Radio detection of extensive air showers

Precision measurements of the properties of cosmic rays

«ETTORE MAJORANA» FOUNDATION AND CENTRE FOR SCIENTIFIC CULTURE

INTERNATIONAL SCHOOL OF COSMIC-RAY ASTROPHYSICS
«MAURICE M. SHAPIRO»

22nd Course: "From cosmic particles to gravitational waves: now and to come"
30 July – 7 August 2022

PRESIDENT AND DIRECTOR OF THE CENTRE: PROFESSOR A. ZICHICHI

DIRECTORS OF THE COURSE: PROFESSORS J.P. WEFEL, T. STANEV, J.R. HÖRANDEL

Jörg R. Hörandel RU Nijmegen, Nikhef, VU Brussel http://particle.astro.ru.nl

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characterize cosmic rays:
-direction
-energy
-mass
@100% duty cycle

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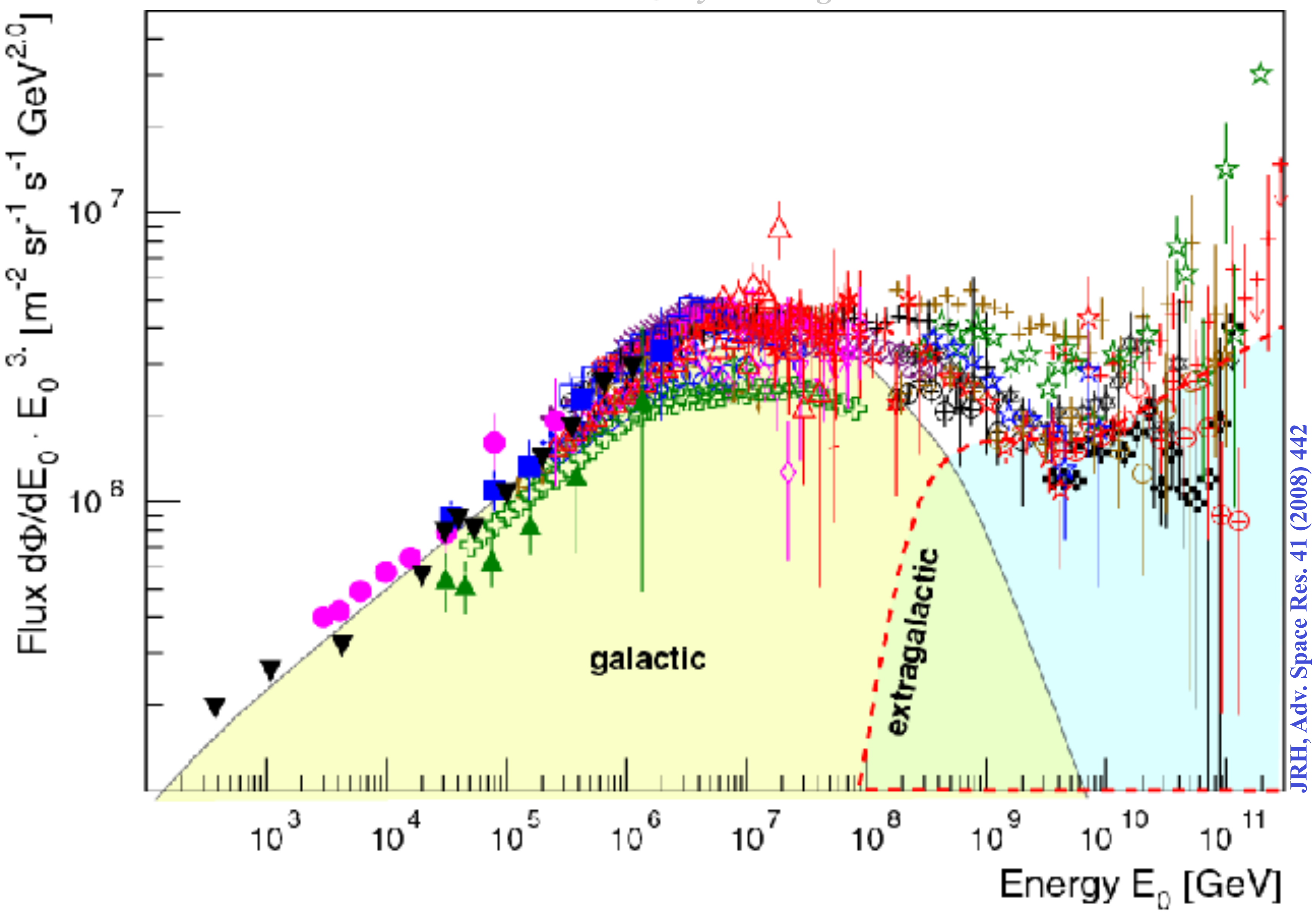

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-direction
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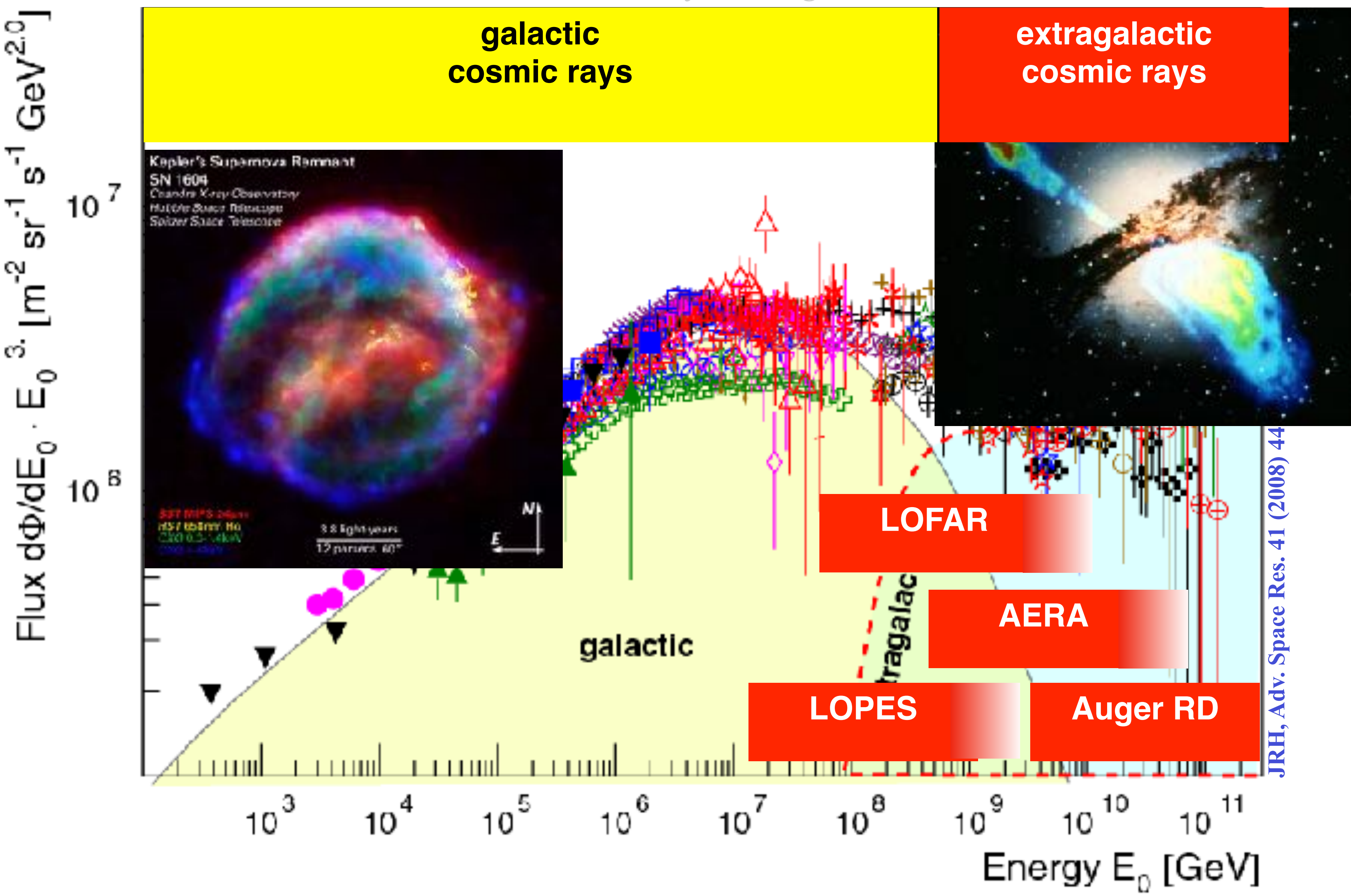

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- -direction
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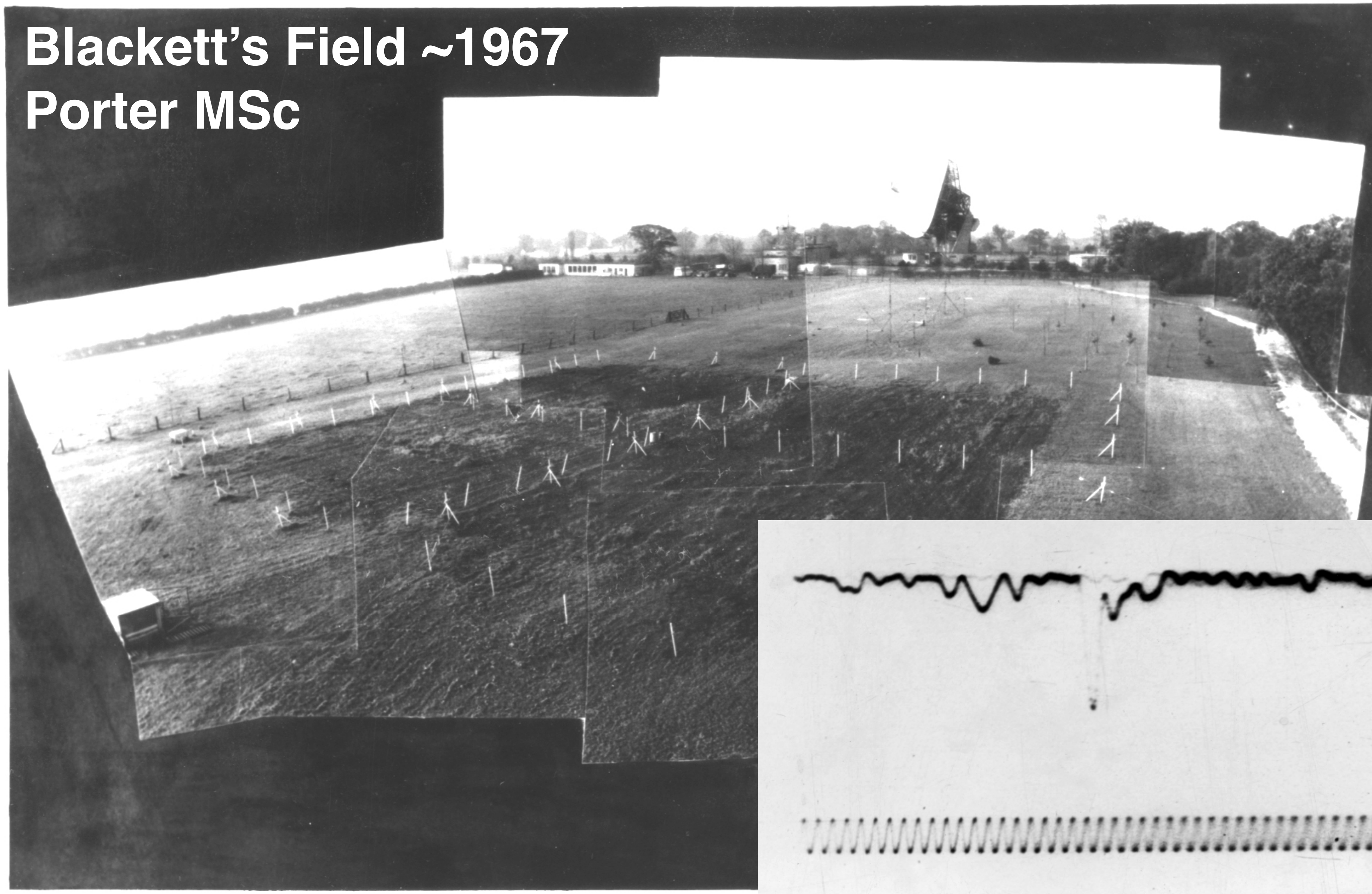
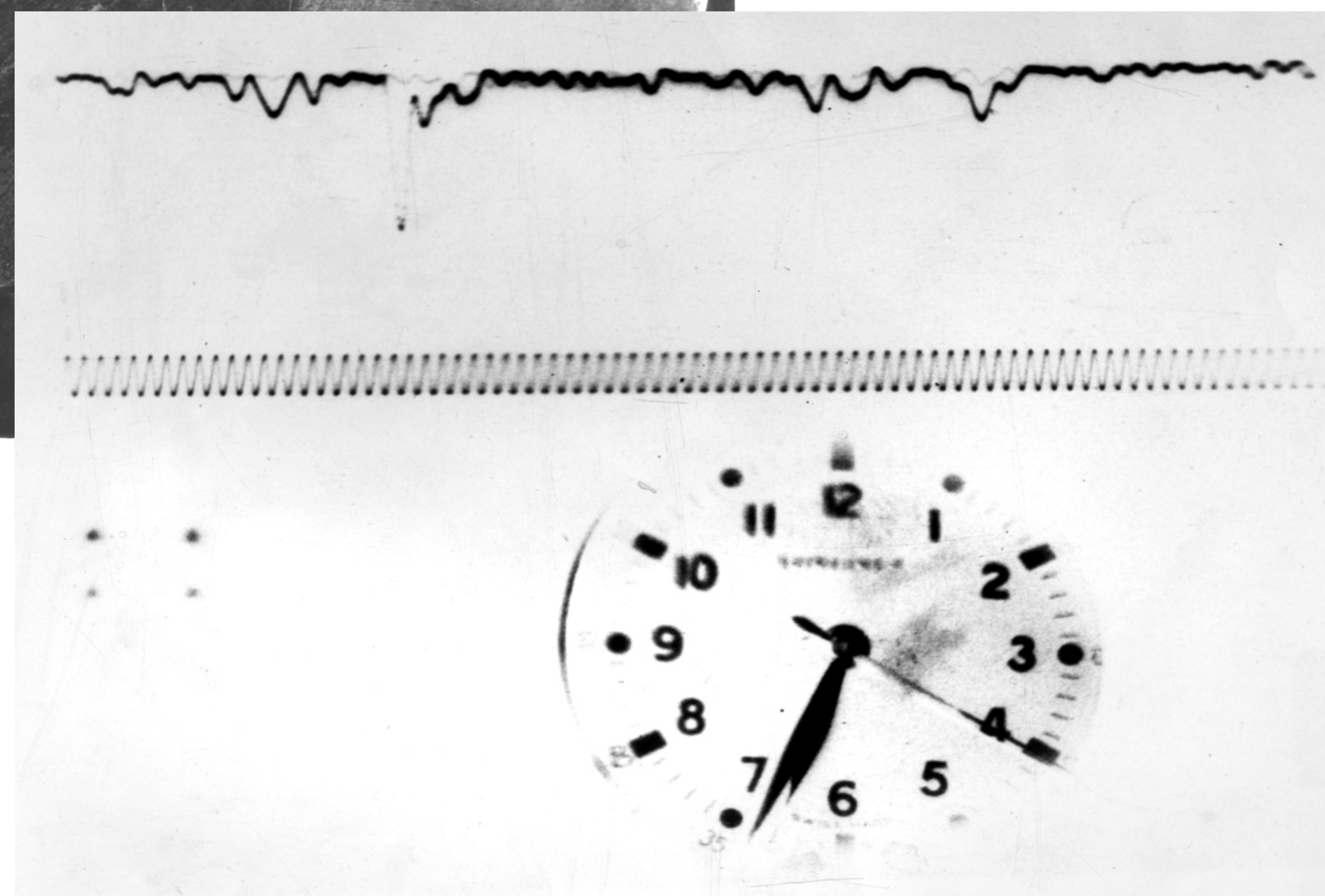
@100% duty cycle

Jörg R. Hörandel RU Nijmegen, Nikhef, VU Brussel http://particle.astro.ru.nl

First radio detection of air showers 1965

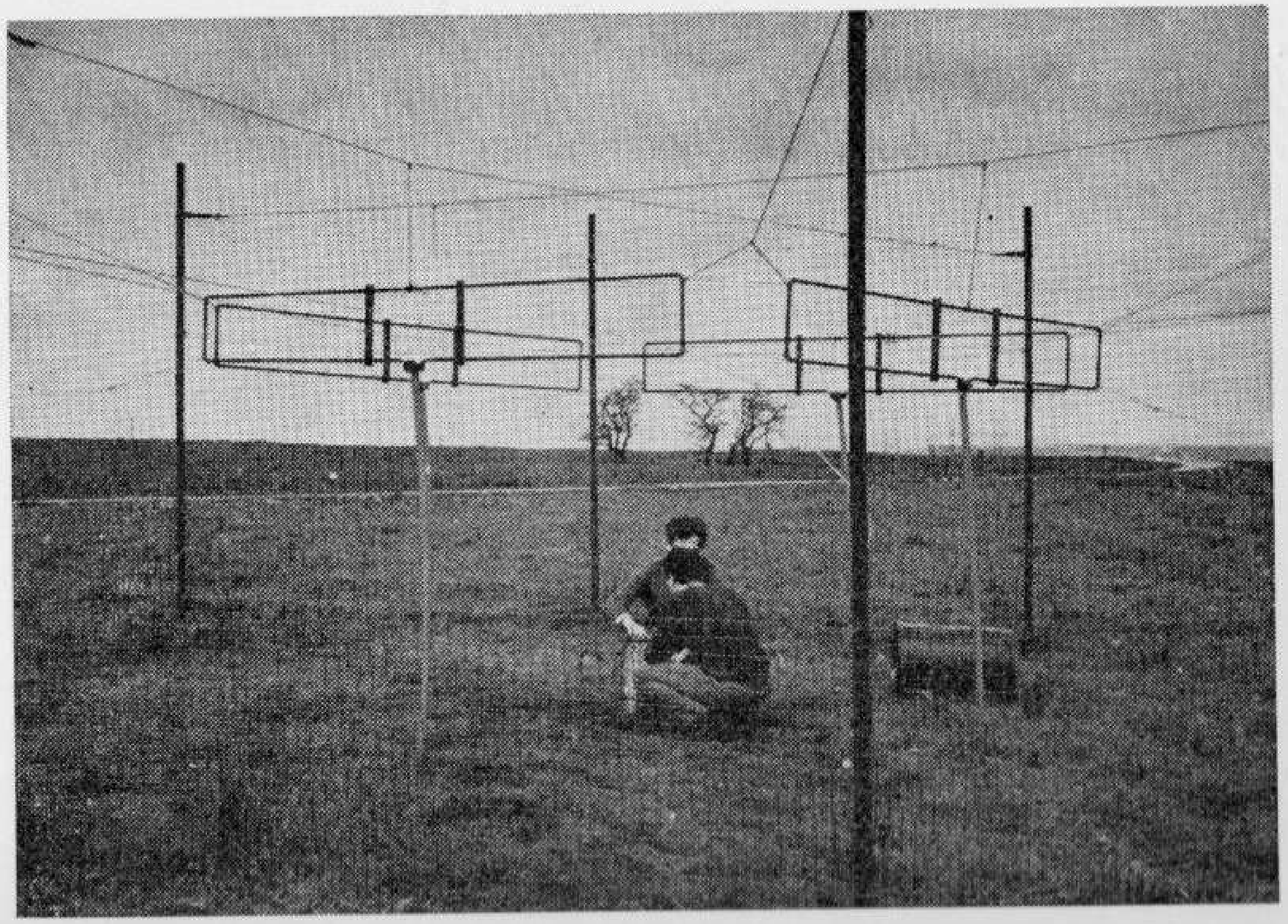
First radio detection of air showers 1965





