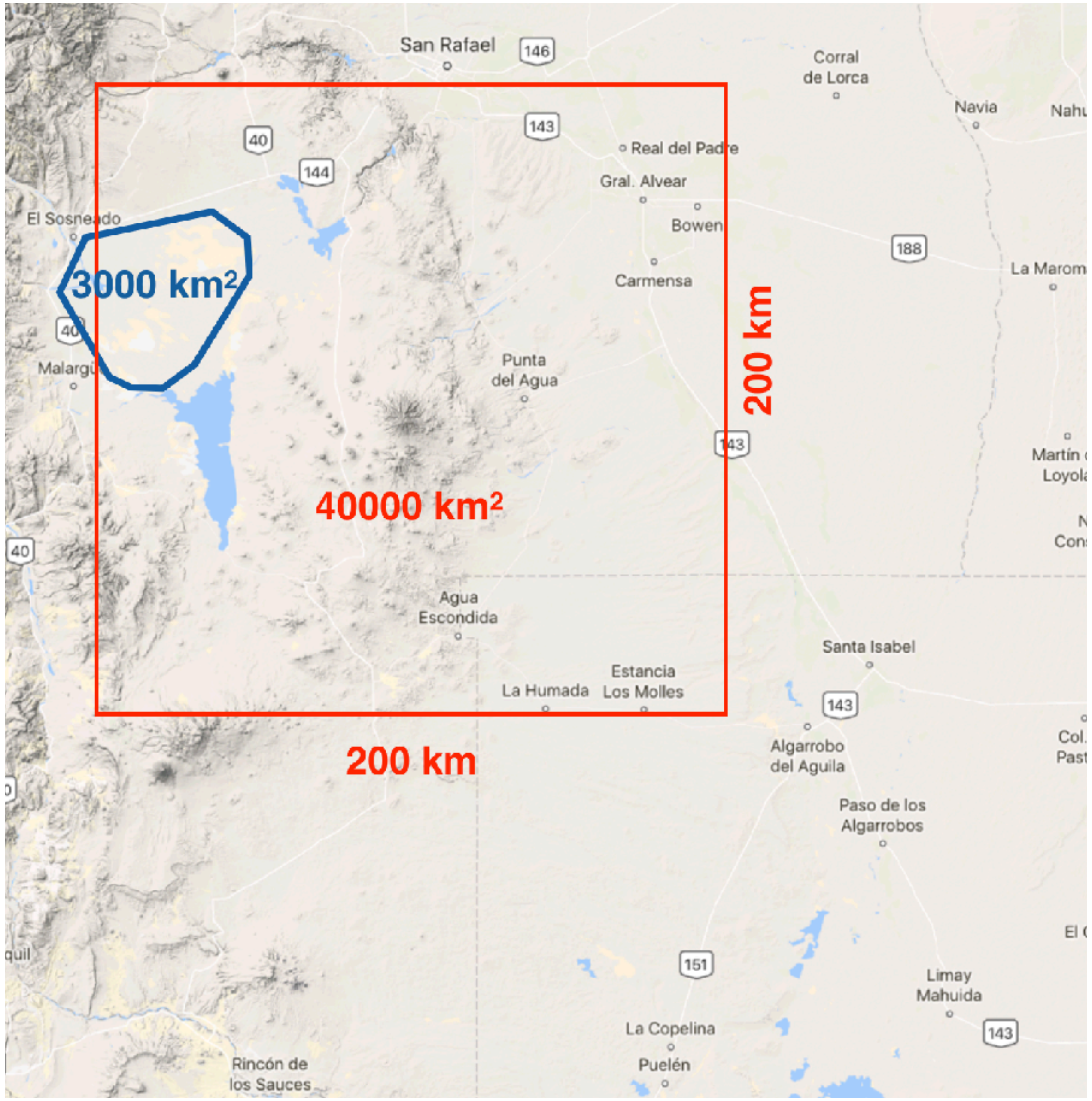
- **isolate protons**
- **proton astronomy**
- **identify sources of CRs**
- **neutrino + photon searches**
- **particle physics**

40000 km² (>10 times PAO)