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

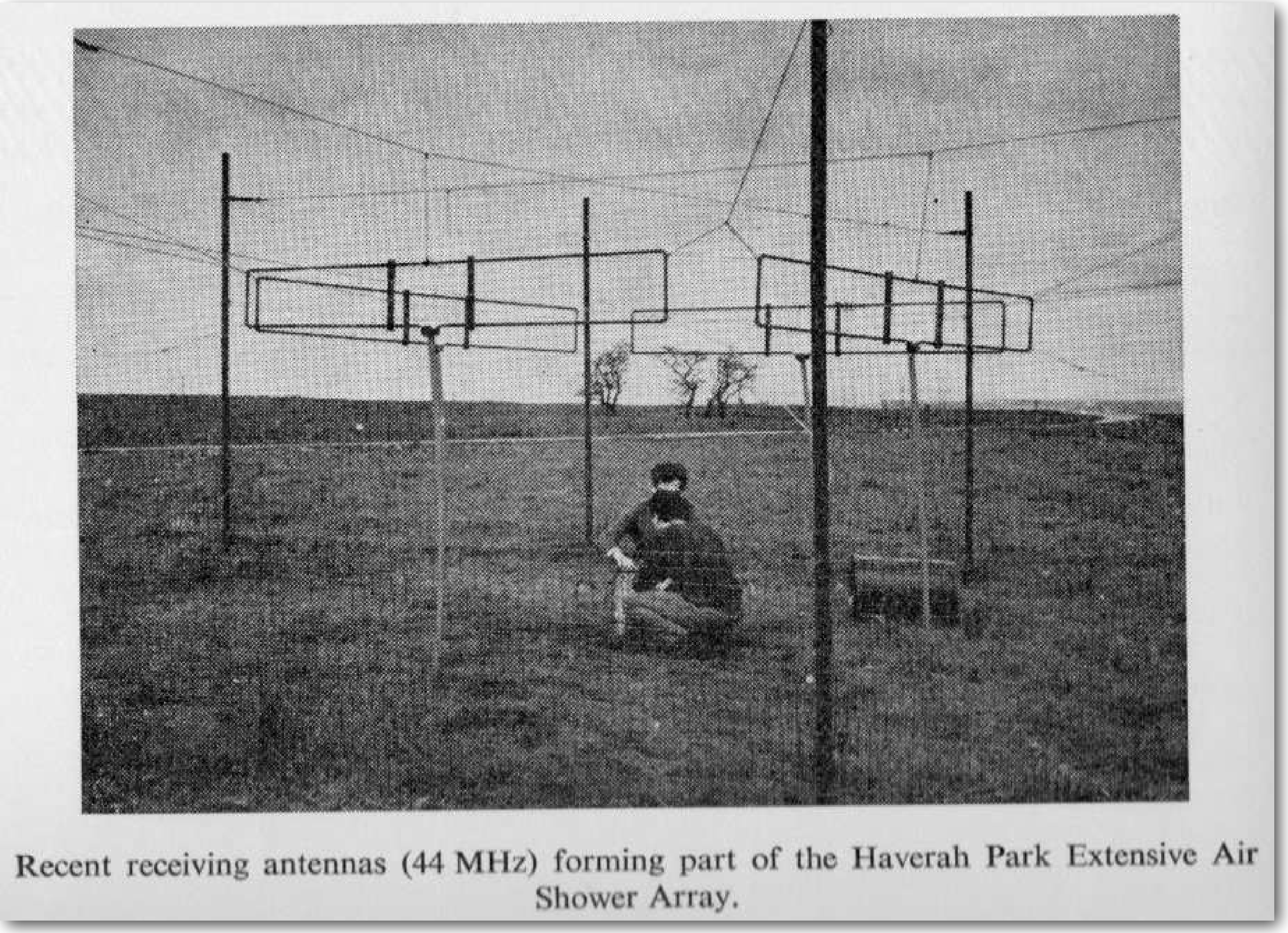
Haverah Park (Leeds) Allan 1971



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



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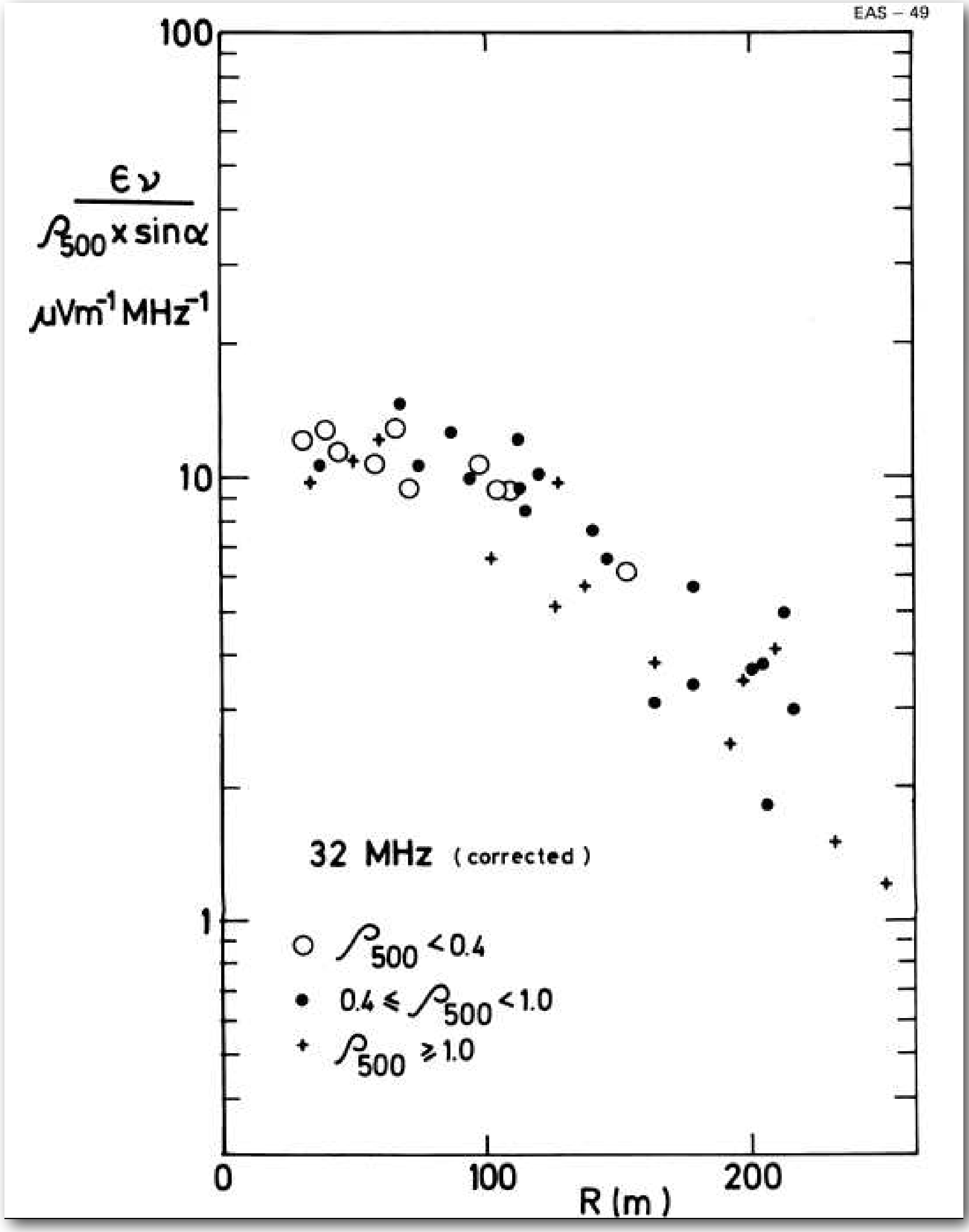
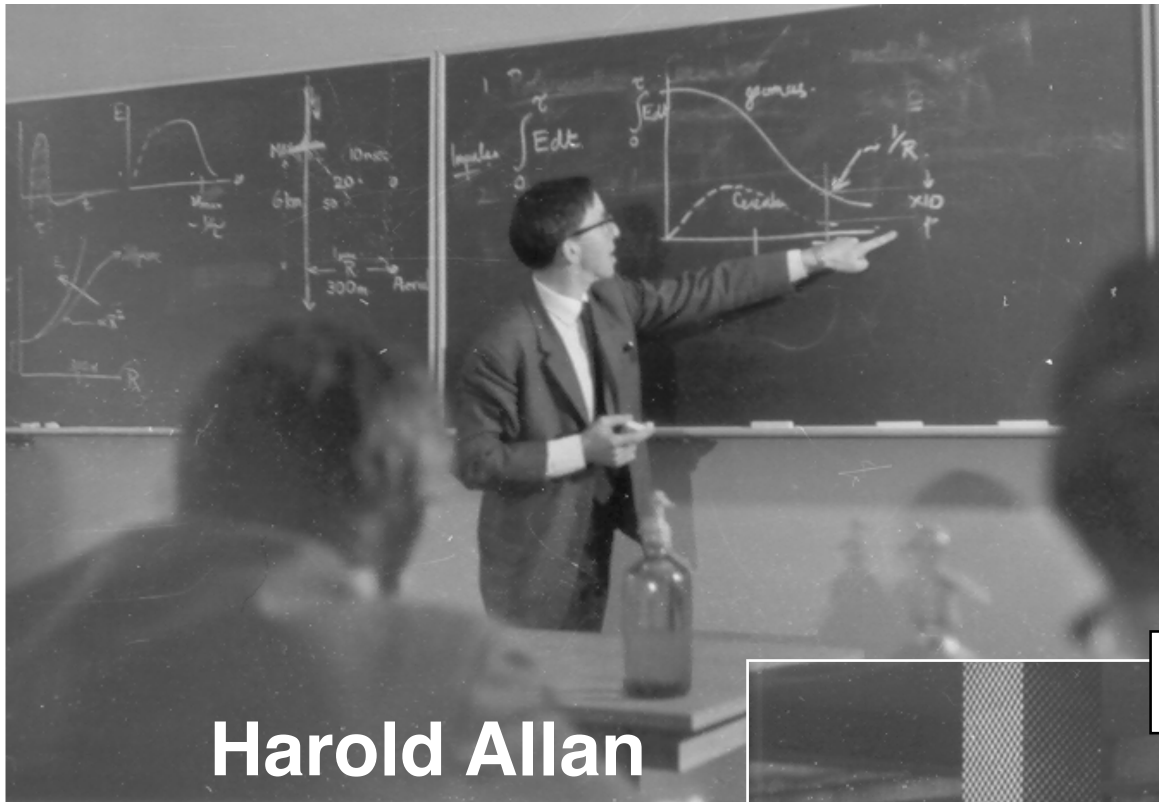
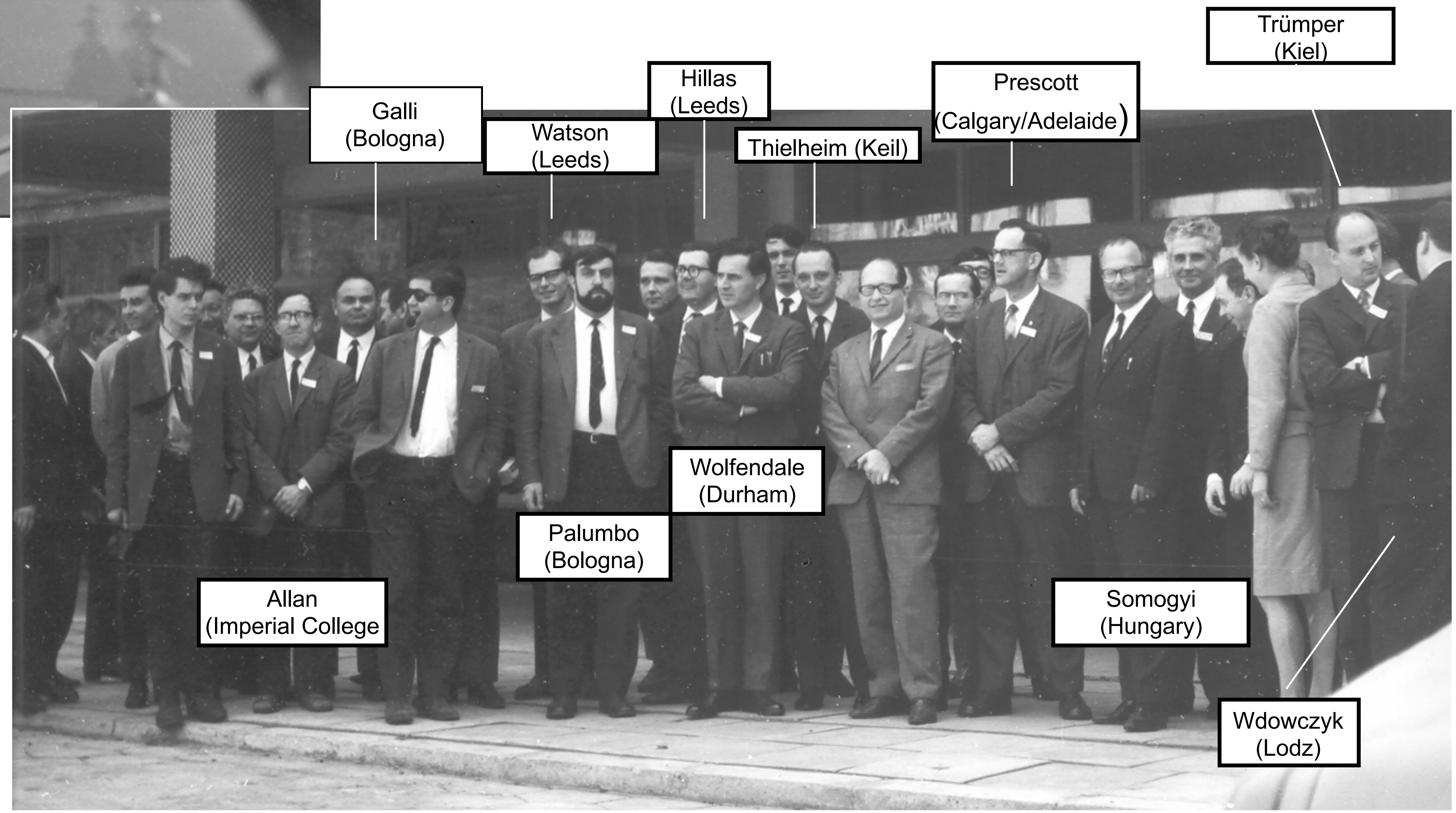


$$\varepsilon_\nu = 2\left(\frac{E_p}{10^{17}}\right)\left(\frac{\sin\alpha\cos\theta}{\sin 45\cos 30}\right)\exp\left(\frac{-r}{r_0}\right)\left(\frac{\nu}{50}\right)^{-1} \quad \mu\text{V/m/MHz}$$

$r_0 = 110$ 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

ICRC 2013

The renaissance of radio detection of cosmic rays

TIM HUEGE[1]

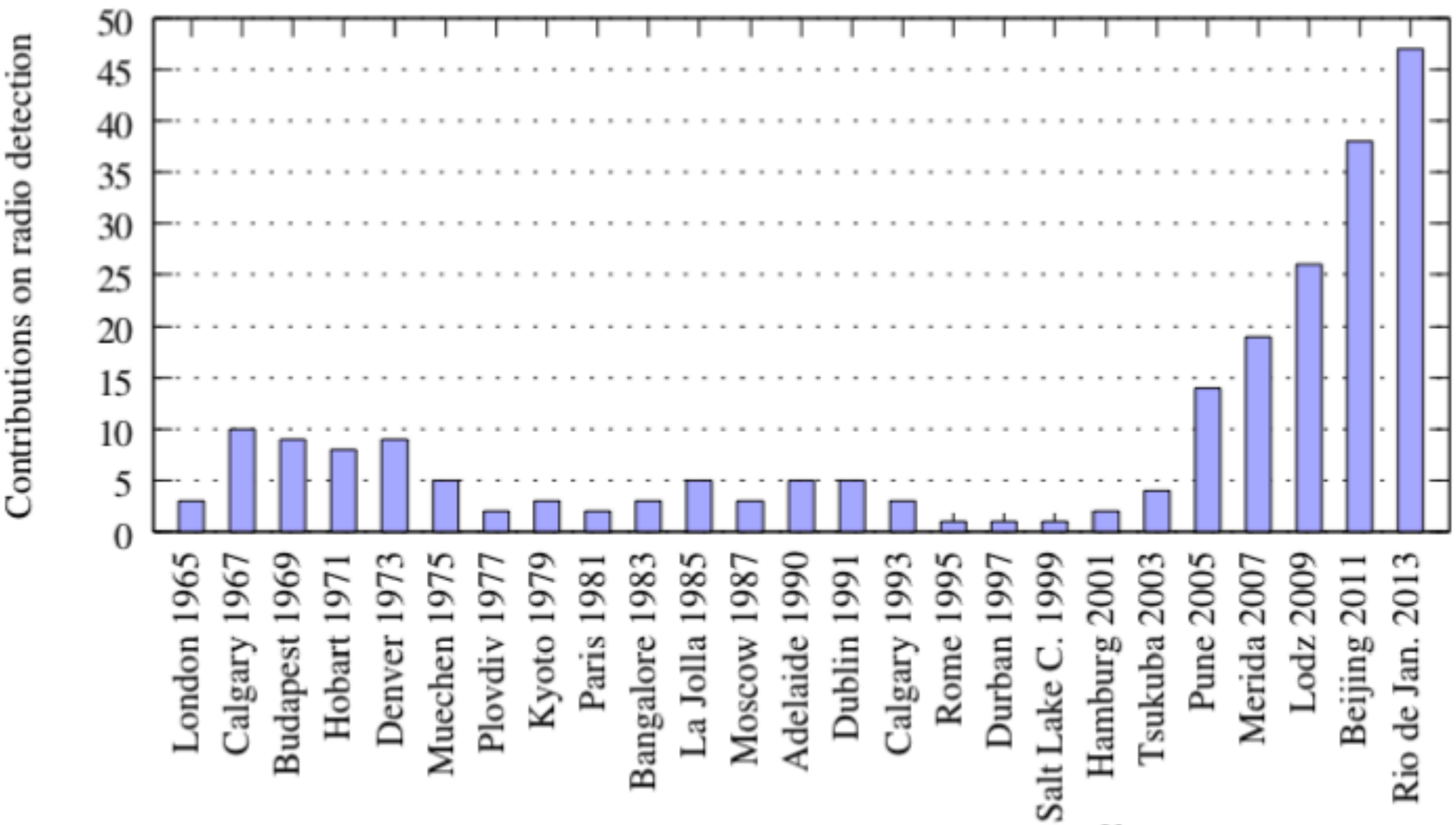


Figure 1: Number of contributions related to radio detection of cosmic rays or neutrinos to the ICRCs since 1965. The field has grown very impressively since the modern activities started around 2003. Data up to 2007 were taken from [11].

33RD INTERNATIONAL COSMIC RAY CONFERENCE, RIO DE JANEIRO 2013
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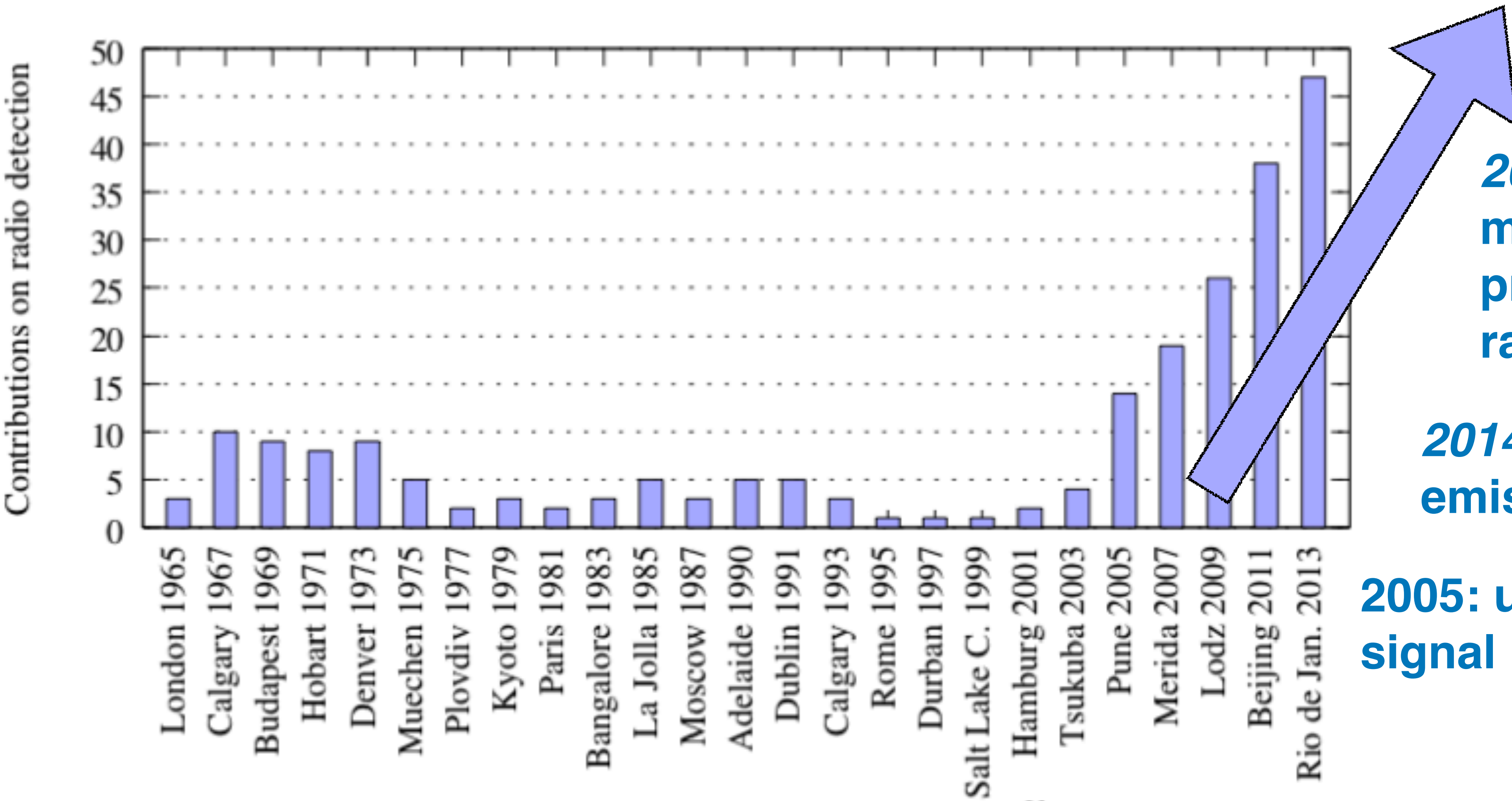


2018: beyond capabilities of standard installations

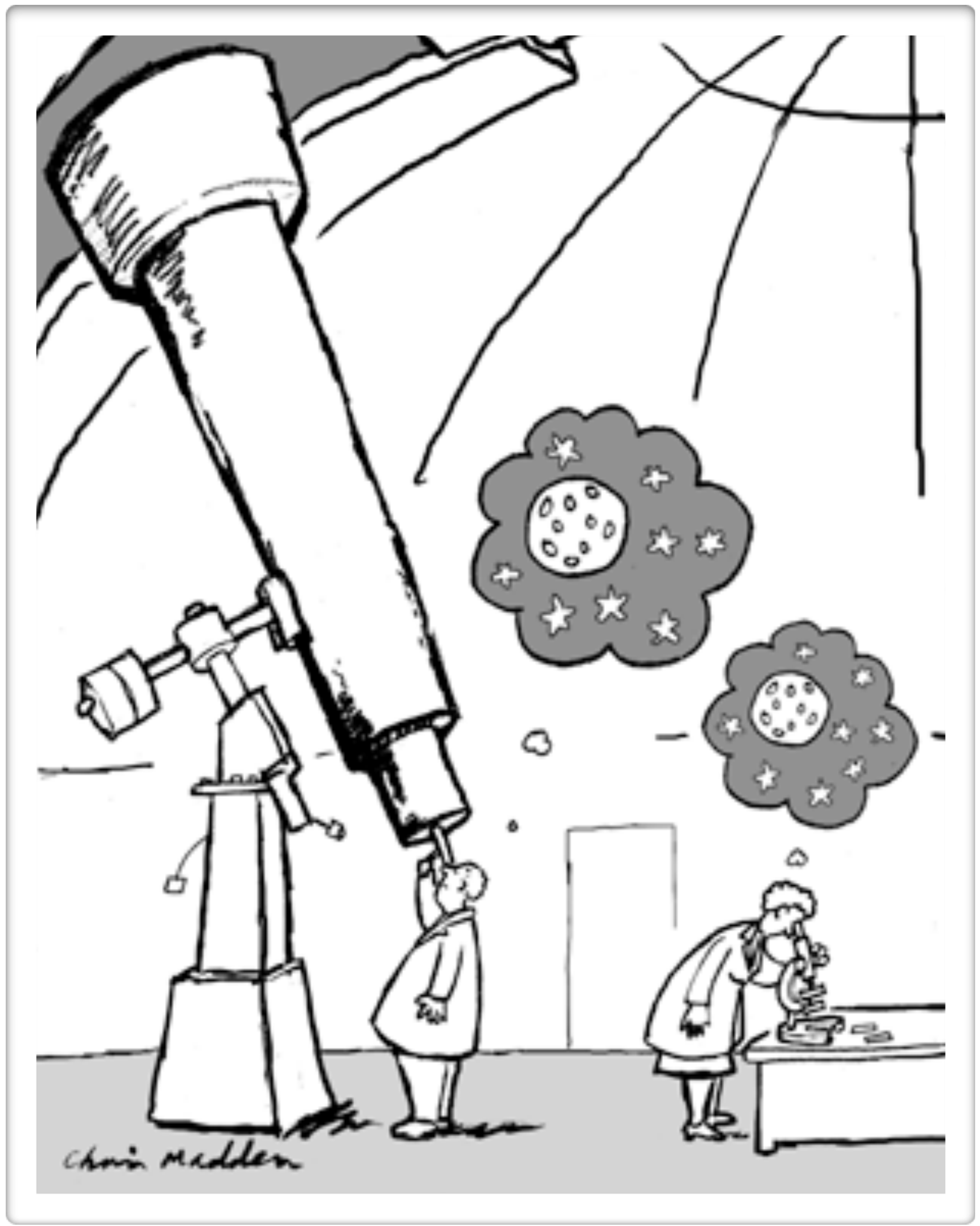
2016: radio technique mature: properties of cosmic rays

2014: understanding the emission processes

2005: understanding the signal

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].

Radio Detectors



Radio detection of extensive air showers around the world

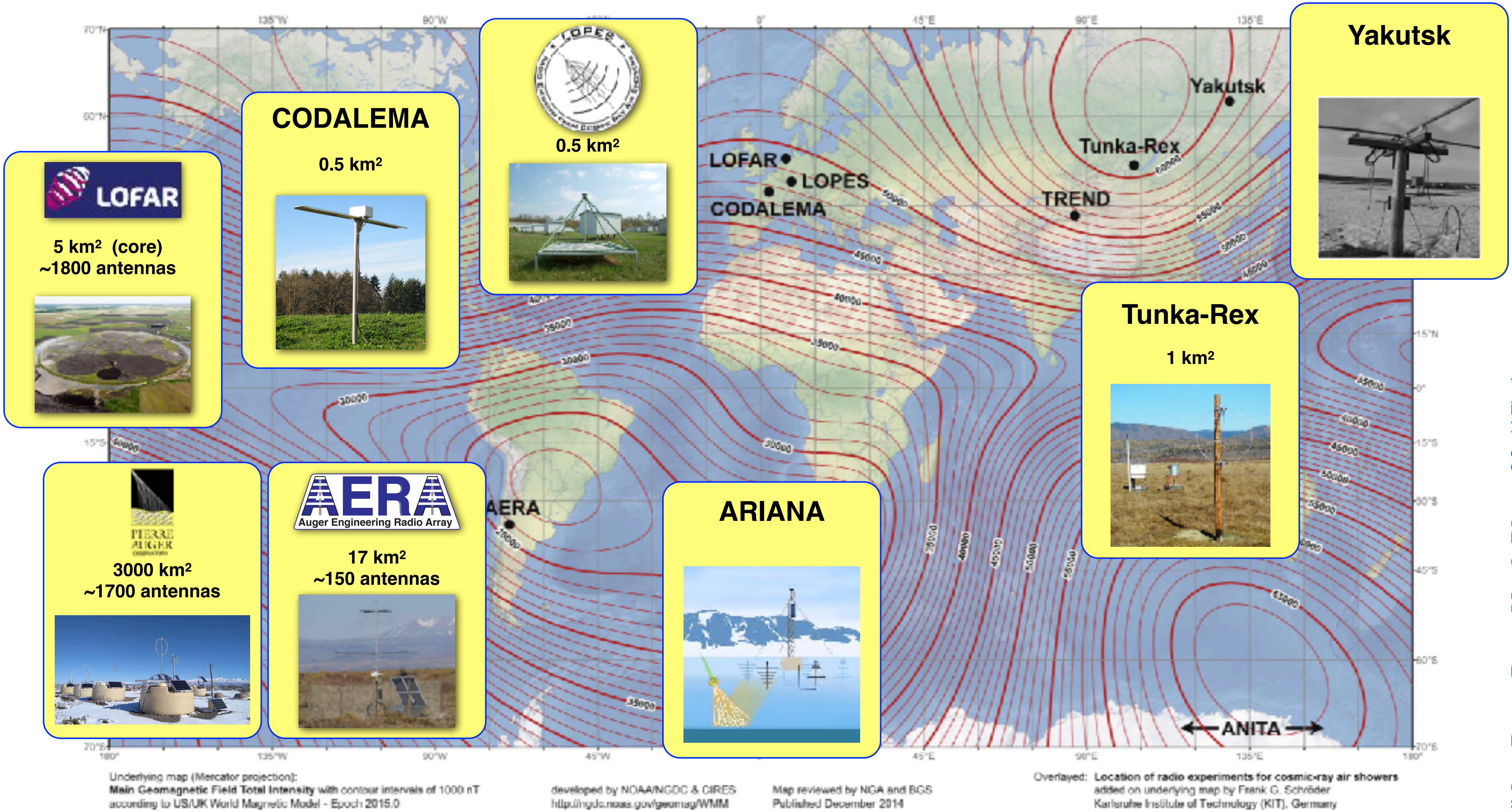
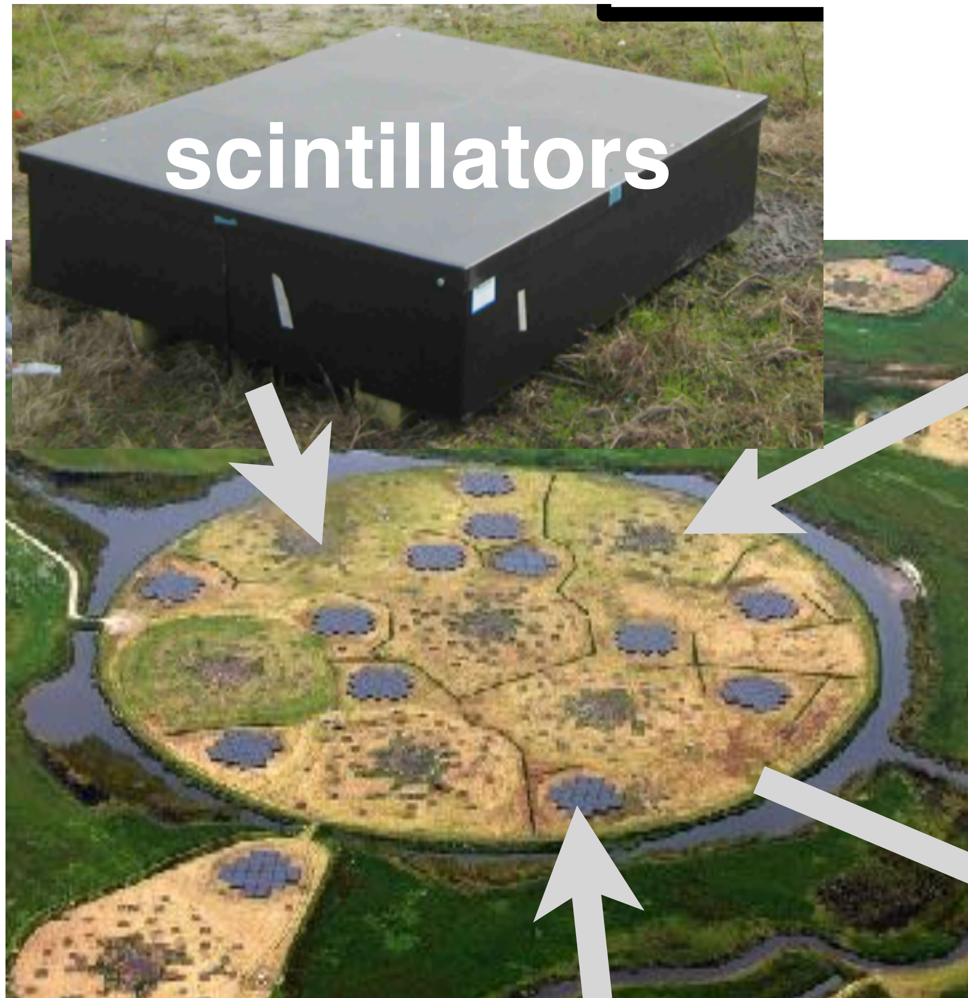


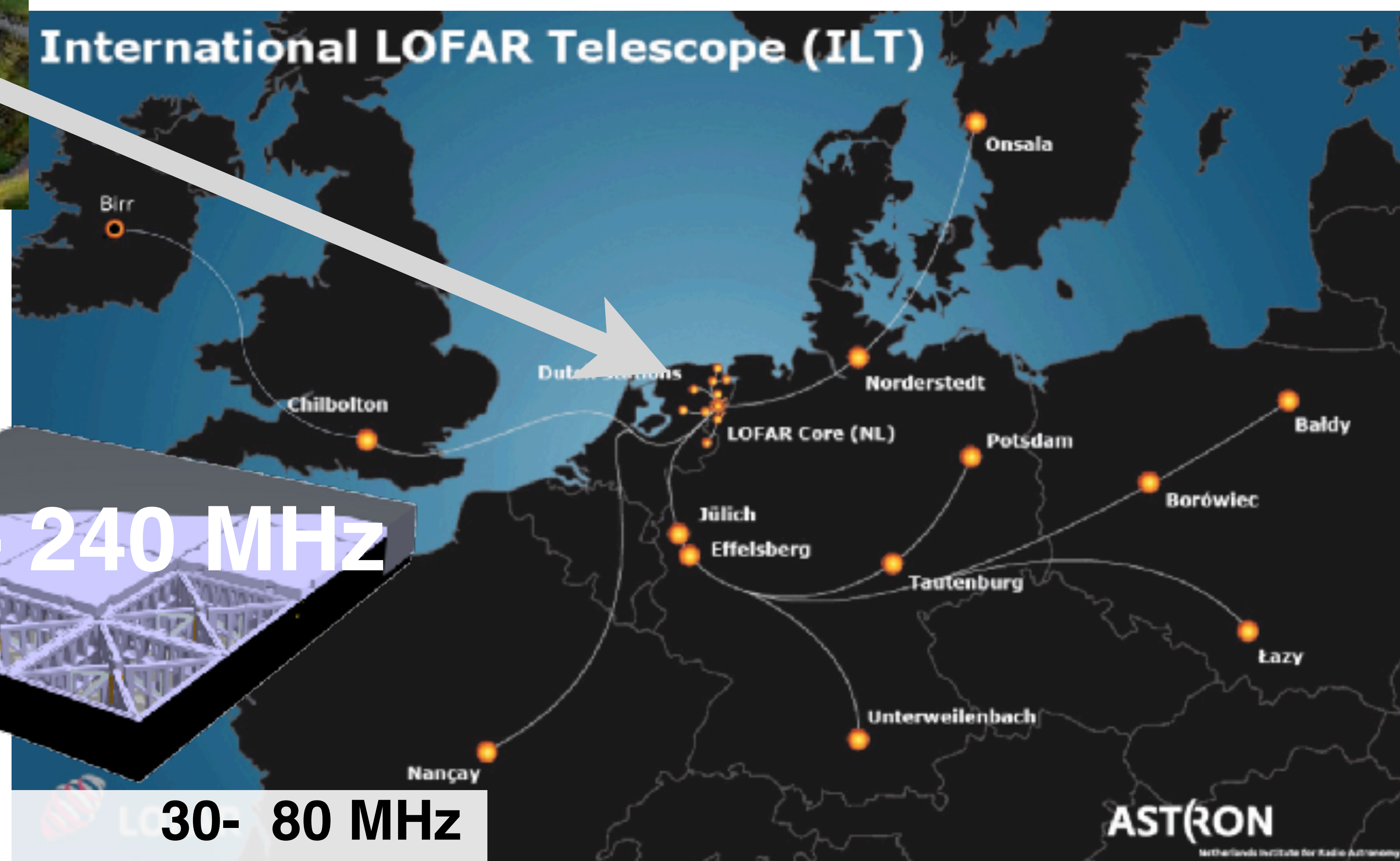
Fig. 21. Map of the total geomagnetic field strengths (world magnetic model [207]) and the location of various radio experiments detecting cosmic-ray air showers.

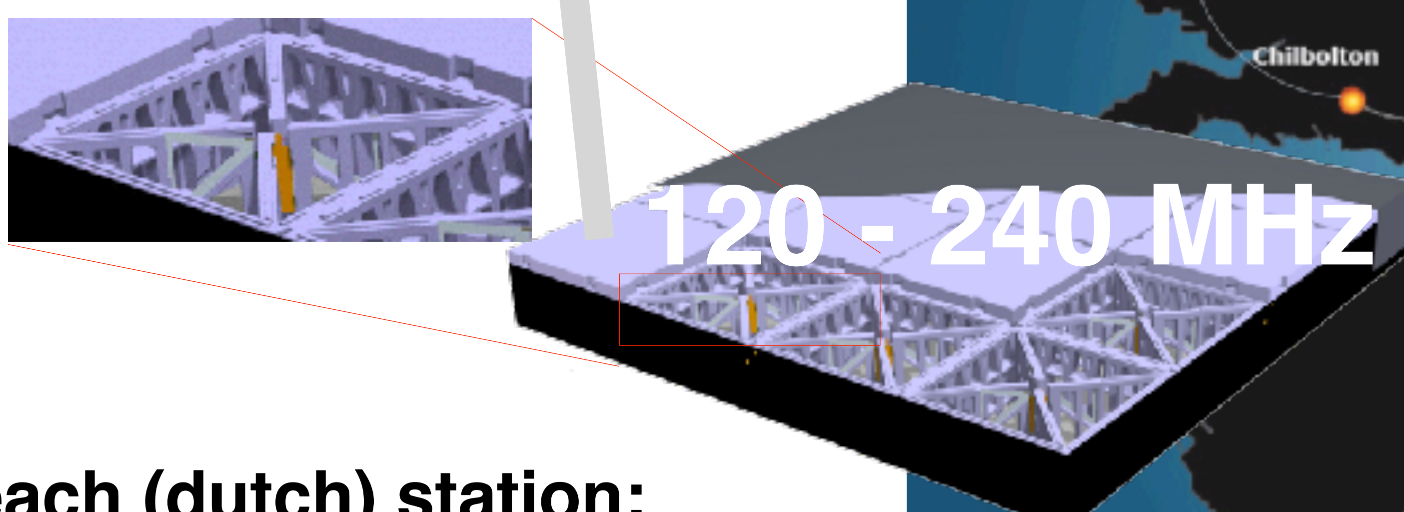
F.G. Schröder, Prog. Part. Nucl. Phys. 92 (17) 1



LOFAR

core
23 stations ~5 km²

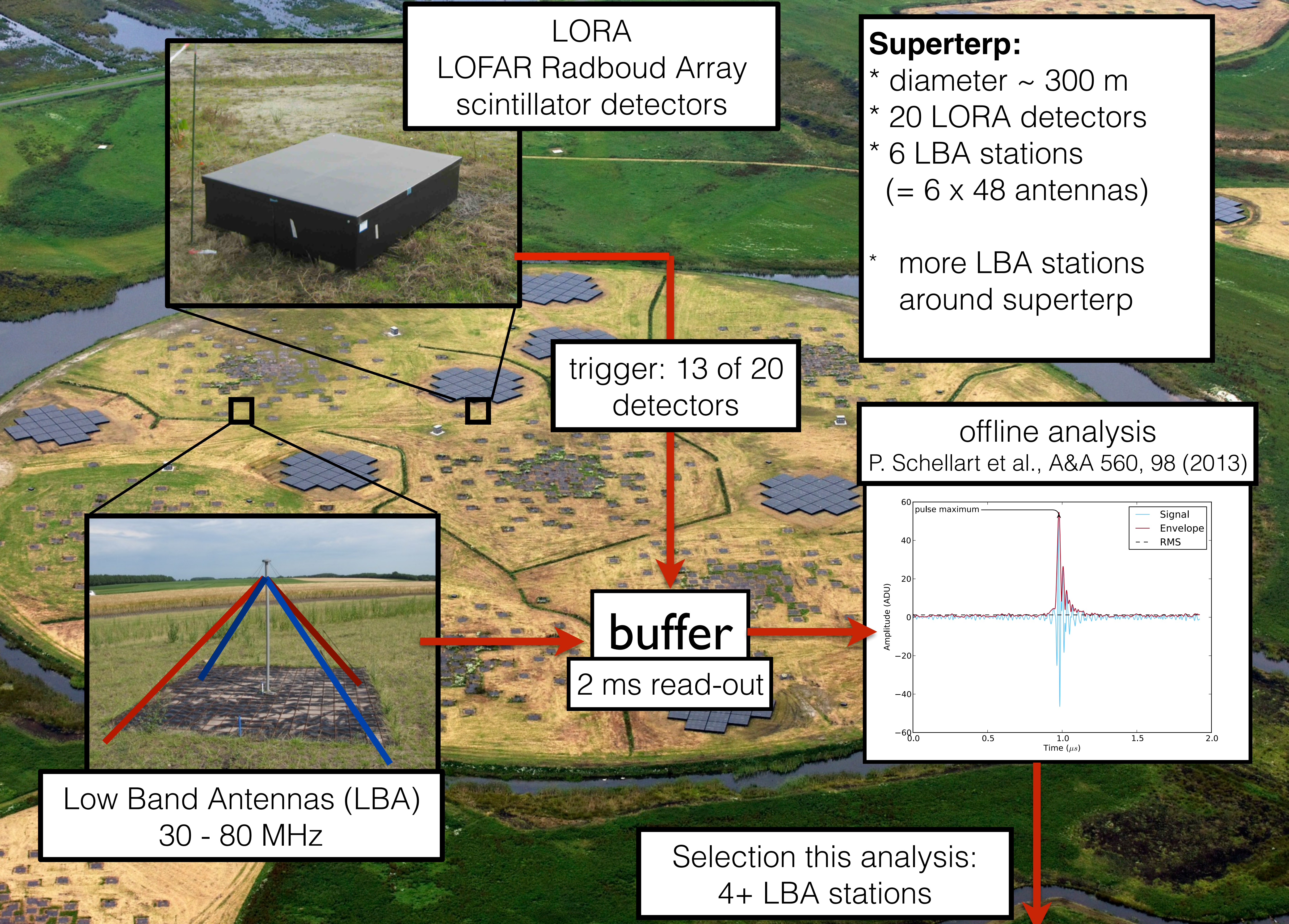




each (dutch) station:
96 low-band antennas 30- 80 MHz
high-band antennas (2x24 tiles) 120-240 MHz

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

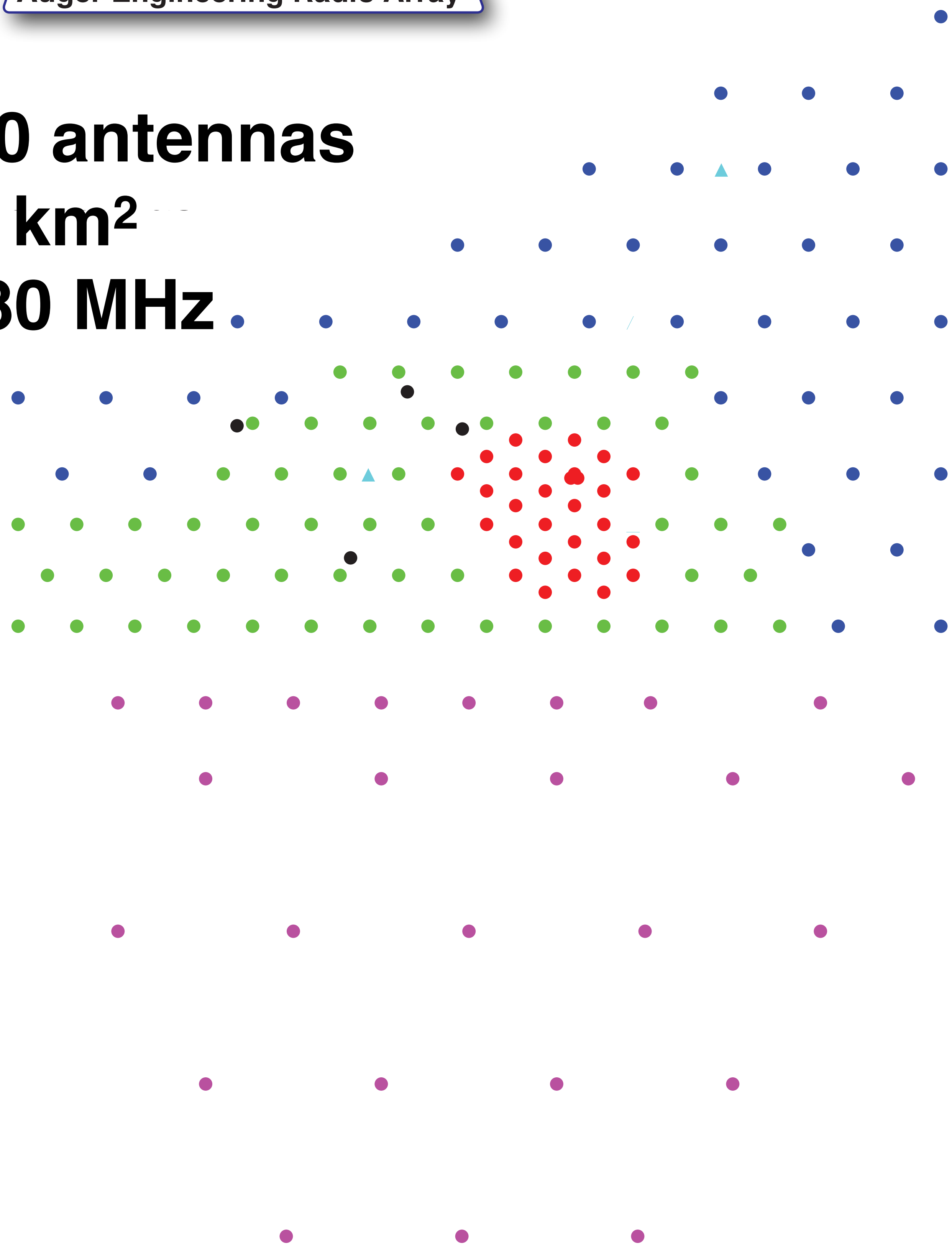
S. Thoudam et al., Nucl. Instr. Meth. A 767 (2014) 339


LORA
LOFAR Radboud Array
scintillator detectors
Superterp:
* diameter ~ 300 m
* 20 LORA detectors
* 6 LBA stations
(= 6 x 48 antennas)
* more LBA stations around superterp
trigger: 13 of 20 detectors
offline analysis
P. Schellart et al., A&A 560, 98 (2013)
pulse maximum
Signal
Envelope
RMS
Amplitude (ADU)
Time (μs)
buffer
2 ms read-out
Low Band Antennas (LBA)
30 - 80 MHz
Selection this analysis:
4+ LBA stations