2 km spacing

--> 10000 detectors

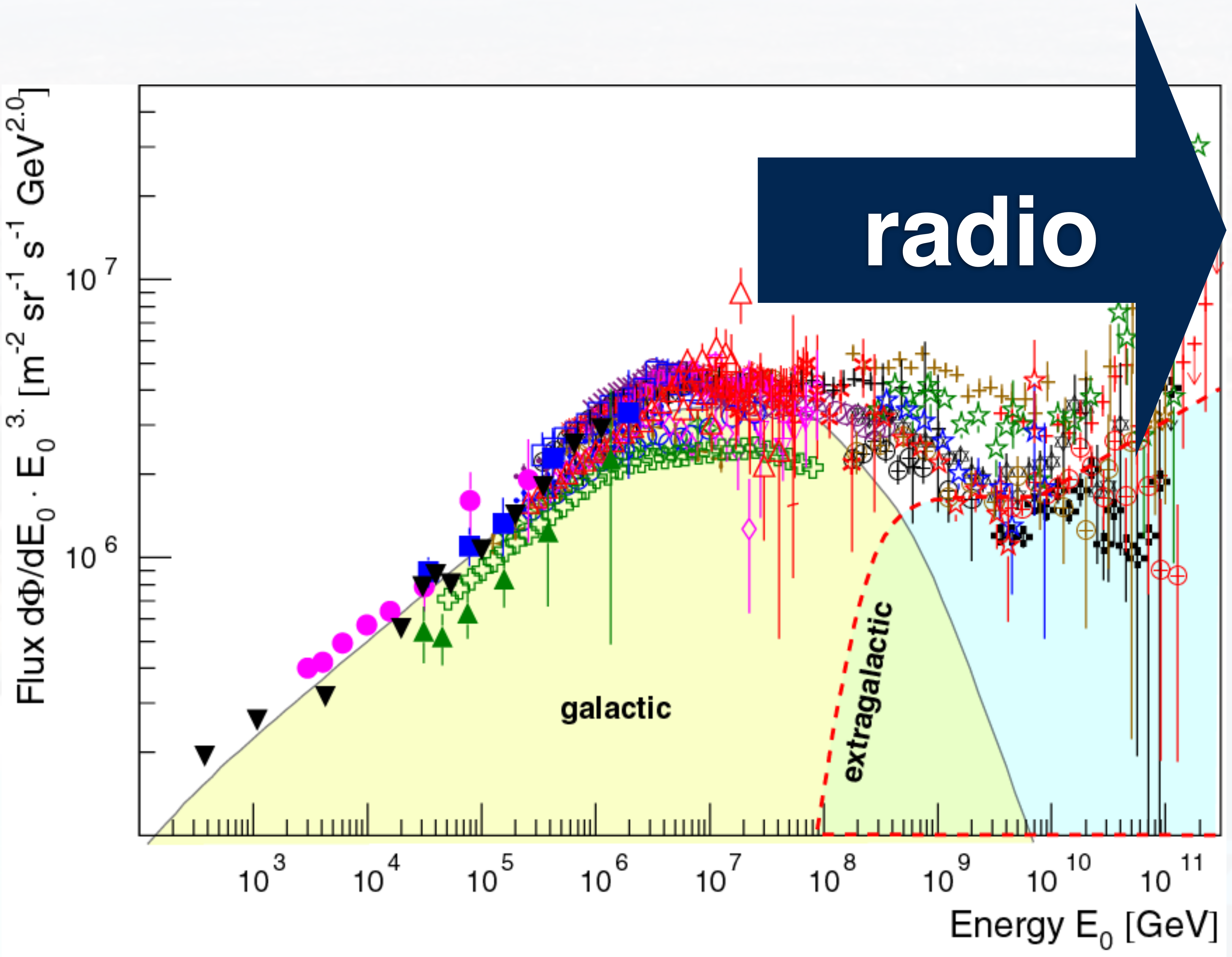
~120 M€



Radio Detection of Extensive Air Showers

Measurements of the properties of cosmic rays with the radio technique

Past - Present - Future

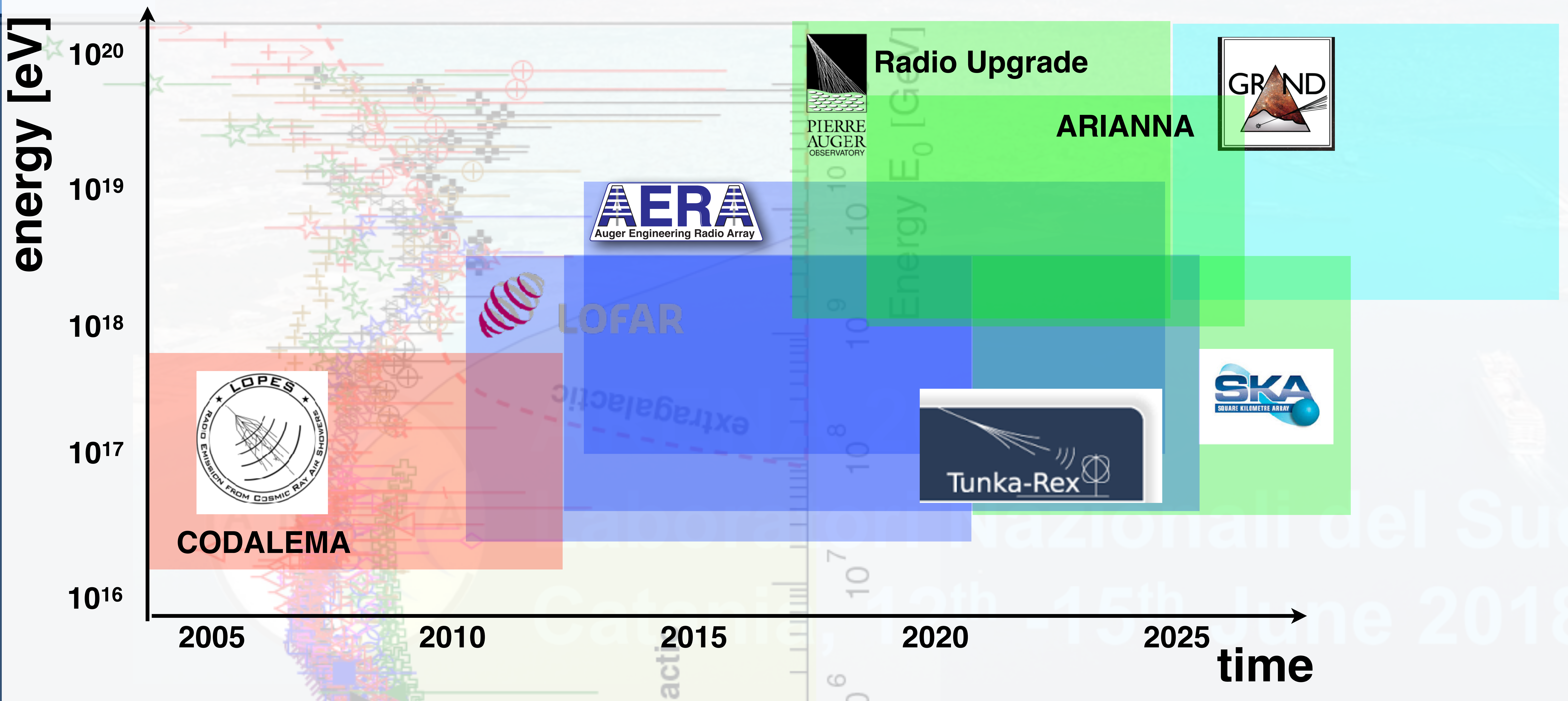


zionali del Sud
Catania, 12th -15th June 2018

Radio Detection of Extensive Air Showers