PIERRE AUGER OBSERVATORY

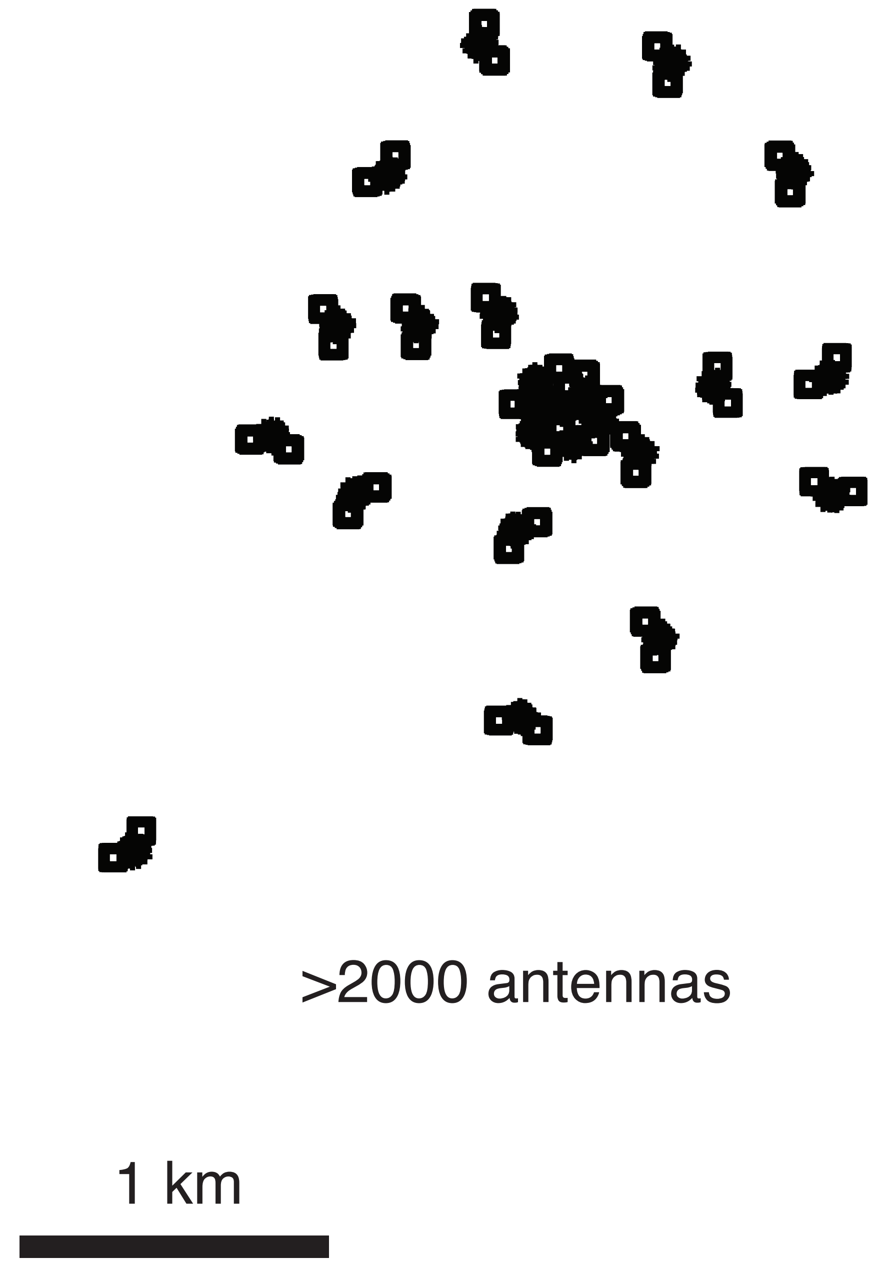
AERA
Auger Engineering Radio Array

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



LOFAR **core**

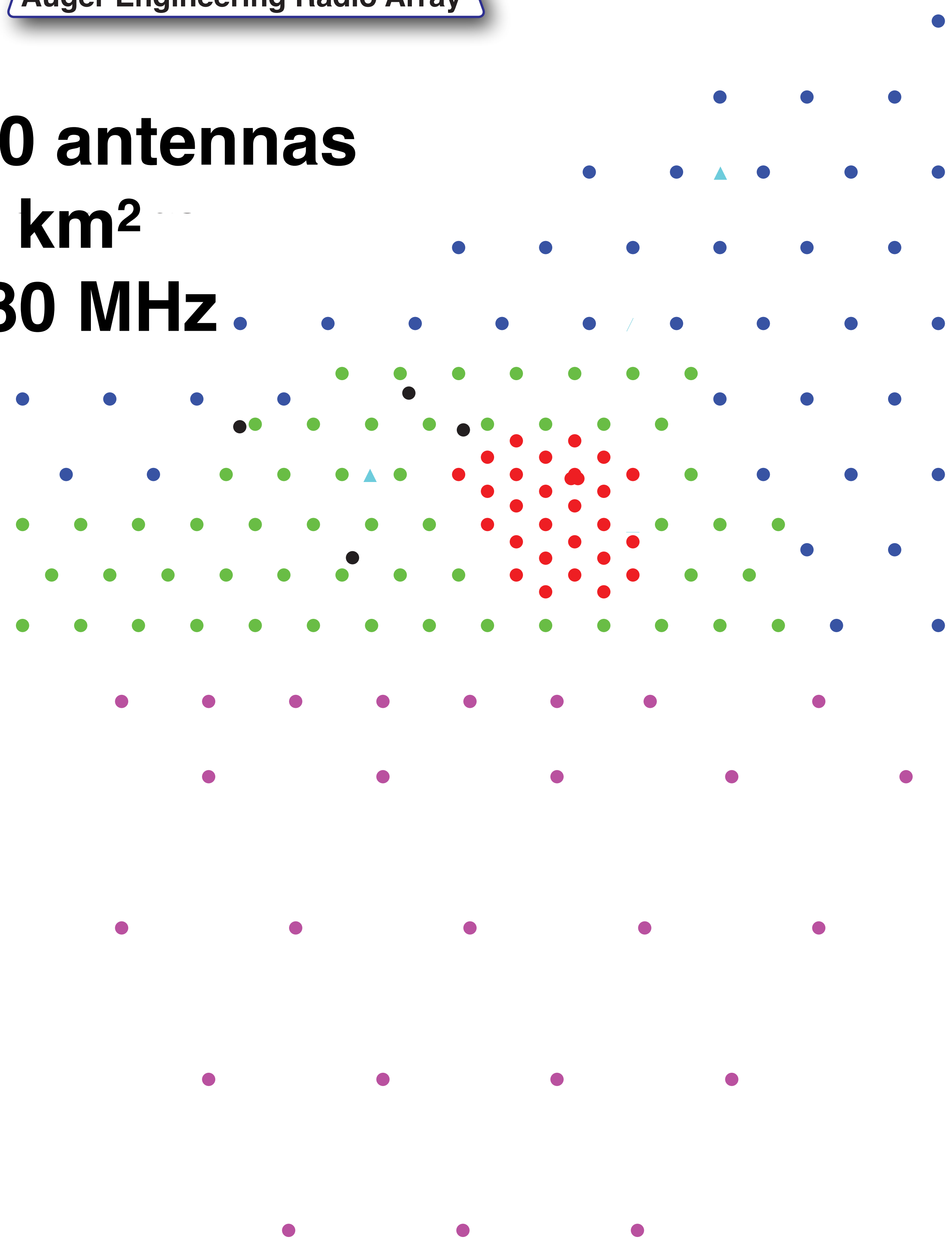
23 stations ~5 km^2

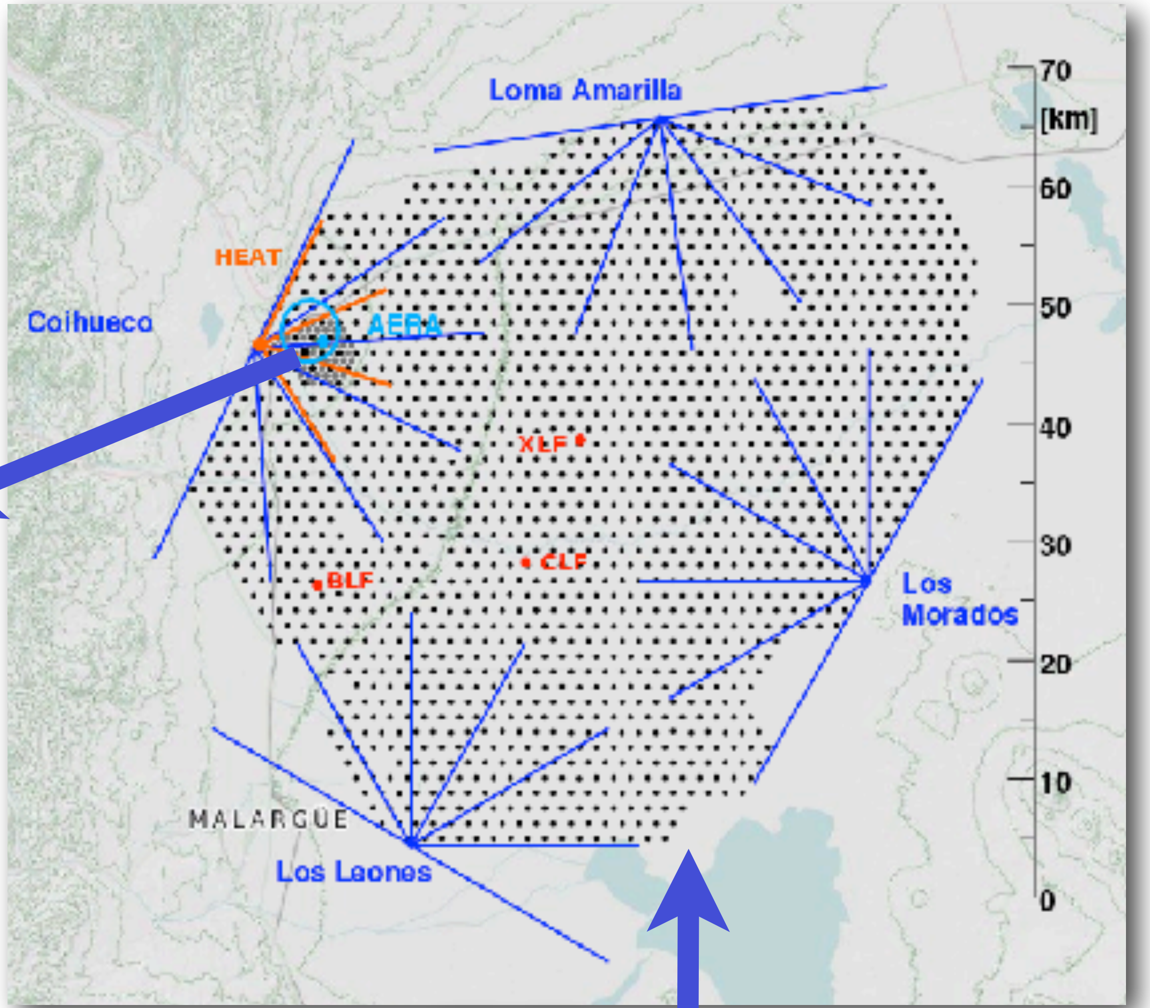


>2000 antennas

Auger Engineering Radio Array

~150 antennas
~17 km²
30-80 MHz

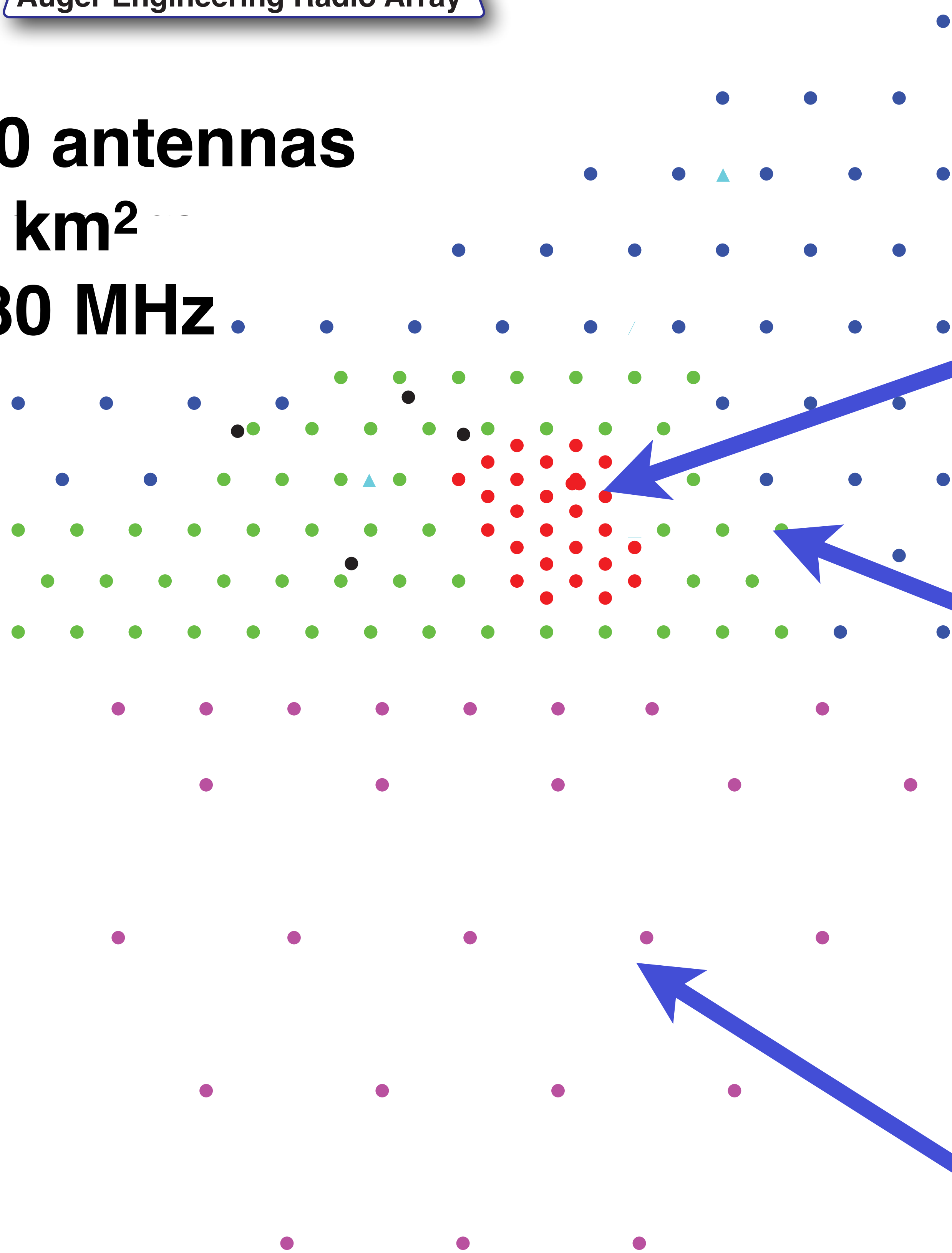


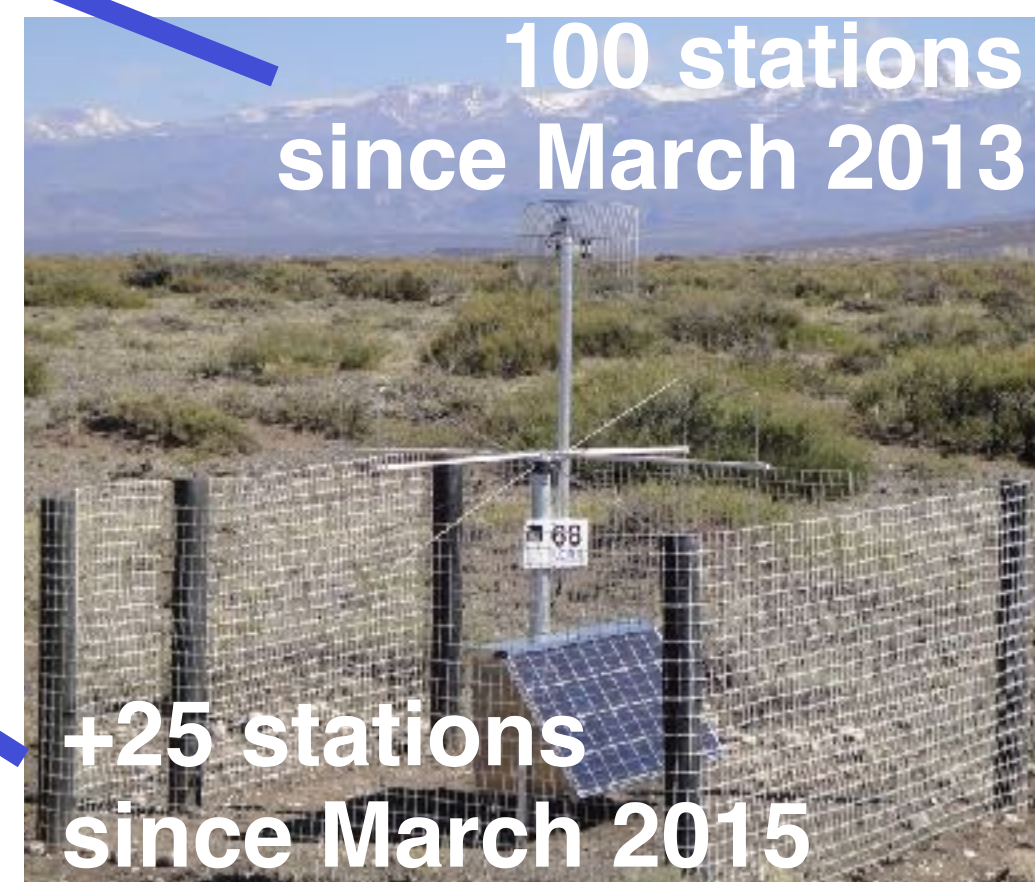


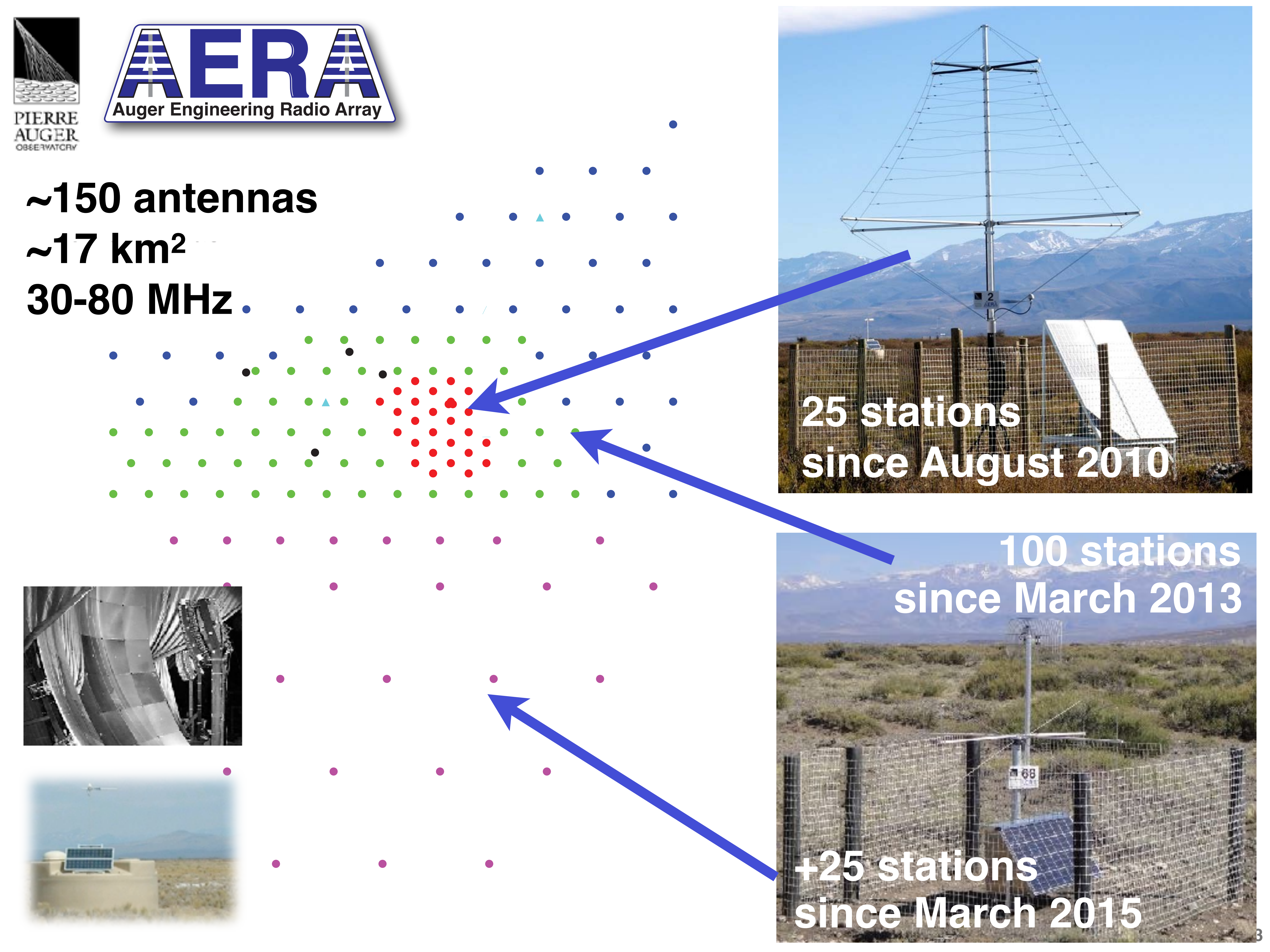
PIERRE AUGER OBSERVATORY

AERA
Auger Engineering Radio Array

~150 antennas
~17 km²
30-80 MHz



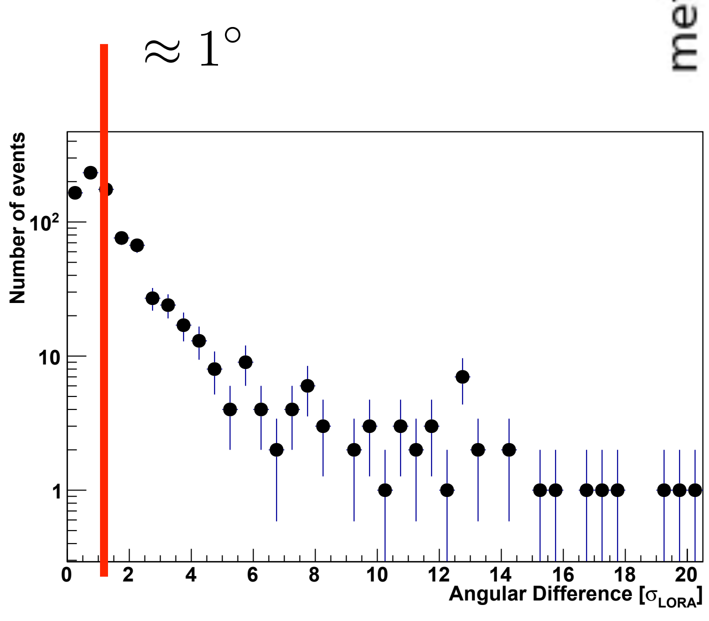


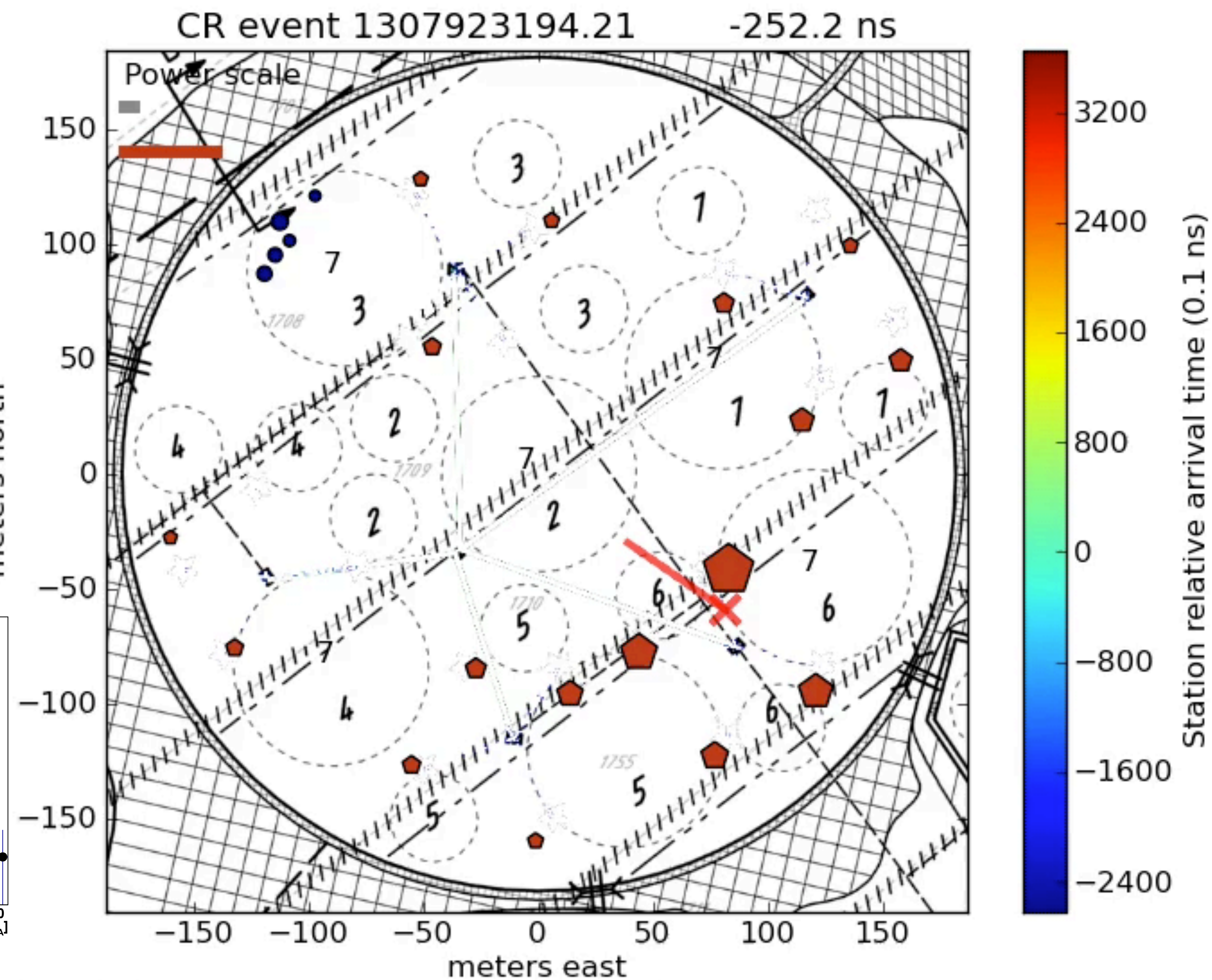


PIERRE AUGER OBSERVATORY
AERA
Auger Engineering Radio Array
~150 antennas
~17 km²
30-80 MHz
25 stations
since August 2010
100 stations
since March 2013
+25 stations
since March 2015

A measured air shower

angular difference particles - radio





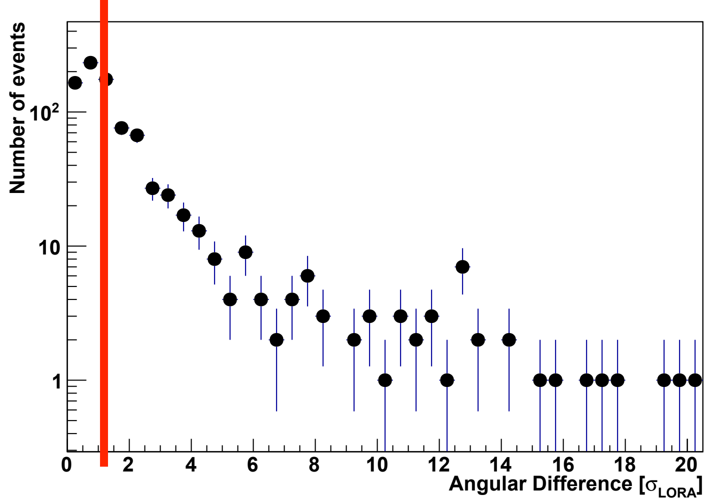
Circles: LOFAR antennas, Pentagons: LORA particle detectors, size denotes signal strength

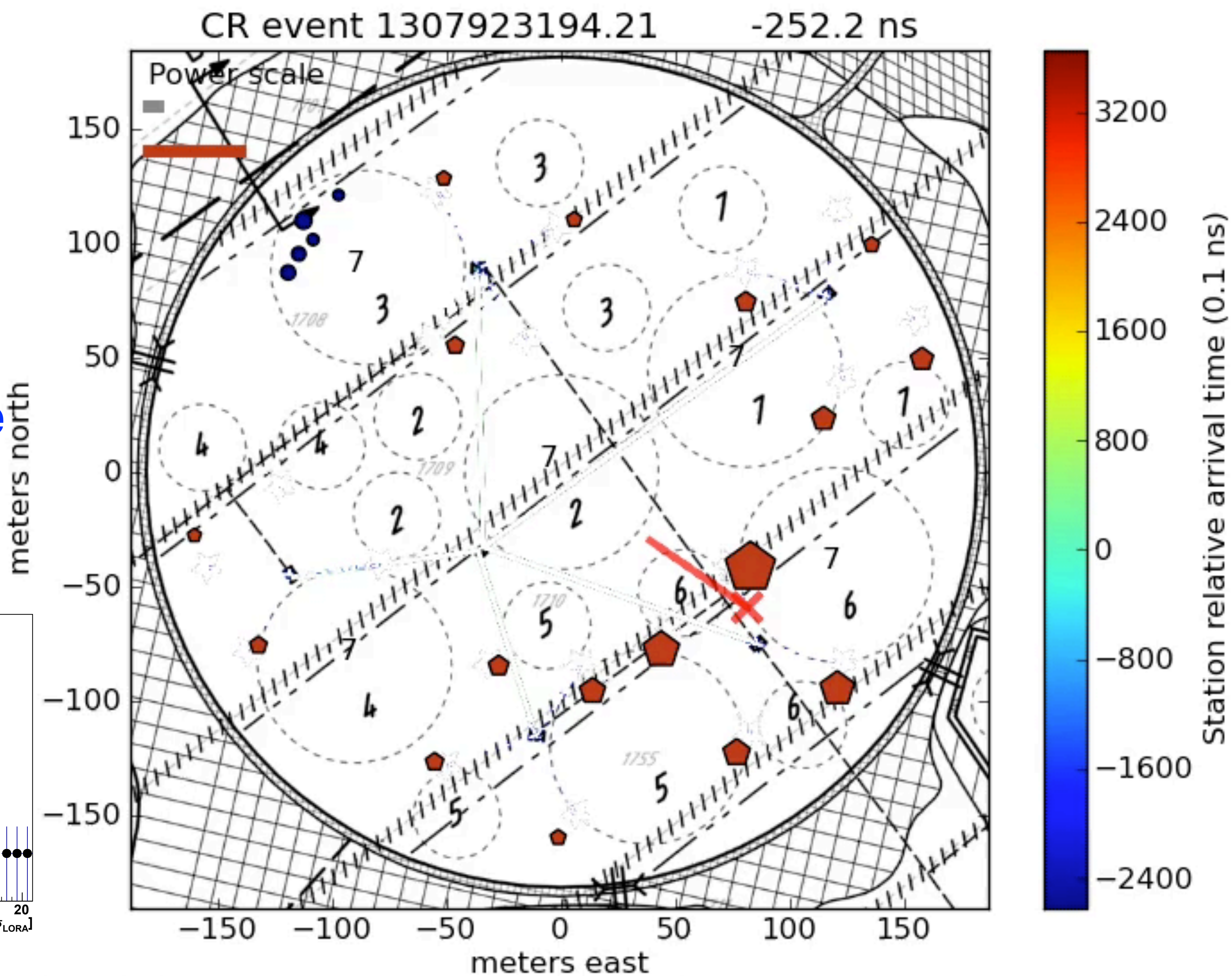
LOFAR

A measured air shower

angular difference particles - radio

$\approx 1^\circ$

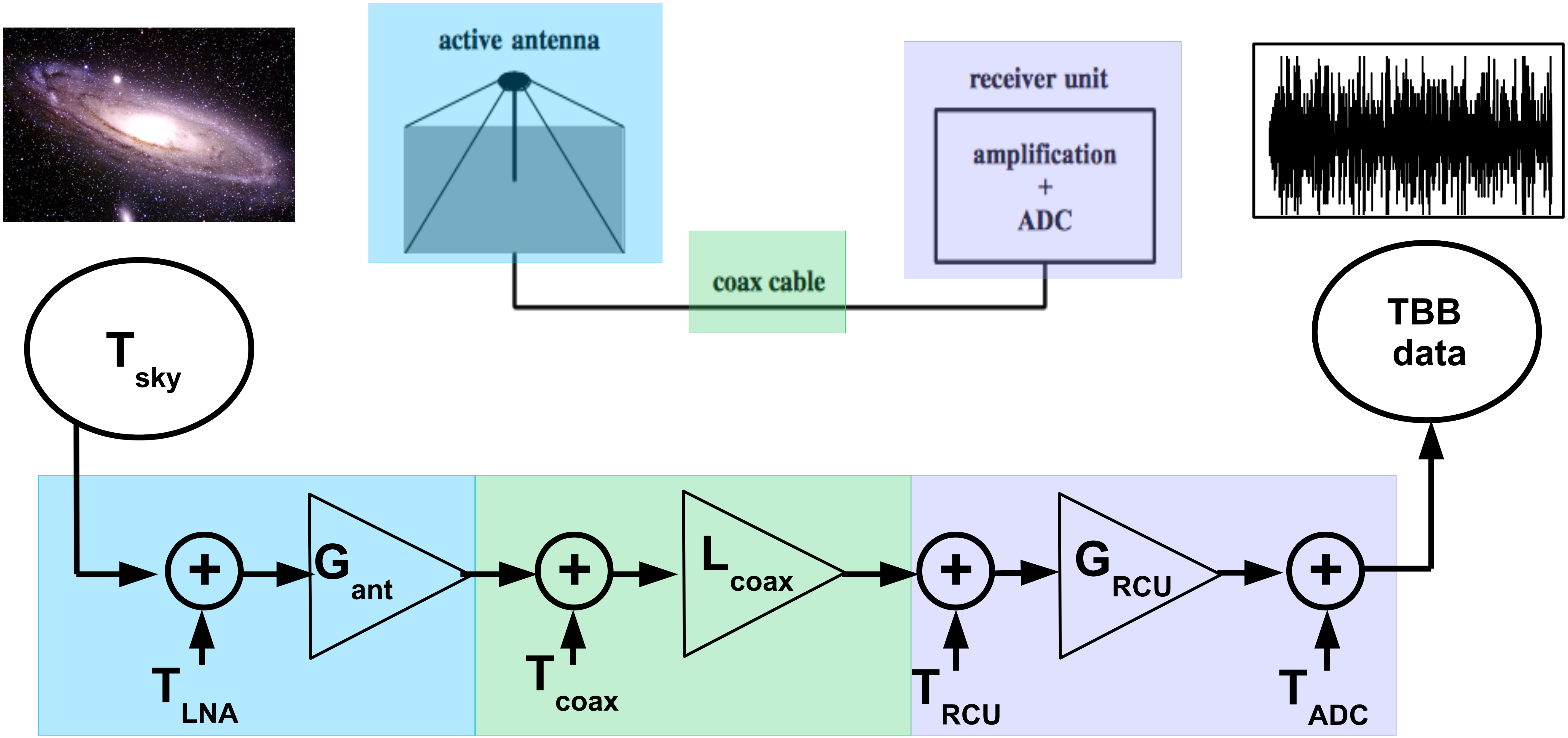




Circles: LOFAR antennas, Pentagons: LORA particle detectors, size denotes signal strength