Measurements of the properties of cosmic rays with the radio technique

Past - Present - Future



Radio Detection of Extensive Air Showers

Measurements of the properties of cosmic rays with the radio technique

Past - Present - Future

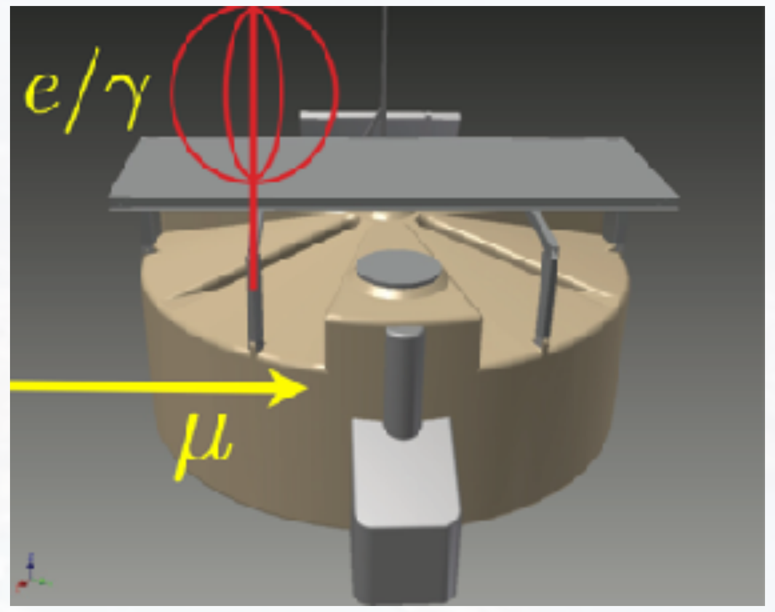
2018: Advanced Grant *Hörandel*
large-scale CR radio detection at PAO (3000 km²)