LOFAR

LOFAR Signal Chain



G_{ant} , L_{coax} , G_{RCU} → **Freq. Dependent losses and gains**

T_{LNA} , T_{coax} , T_{RCU} , T_{ADC} → **Constant noise values**

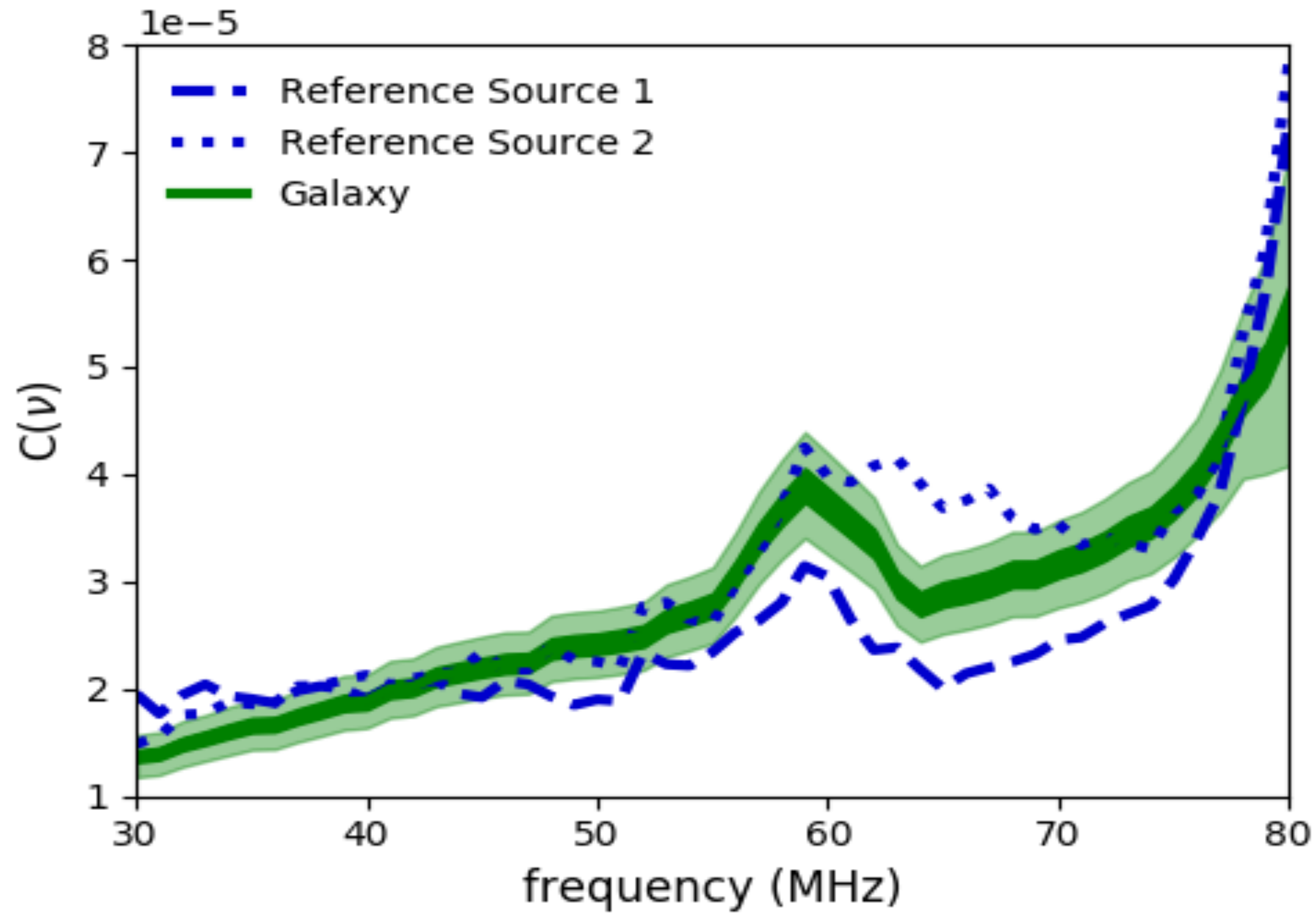
7

K. Mulrey, ARENA 2018

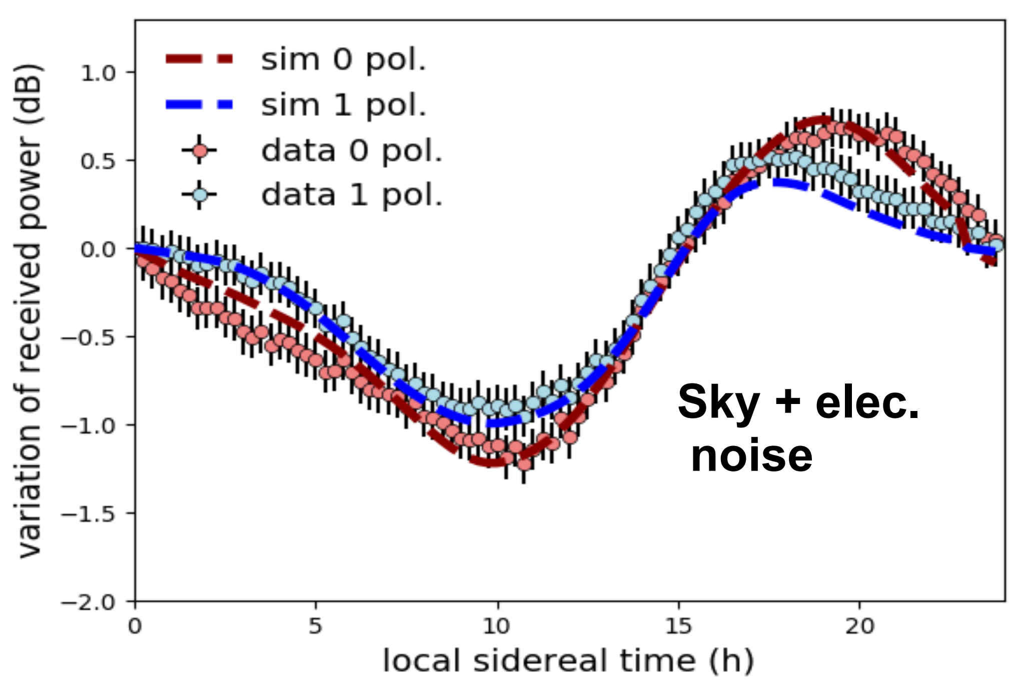
Calibration Results

LOFAR

$$\mathbf{C^2}(\nu) = \mathbf{A}(\nu)\mathbf{L}_{\mathrm{coax}}(\nu)\mathbf{G}_{\mathrm{RCU}}(\nu)\mathbf{S}$$



Uncertainty	Percentage
event-to-event fluctuation	4
galaxy model	12
electronic noise < 77 MHz	5-6
electronic noise > 77 MHz	10-20
total < 77 MHz	**14**

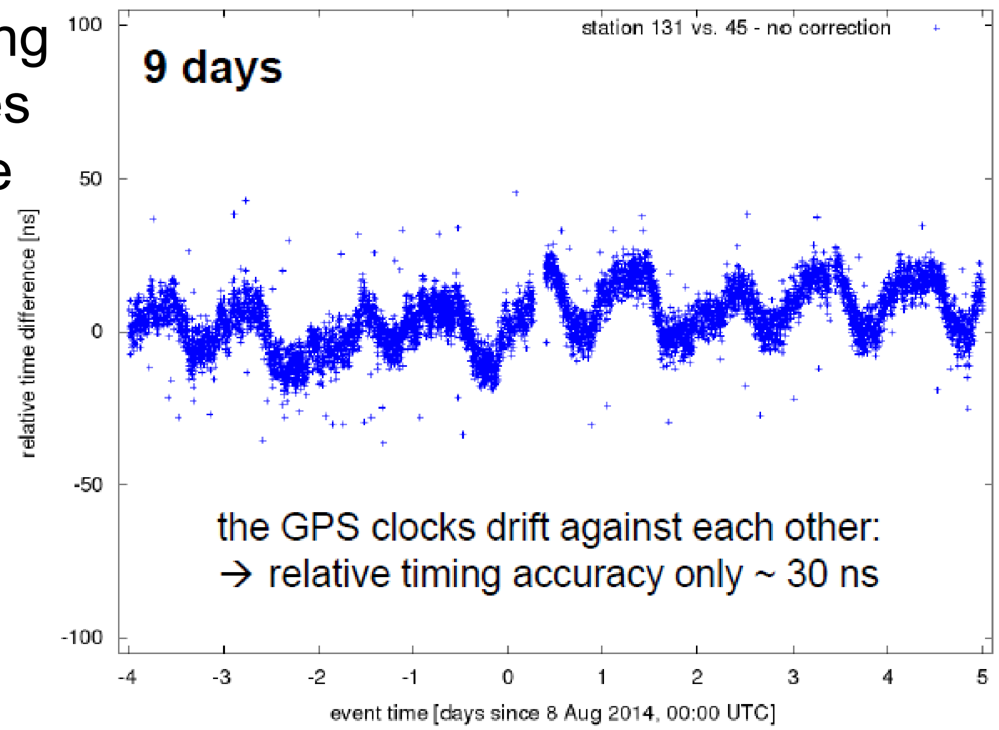


- Galaxy model now limits systematic uncertainties
- Uncertainties from electronic noise are found by comparing resulting calibration constants for different antennas

K. Mulrey, ARENA 2018

Timing calibration

Use beacon broadcasting at 4 different frequencies to measure relative time shifts



A. Aab et al., JINST 11 (2016) no.01, P01018

Timing calibration

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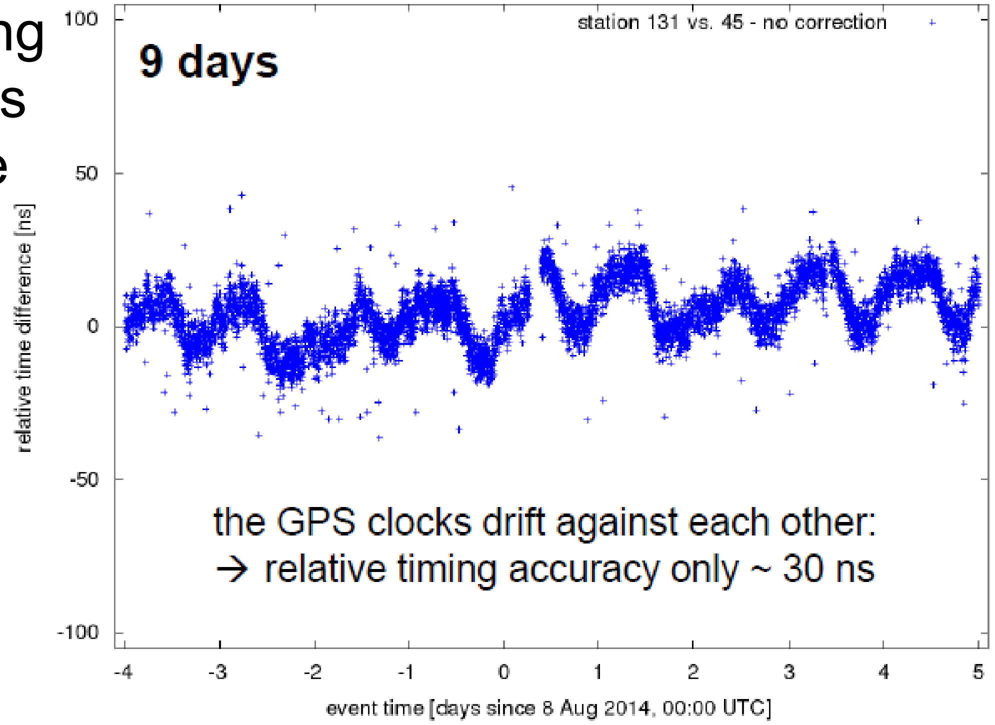
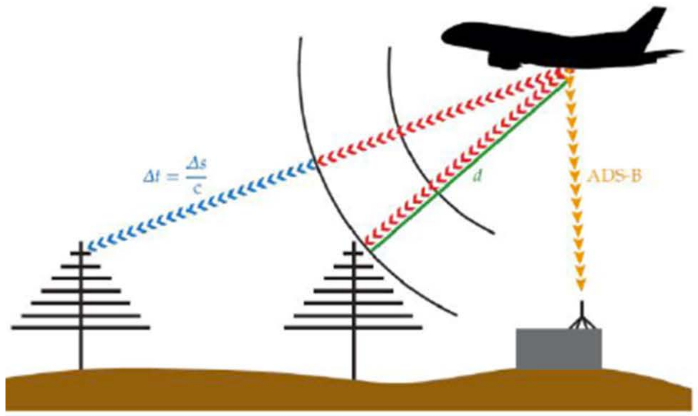
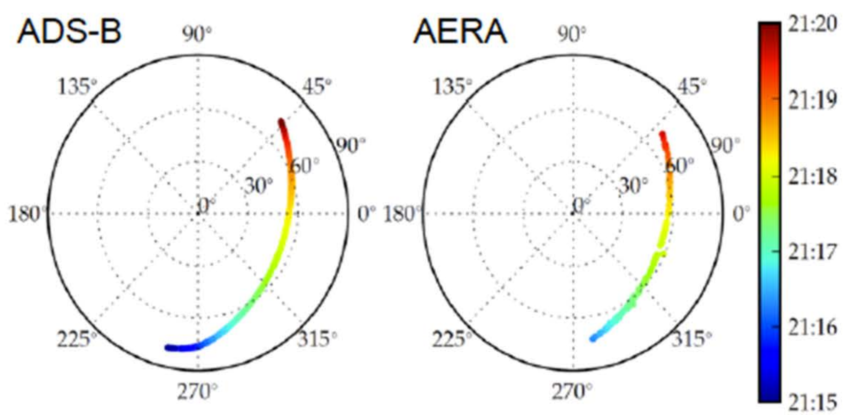
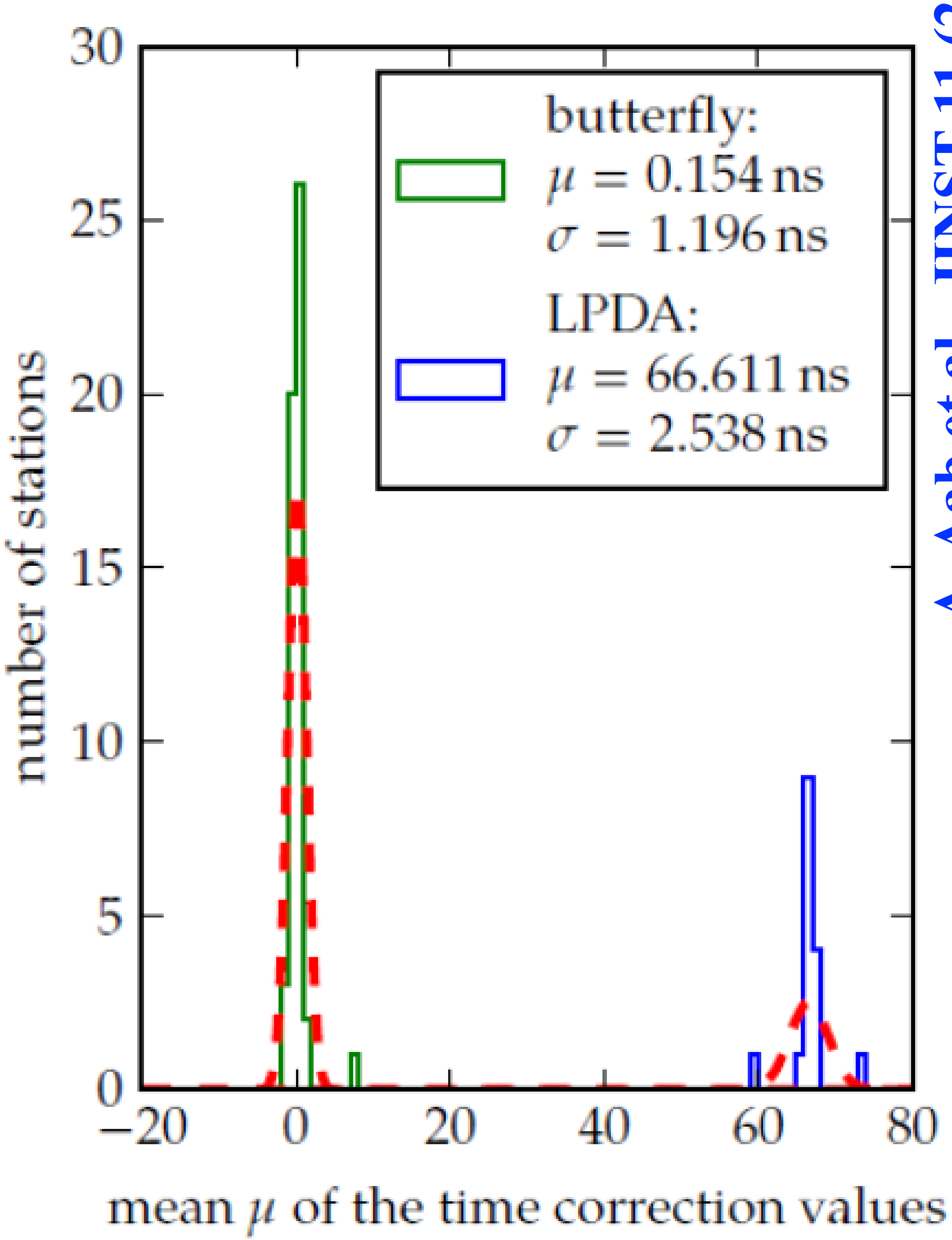


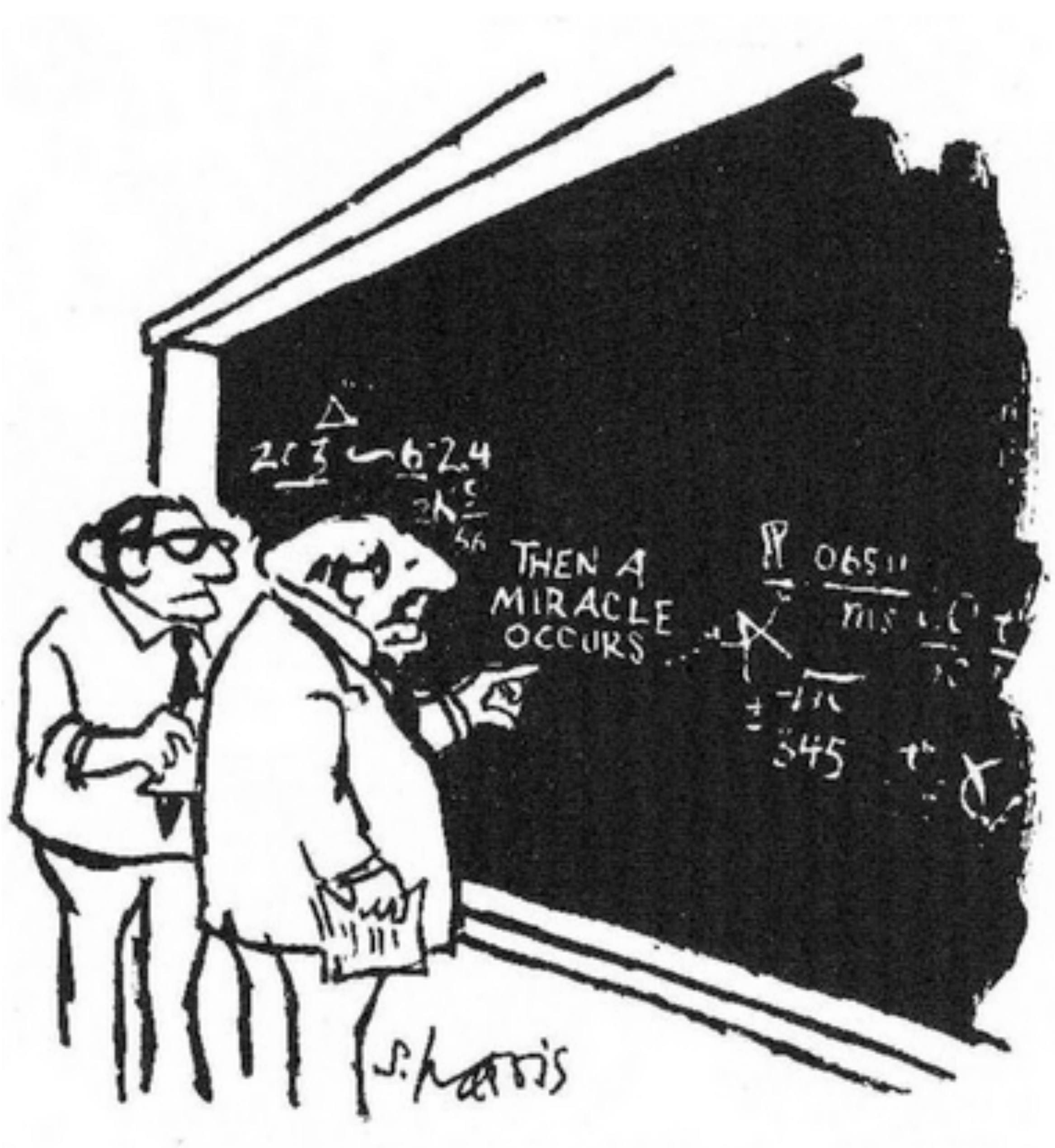




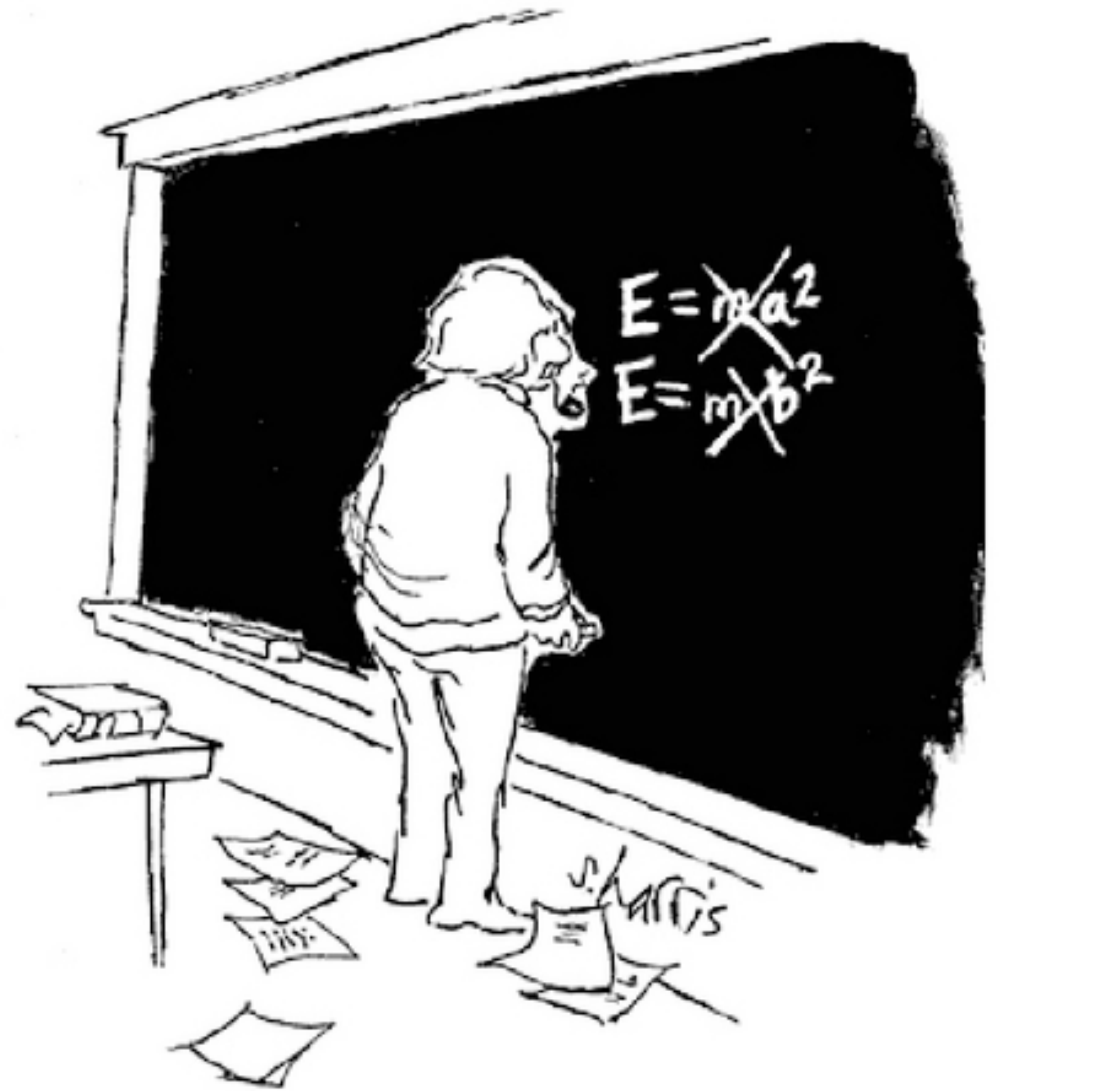


A. Aab et al., JINST 11 (2016) no.01, P01018

Radiation Processes

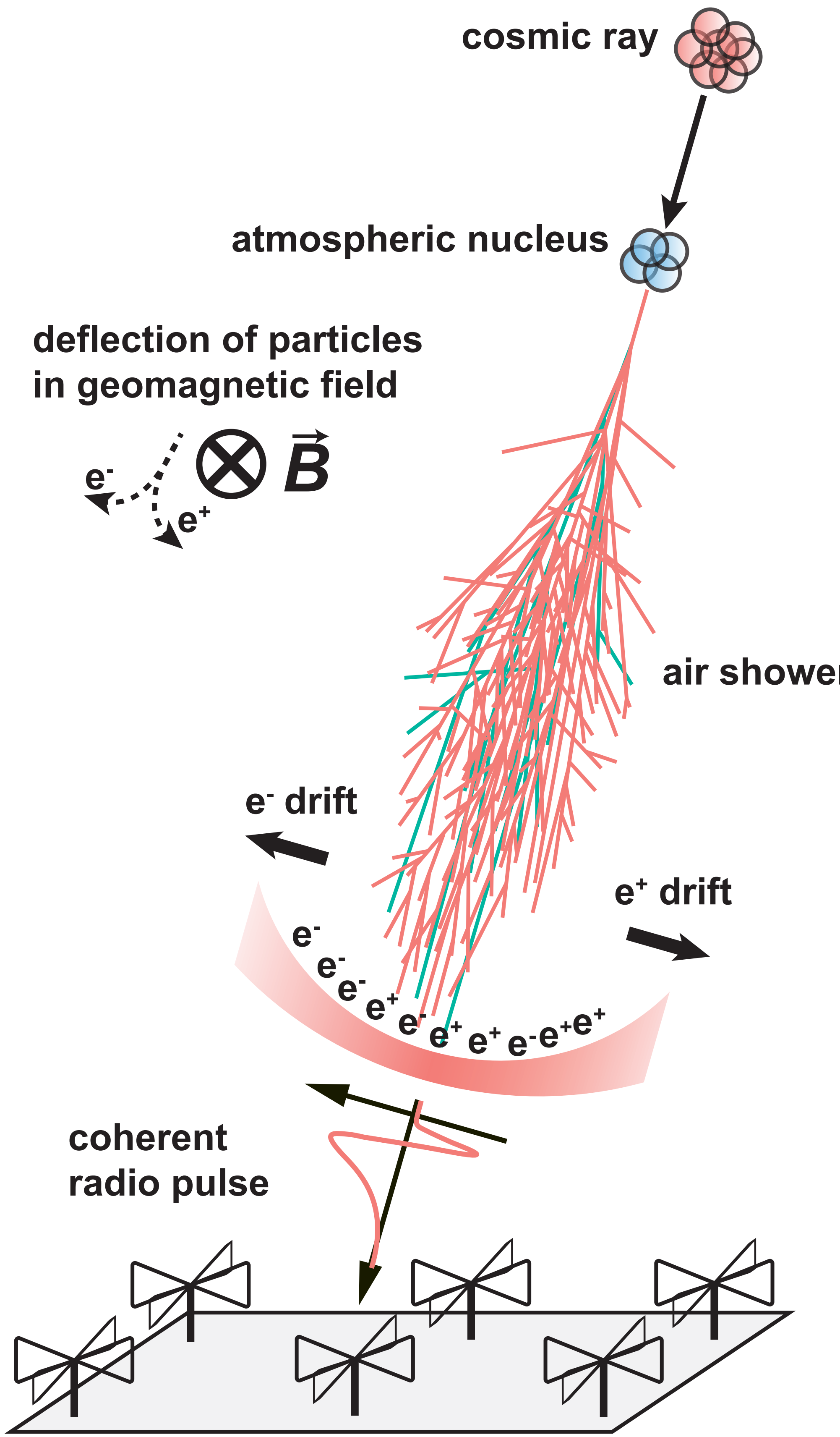


"I think you should be more explicit here in step two."



Radio Emission in Air Showers

- **Mainly: Charge separation in geomagnetic field**
  $\vec{E} \propto \vec{v} \times \vec{B}$



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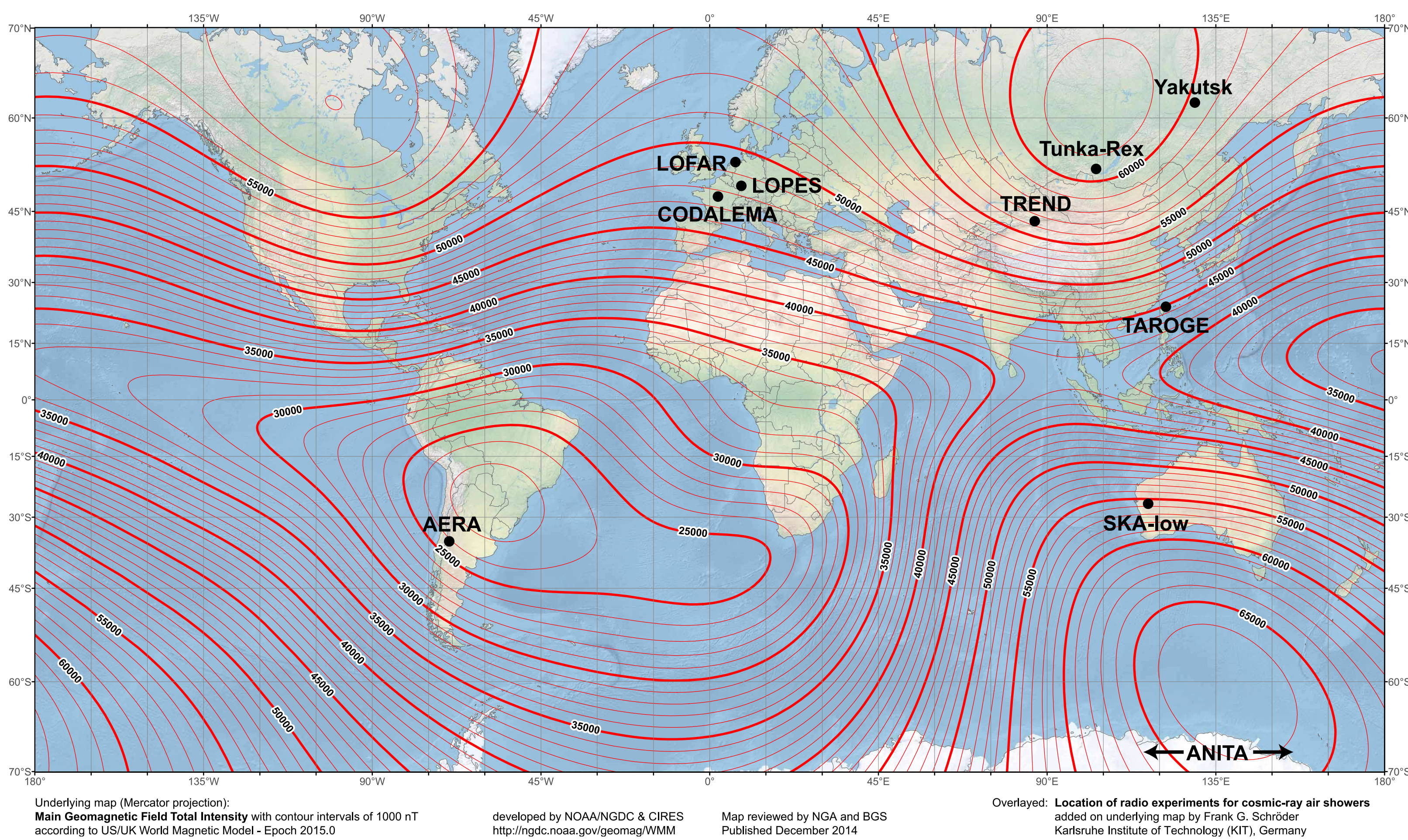
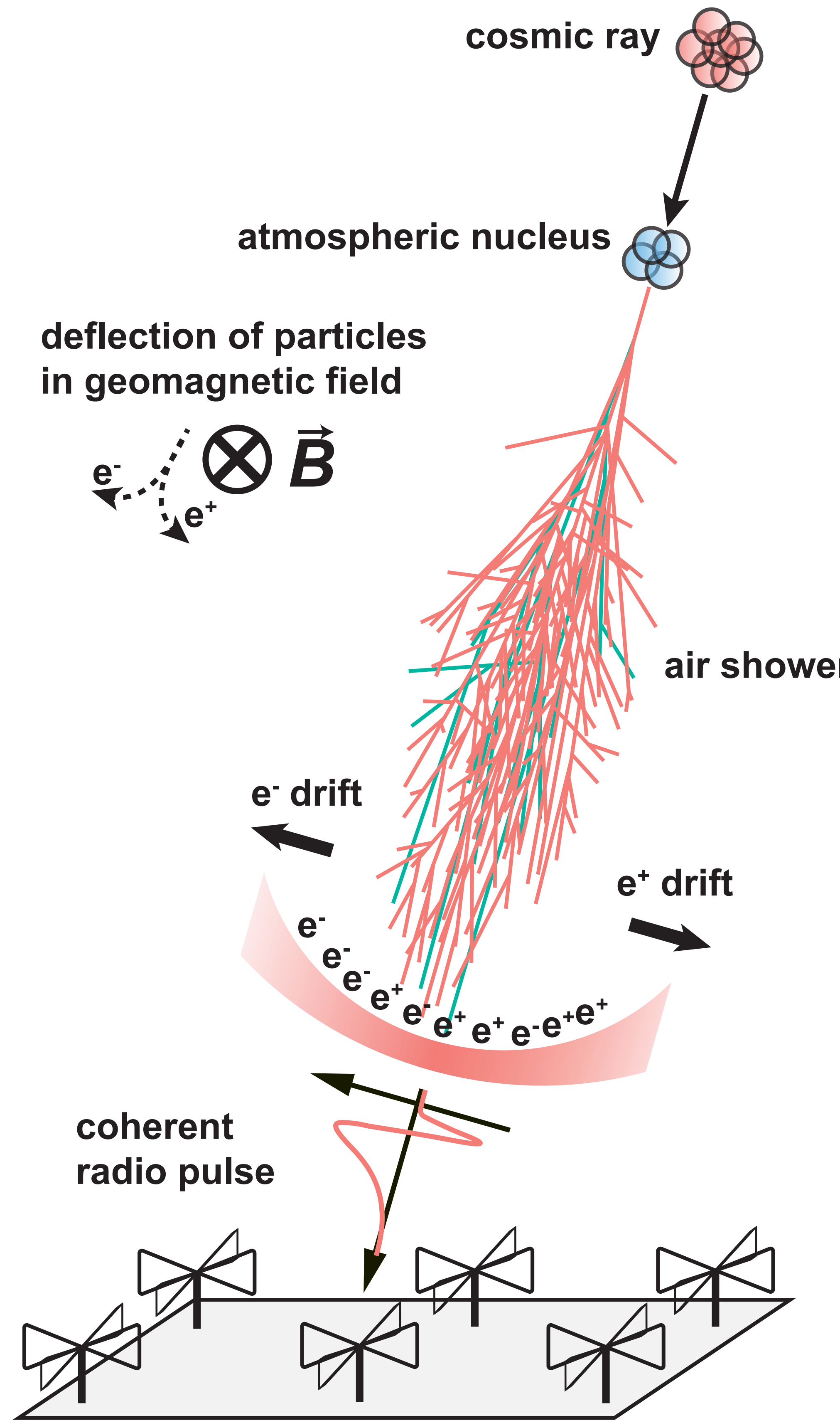
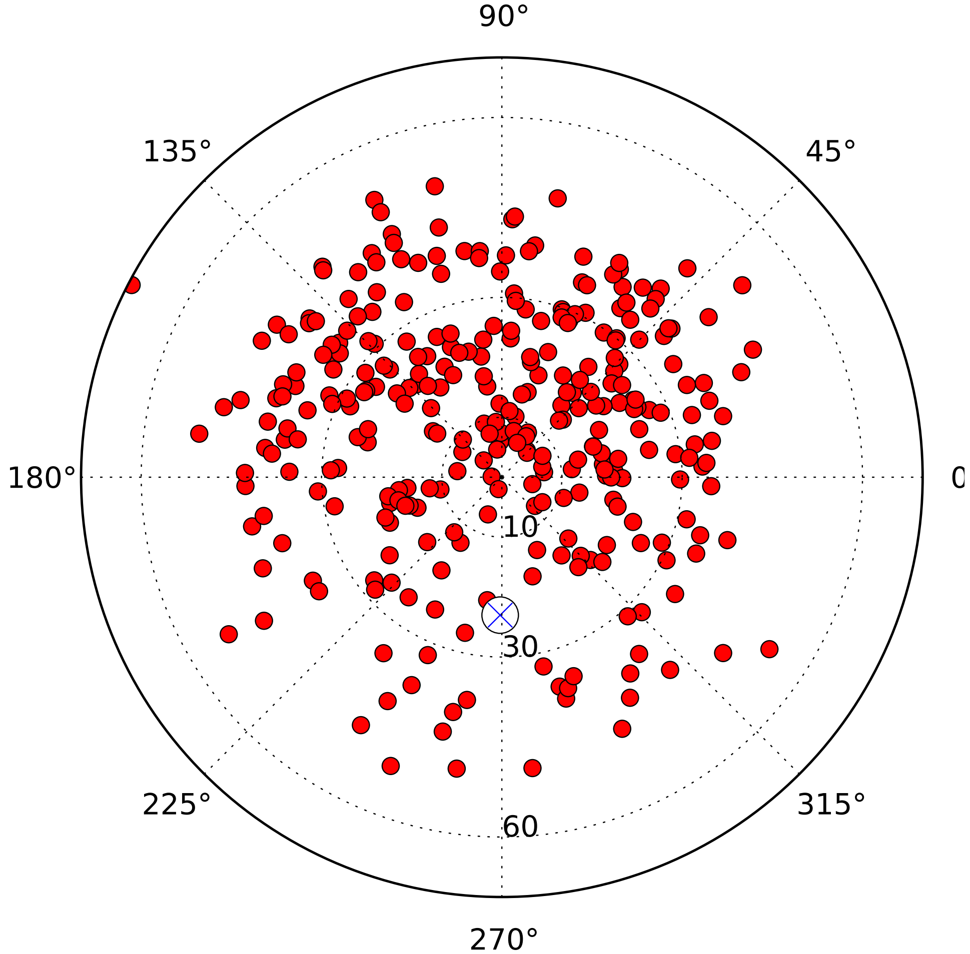


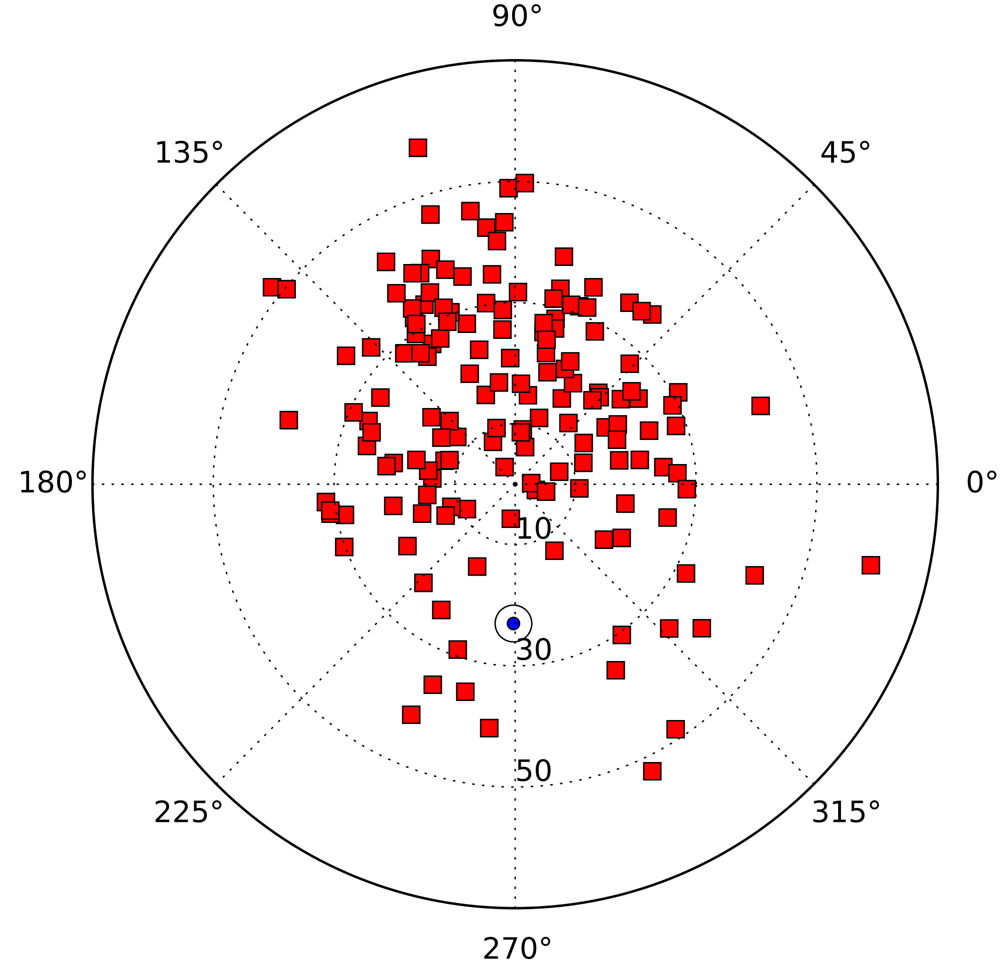
F. Schröder, Prog. Part. Nucl. Phys. 93 (2017) 1

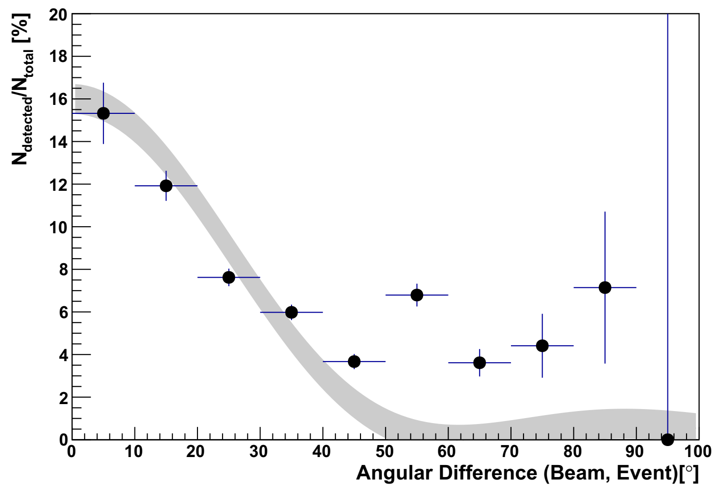


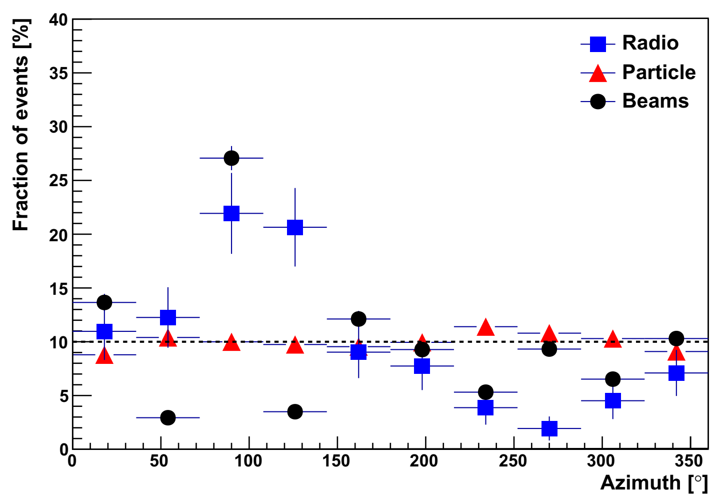
Arrival direction of showers with strong radio signals

north-south asymmetry
v x B effect









LOFAR

30 - 80 MHz

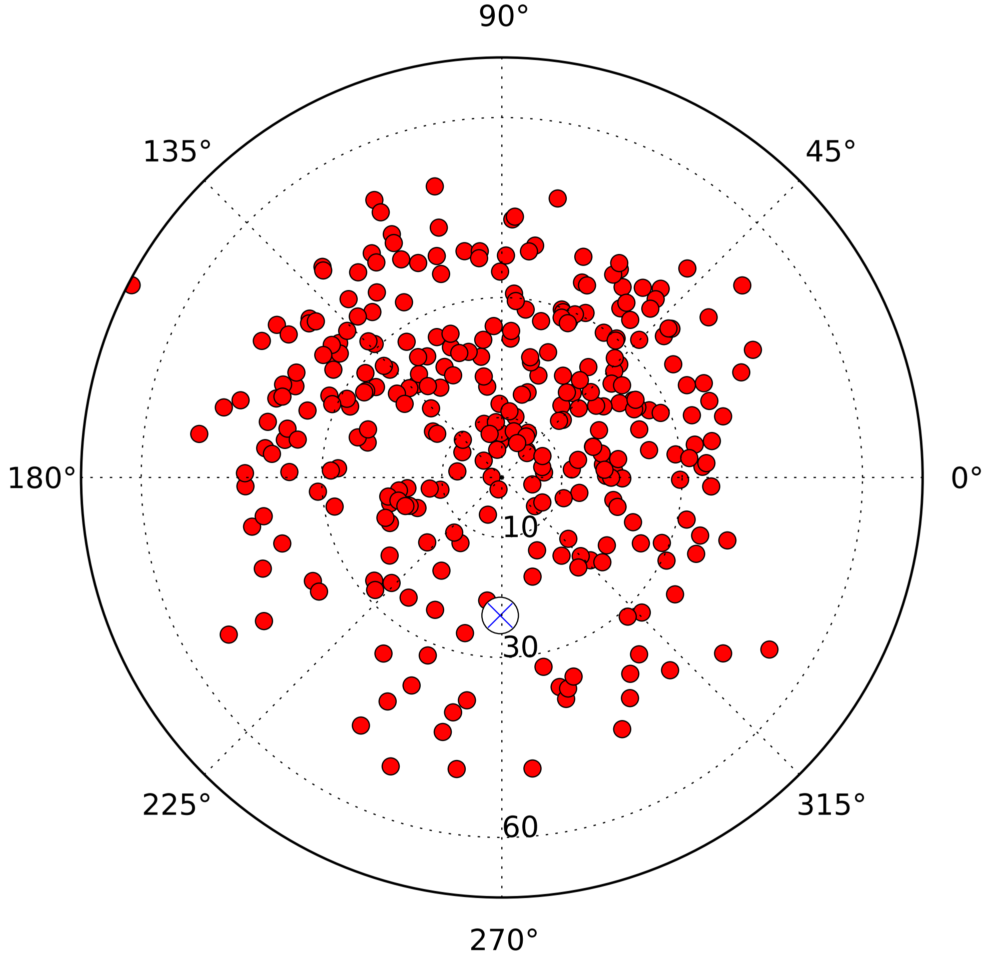
110 - 190 MHz

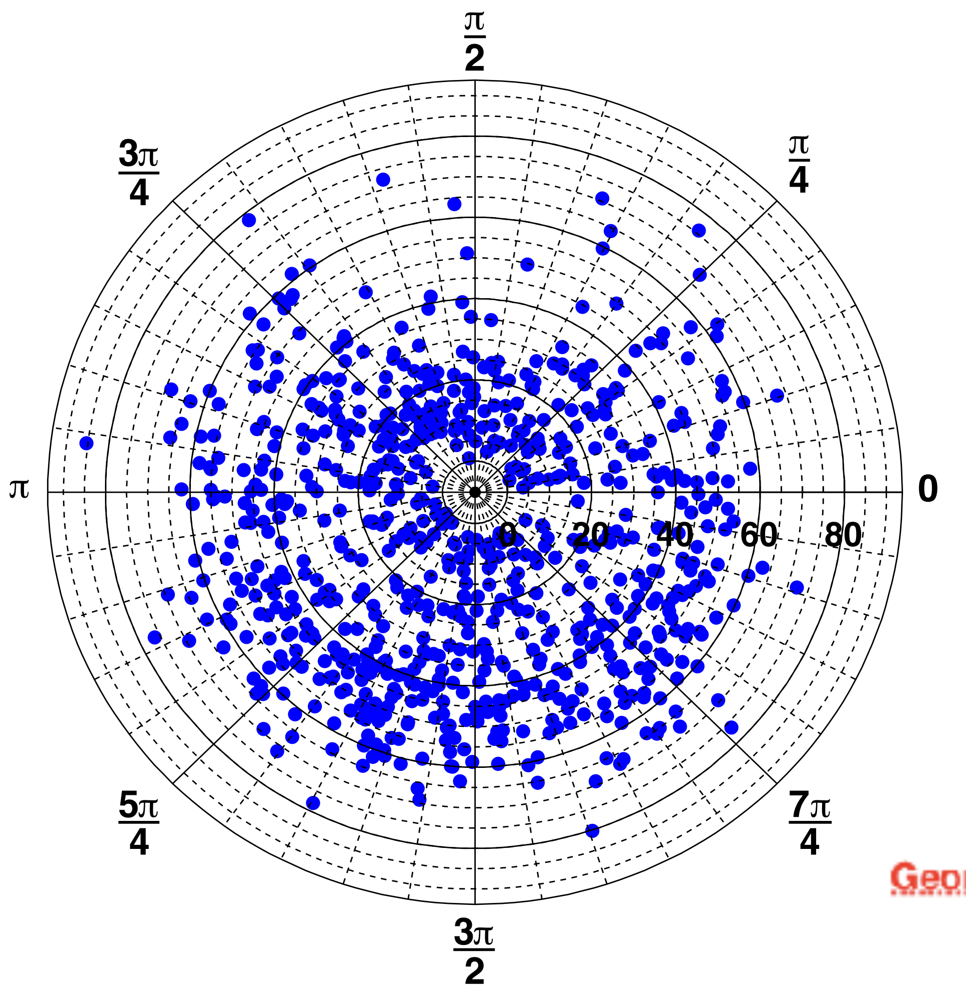
A. Nelles et al., Astroparticle Physics 65 (2015) 11