2014: Starting Grant *Buitink*
CR radio detection at LOFAR

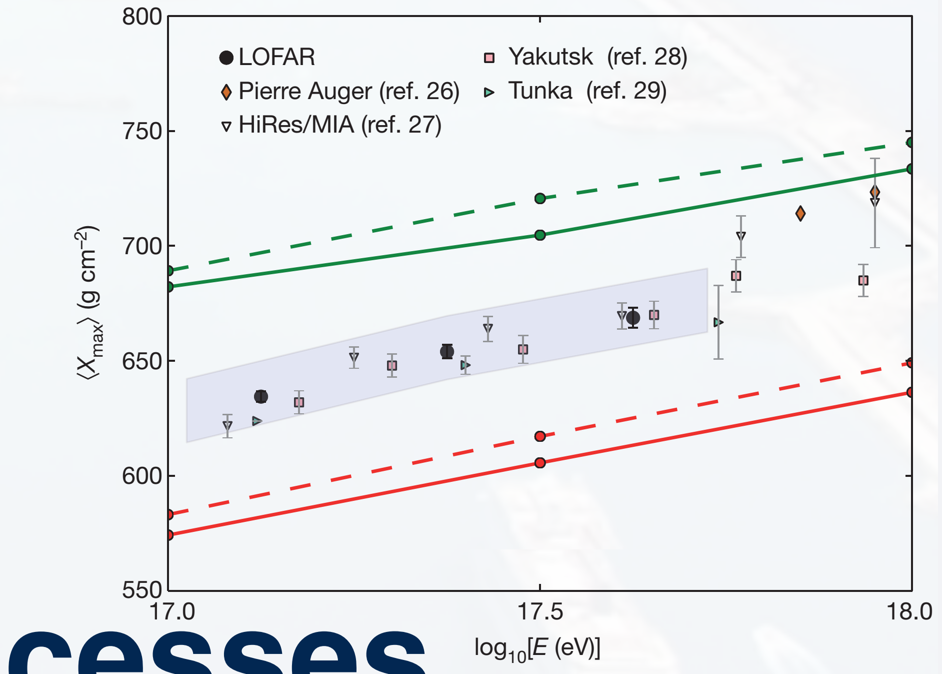
2008: Advanced Grant *Falcke*
principles of CR radio detection at PAO (17 km²)

huge progress in last decade

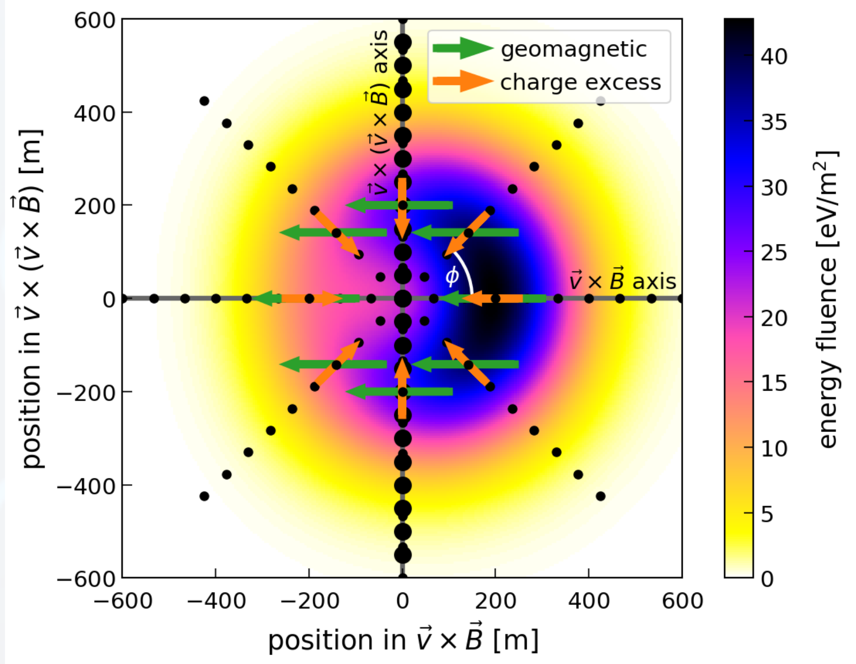
2018: beyond capabilities of standard installations



2016: radio technique mature: properties of cosmic rays



2014: understanding the emission processes



2011: endpoint formalism

2005: understanding the radio signal