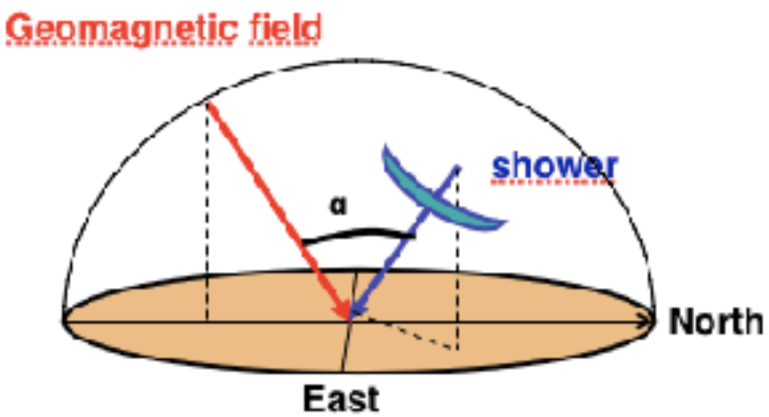
P. Schellart et al., A&A 560 (2013) A98

Arrival direction of showers with strong radio signals

north-south asymmetry
v x B effect







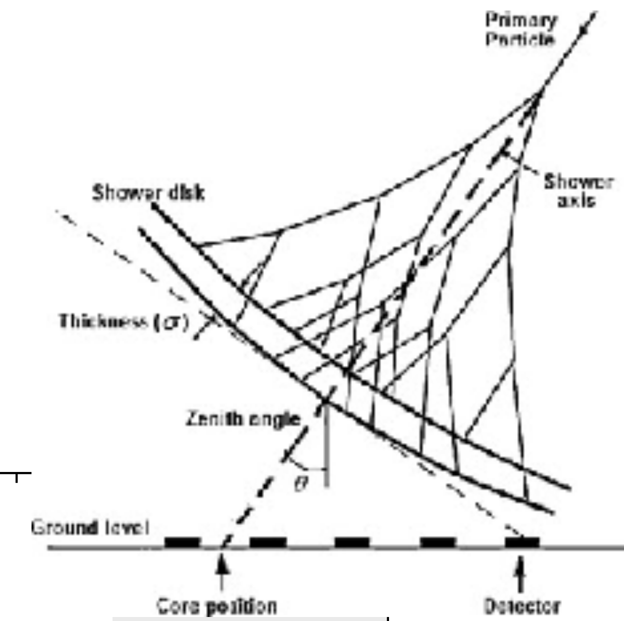
LOFAR

AERA Auger Engineering Radio Array

30 - 80 MHz

P. Schellart et al., A&A 560 (2013) A98

Geomagnetic effect



T. Huege / Physics Reports 620 (2016) 1–52

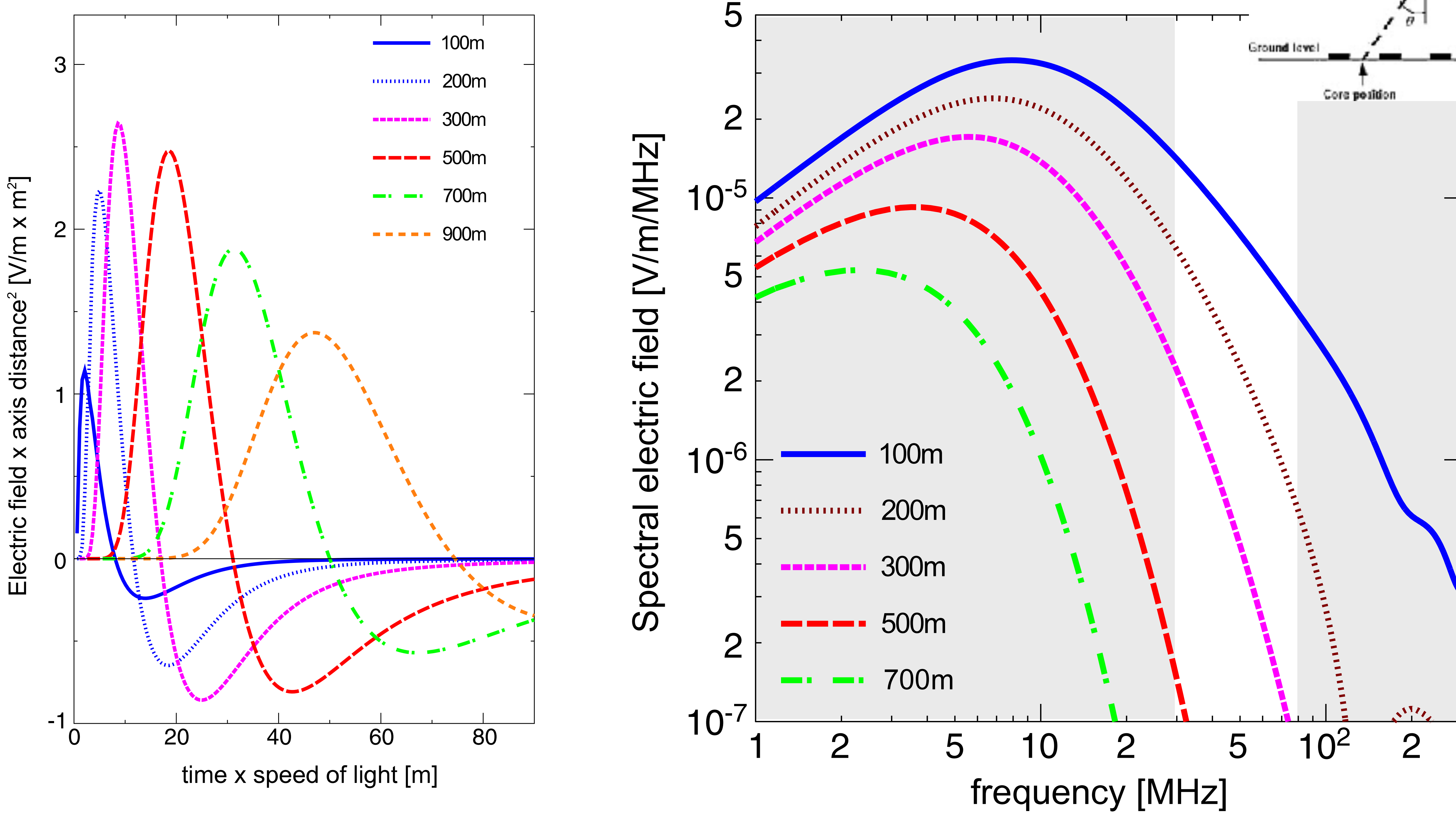


Fig. 4. Radio pulses (top) arising from the time-variation of the geomagnetically induced transverse currents in a 10^{17} eV air shower as observed at various observer distances from the shower axis and their corresponding frequency spectra (bottom). Refractive index effects are not included.
Source: Adapted from [18].

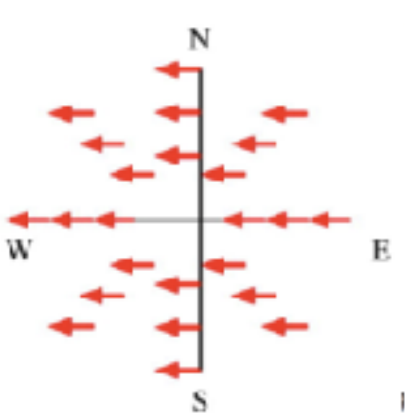
Radio Emission in Air Showers

- Mainly: Charge separation in geomagnetic field
  $\vec{E} \propto \vec{v} \times \vec{B}$

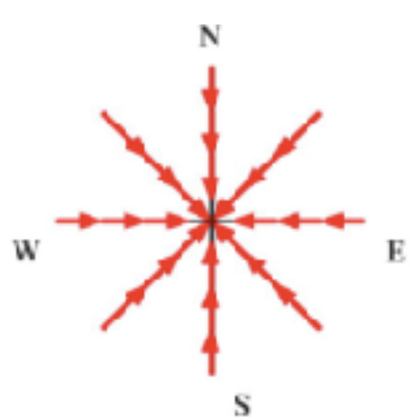
  Theory predicts additional mechanisms:
- excess of electrons in shower: charge excess
- superposition of emission due to Cherenkov effects in atmosphere

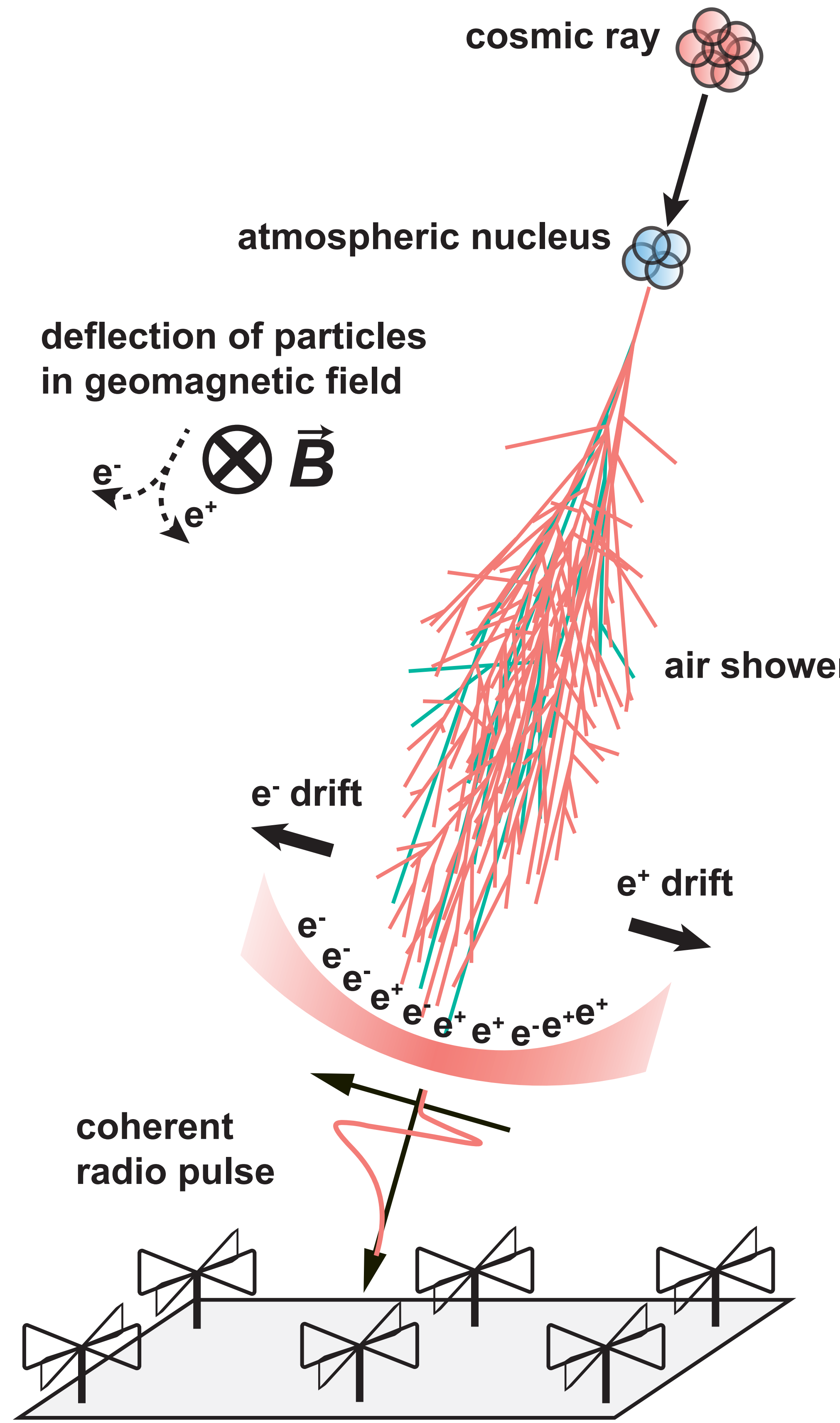
polarization of radio signal

geomagnetic



Askaryan

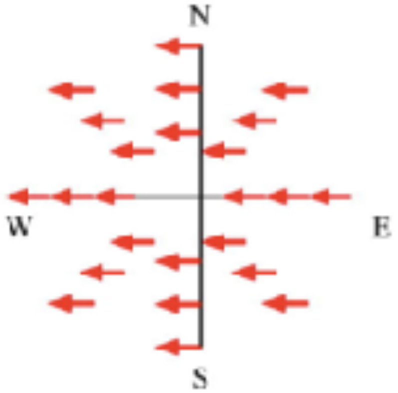




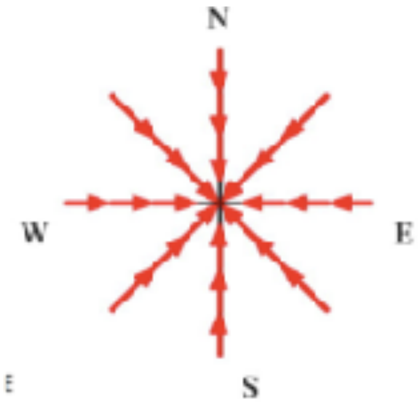
Polarization footprint

of an individual air shower

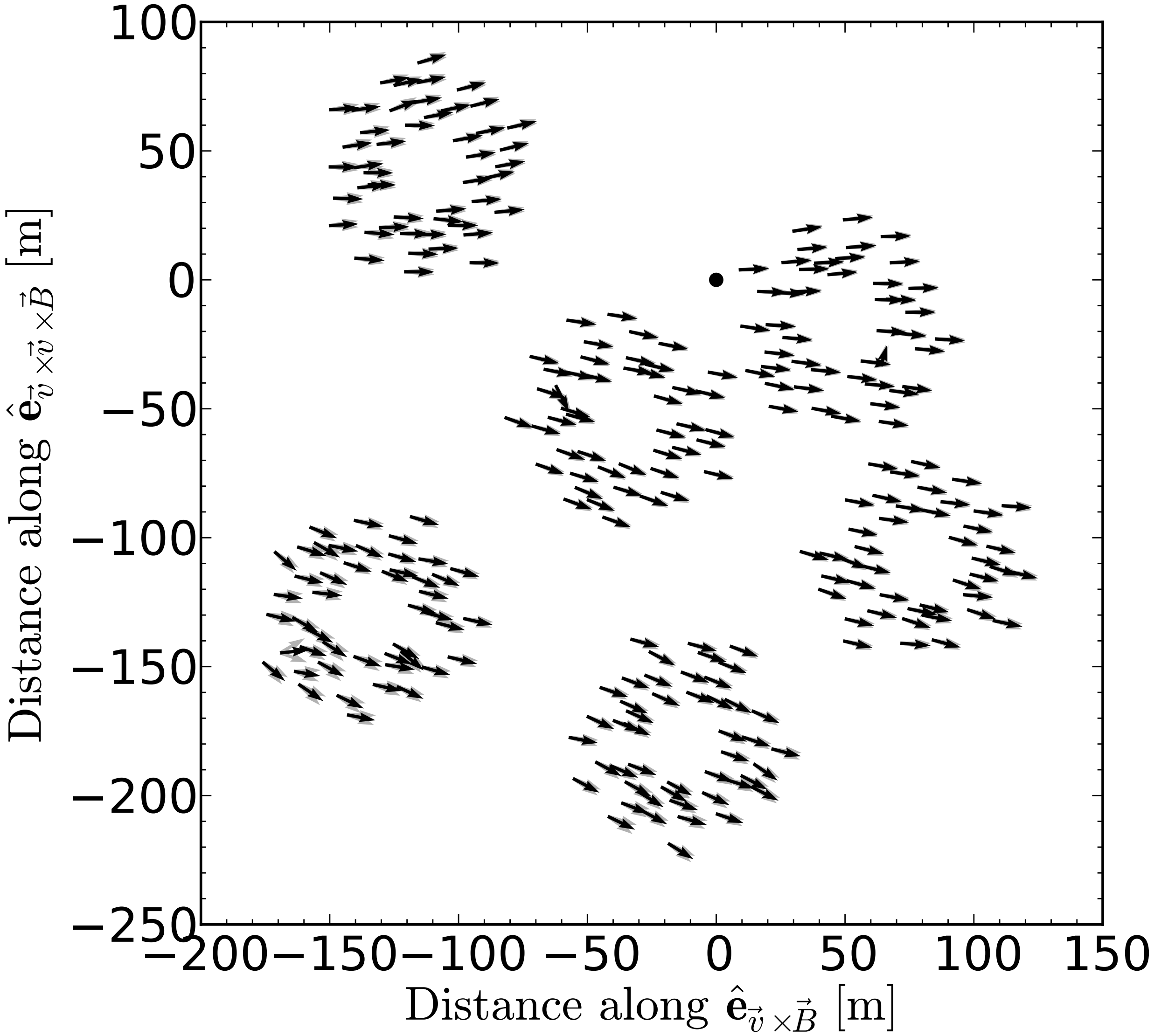
geomagnetic



Askaryan



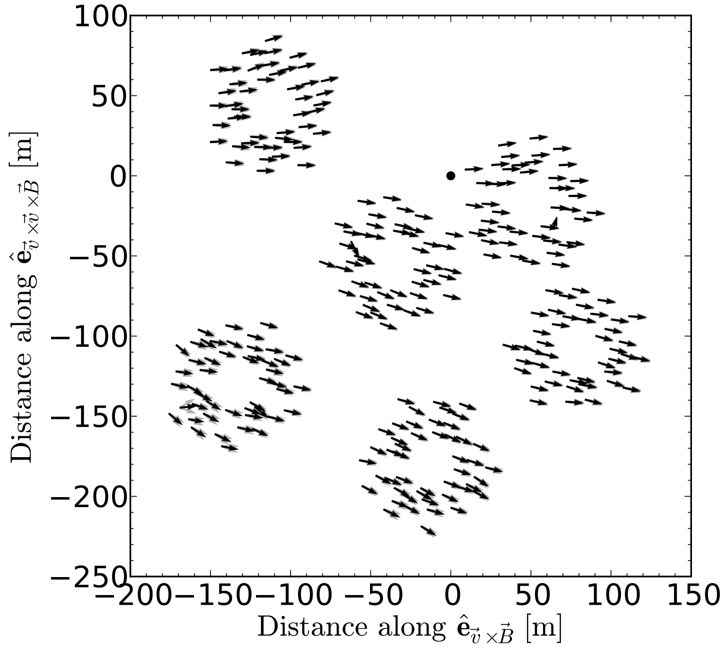
LOFAR



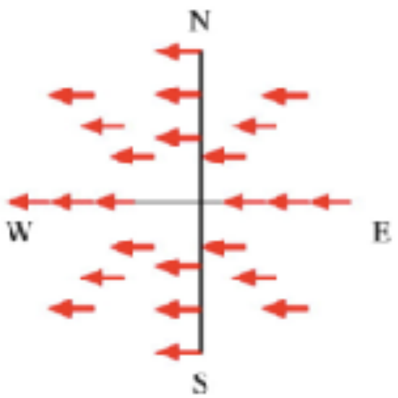
P. Schellart et al., JCAP 10 (2014) 014

Polarization footprint

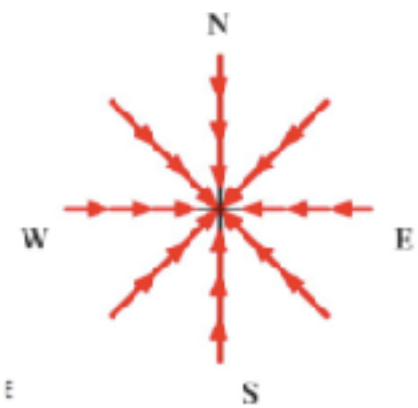
of an individual air shower



geomagnetic



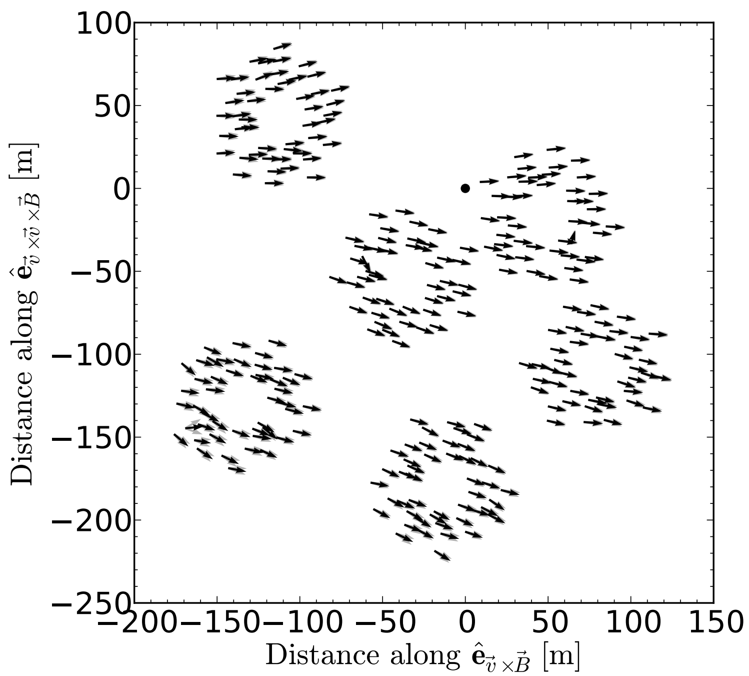
Askaryan



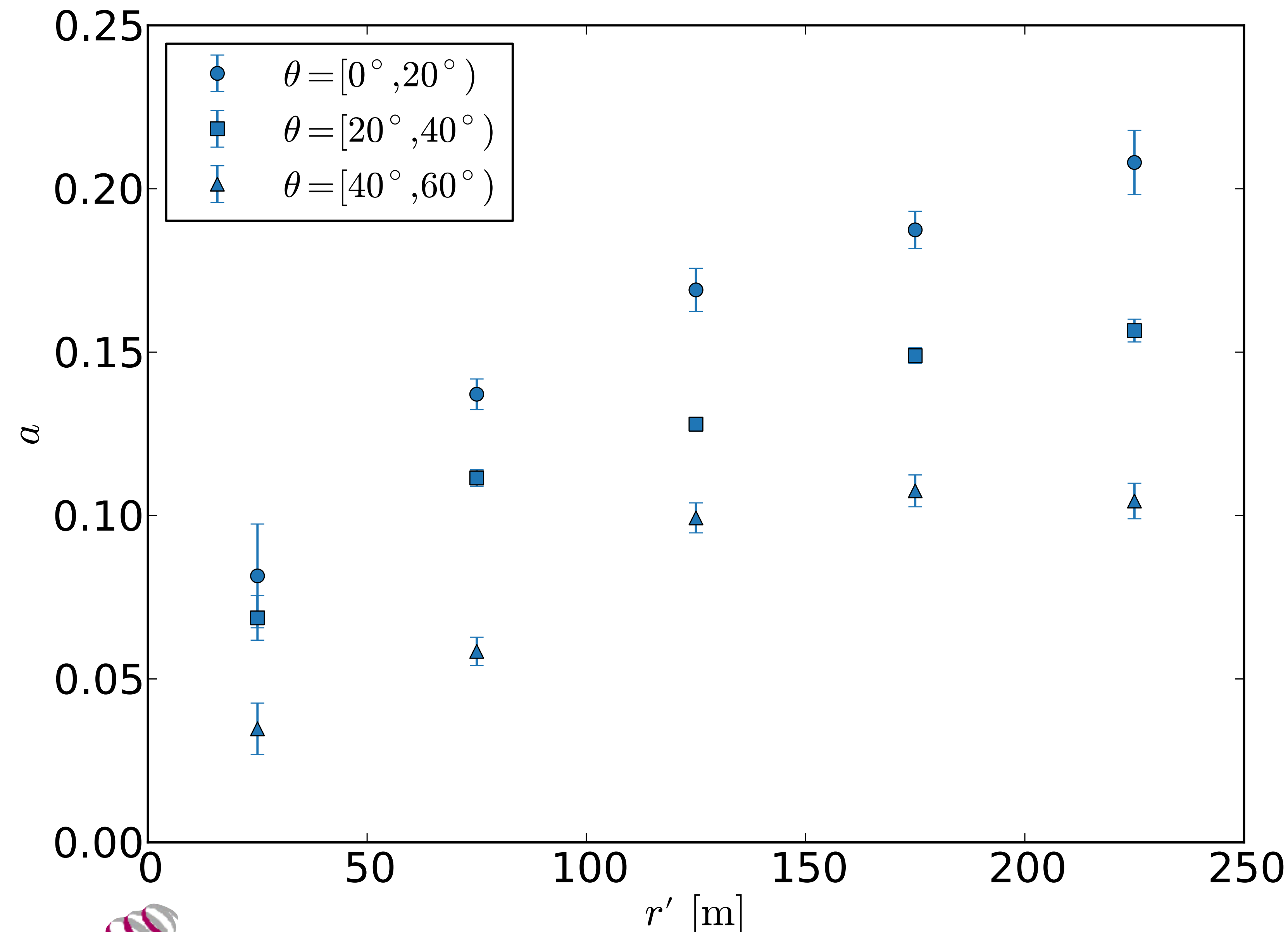
LOFAR

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

Charge excess fraction

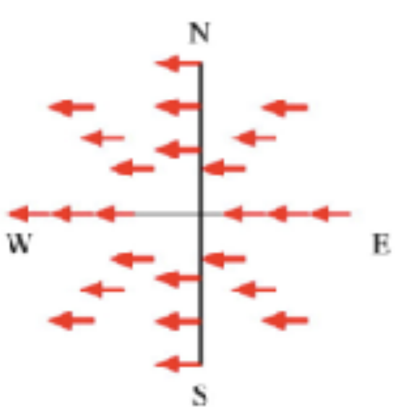


$\frac{\text{Askaryan}}{\text{geomagnetic}}$

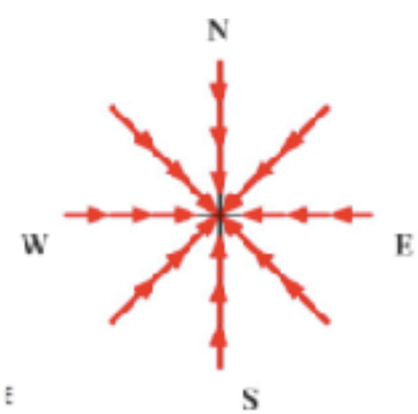


LOFAR

geomagnetic



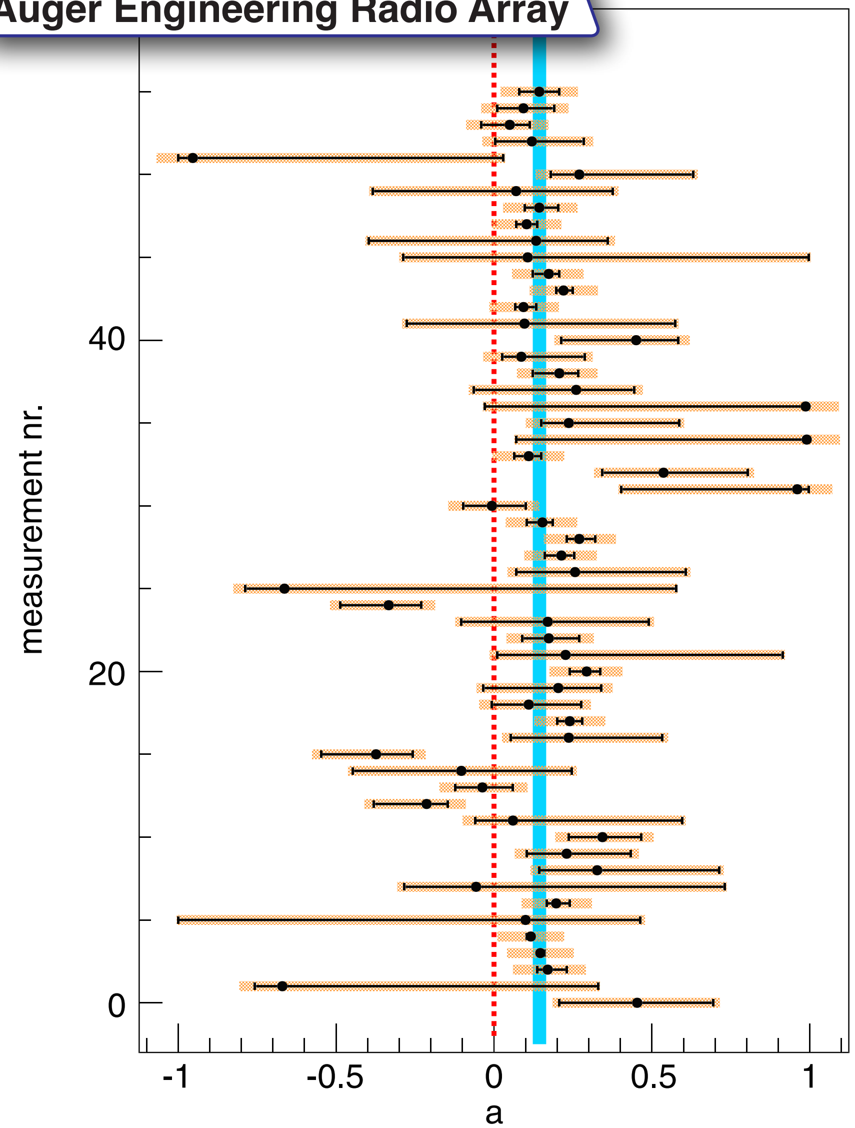
Askaryan



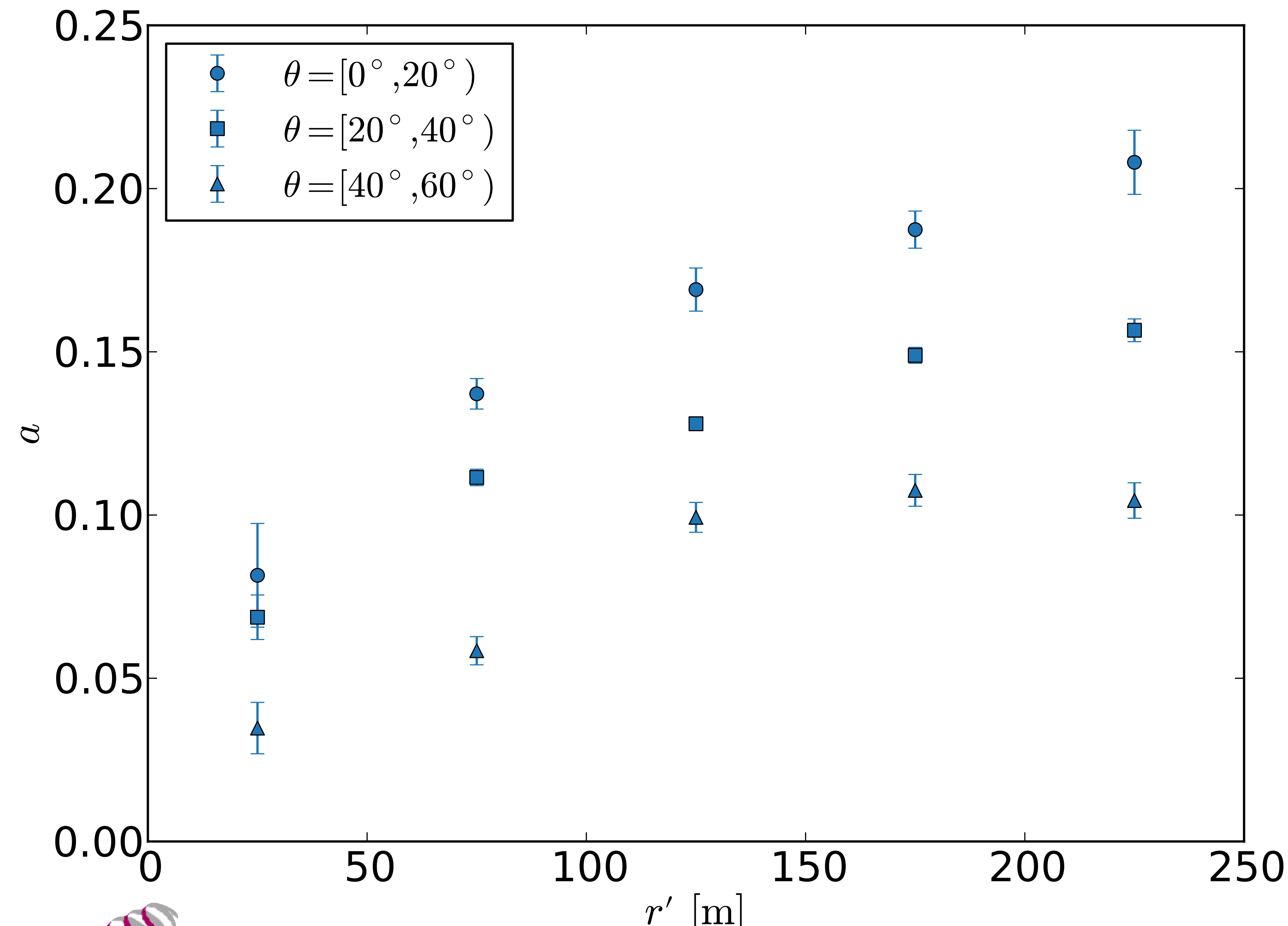
P. Schellart et al., JCAP 10 (2014) 014

Charge excess fraction

Auger Engineering Radio Array



$\frac{\text{Askaryan}}{\text{geomagnetic}}$

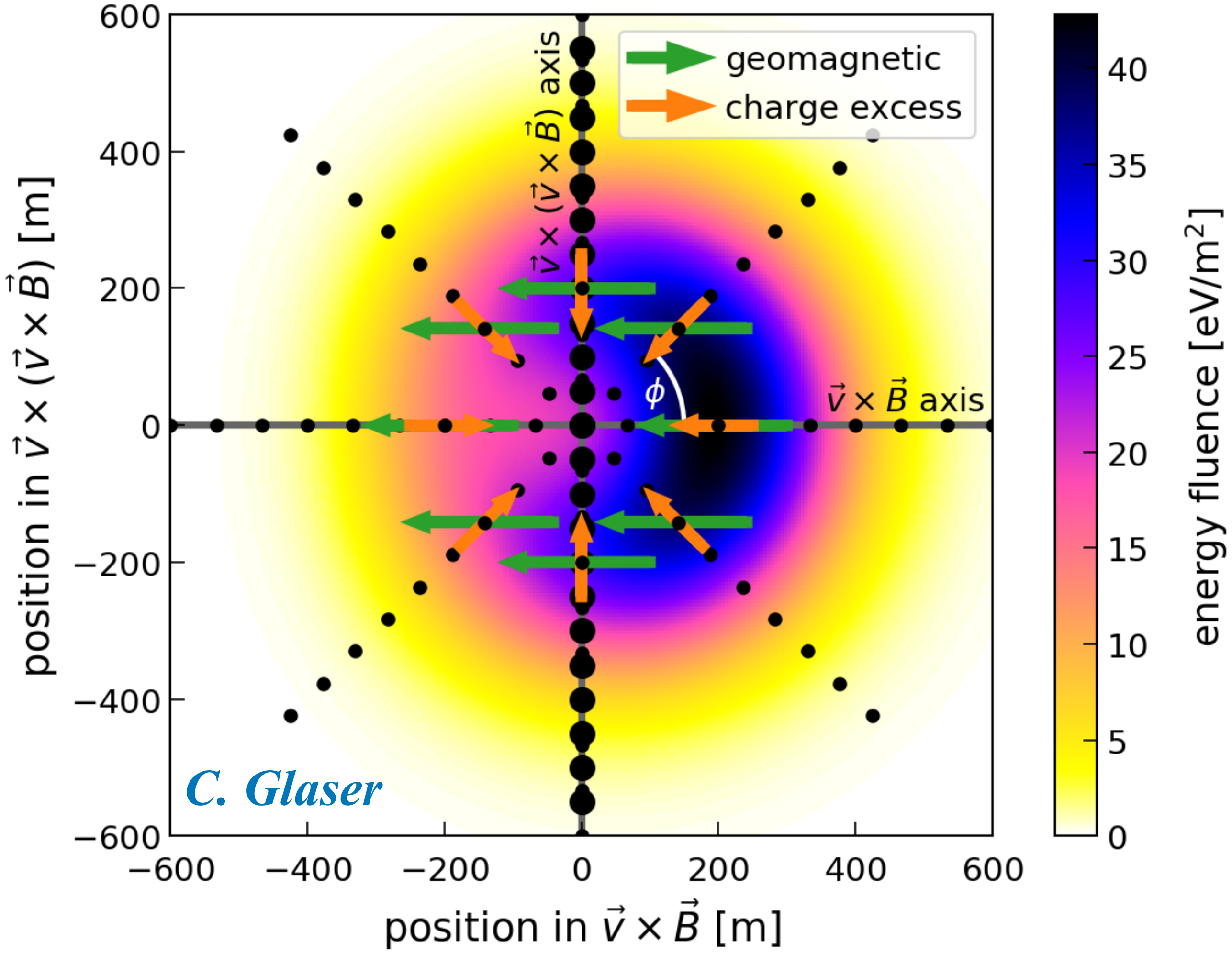


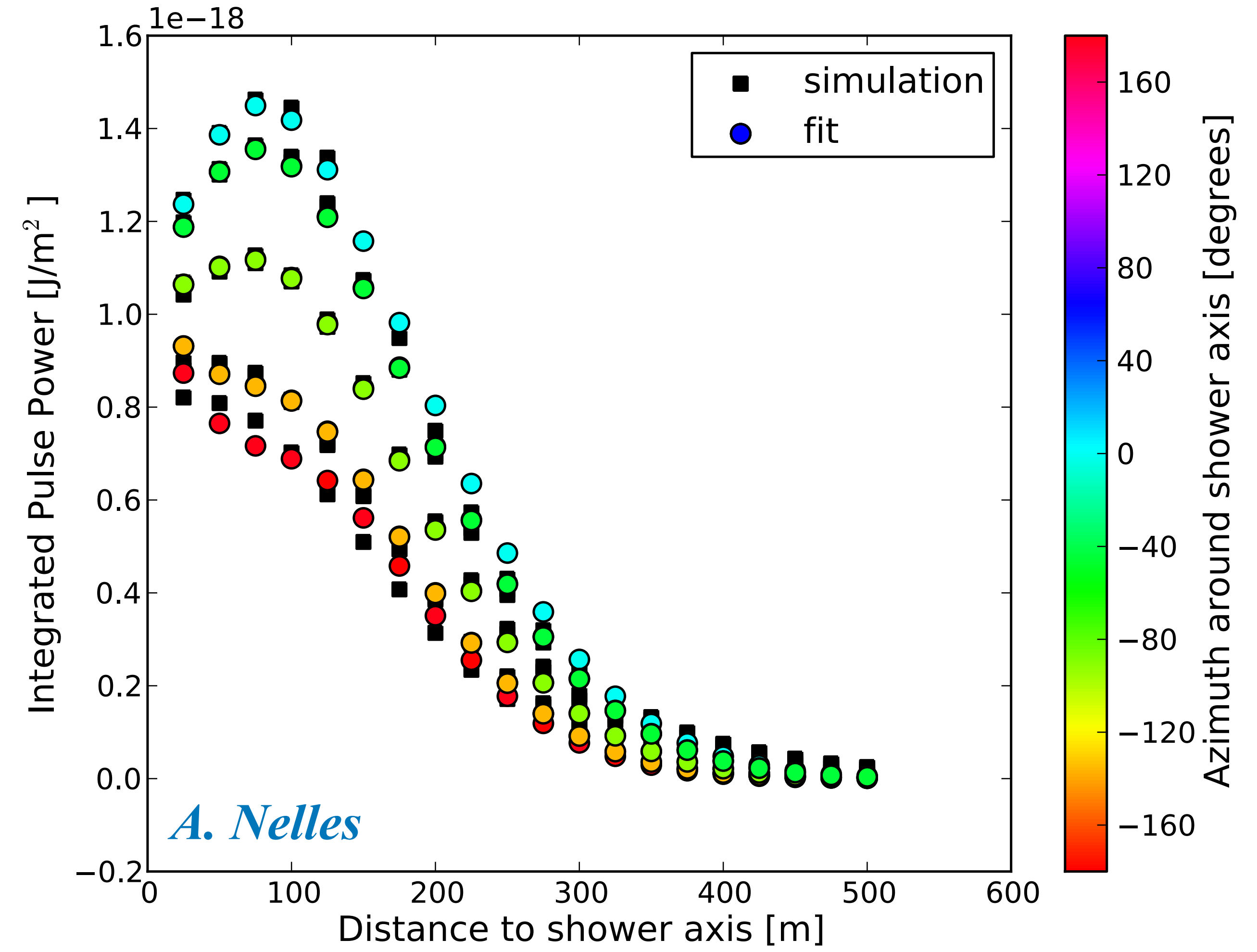
LOFAR

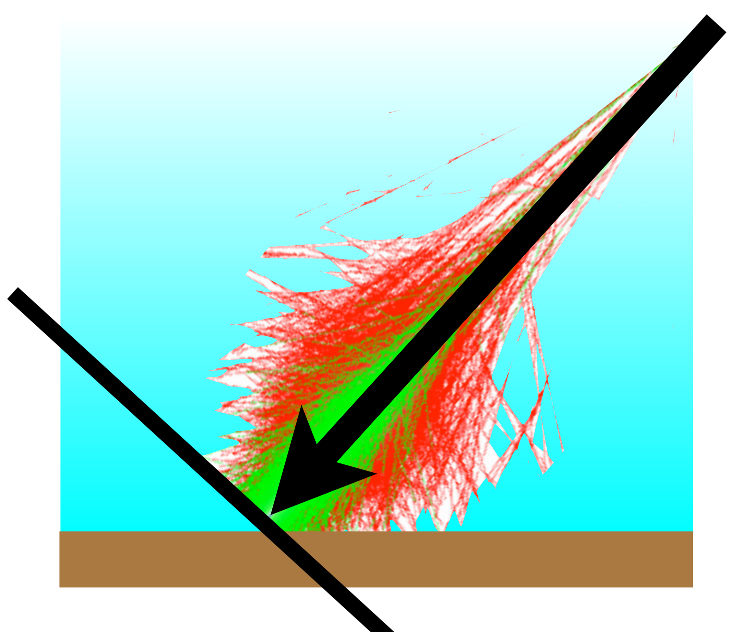
A. Aab, PRD 89 (2014) 052002

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

Footprint of radio emission on the ground



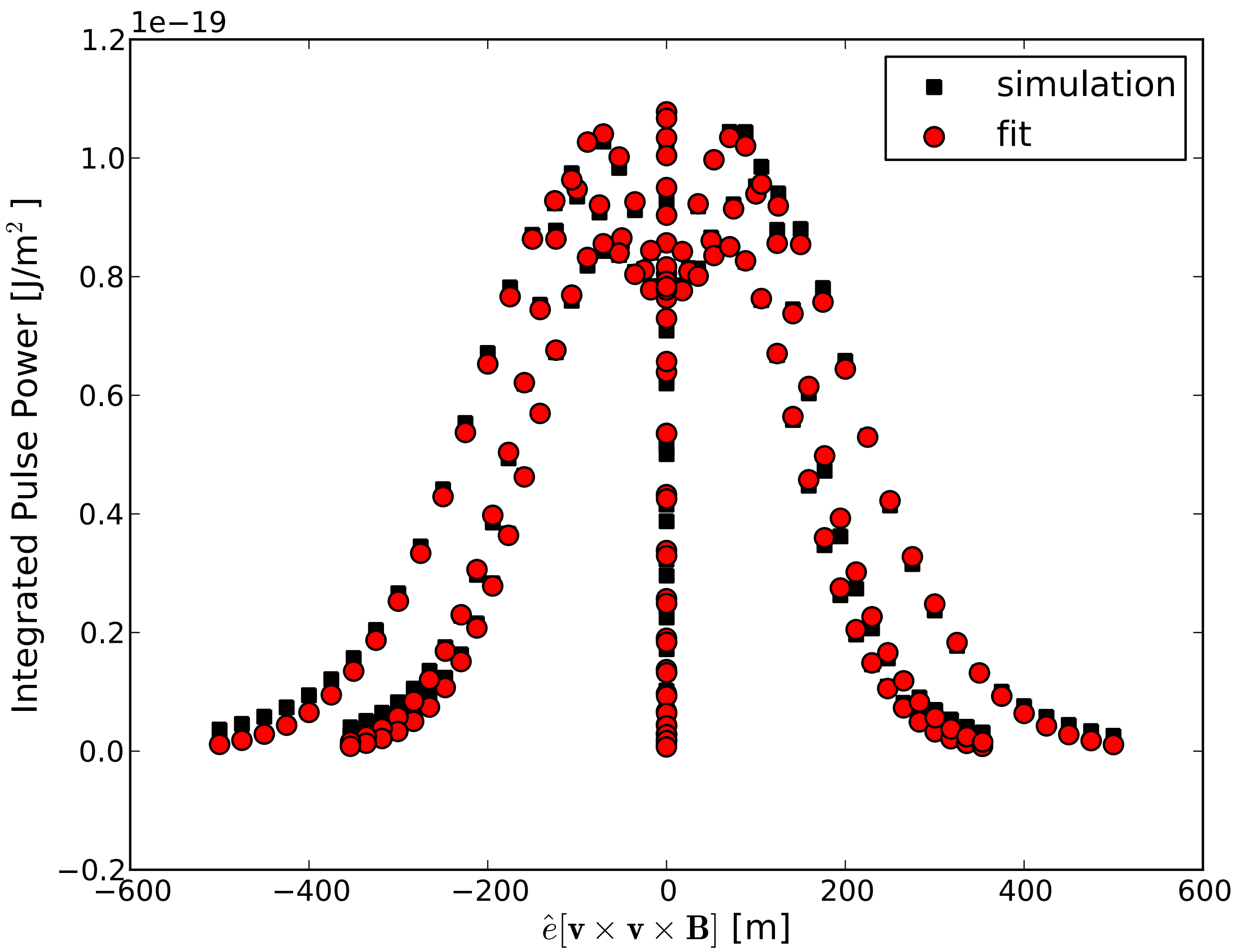




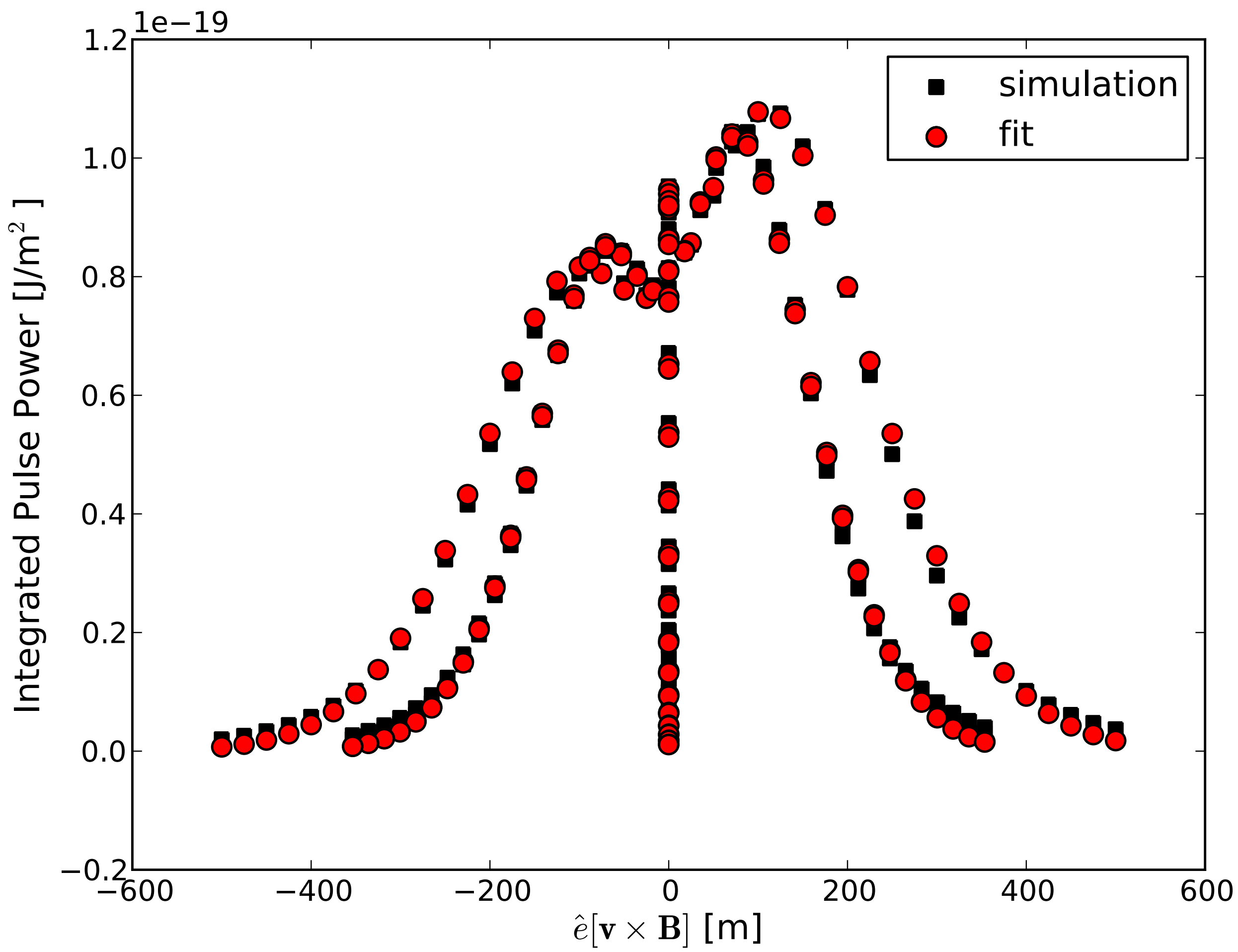
Lateral distribution of radio signals

not rotationally symmetric —> fit two Gaussian functions

v x (v x B)



v x B



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

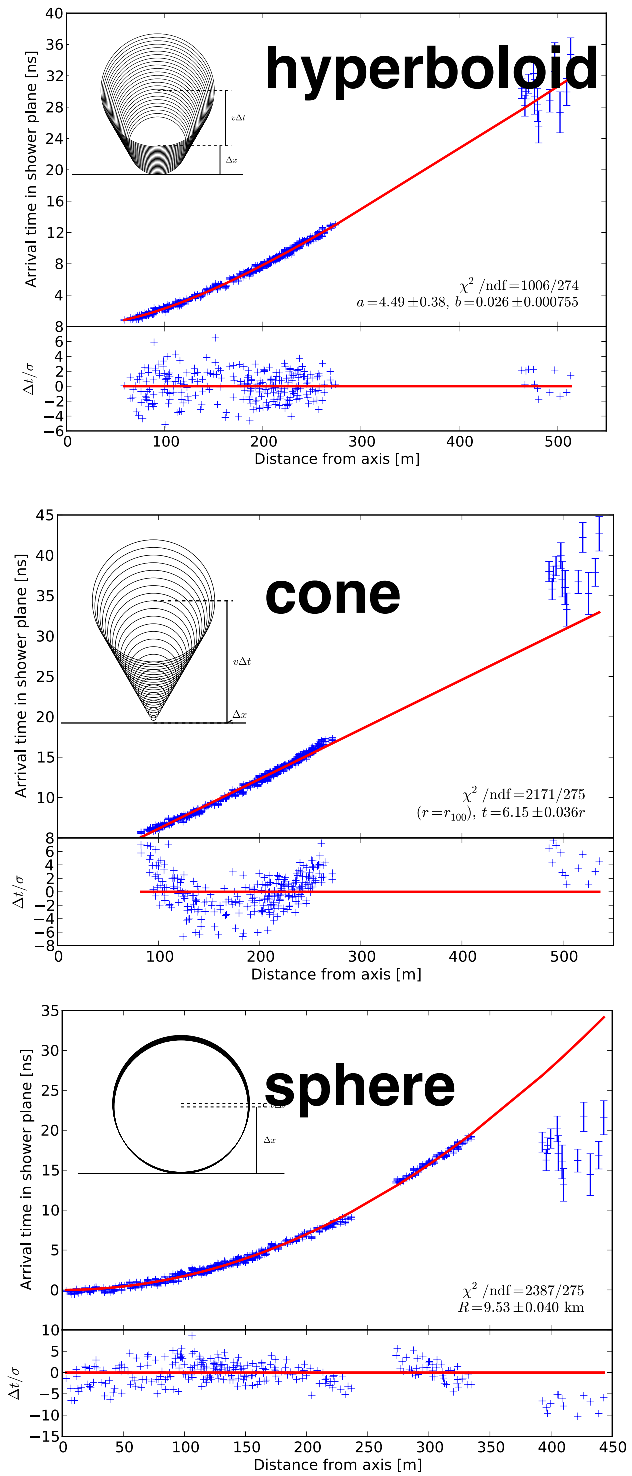
A. Nelles et al., Astropart. Phys. 60 (2015) 13

Properties of incoming cosmic ray

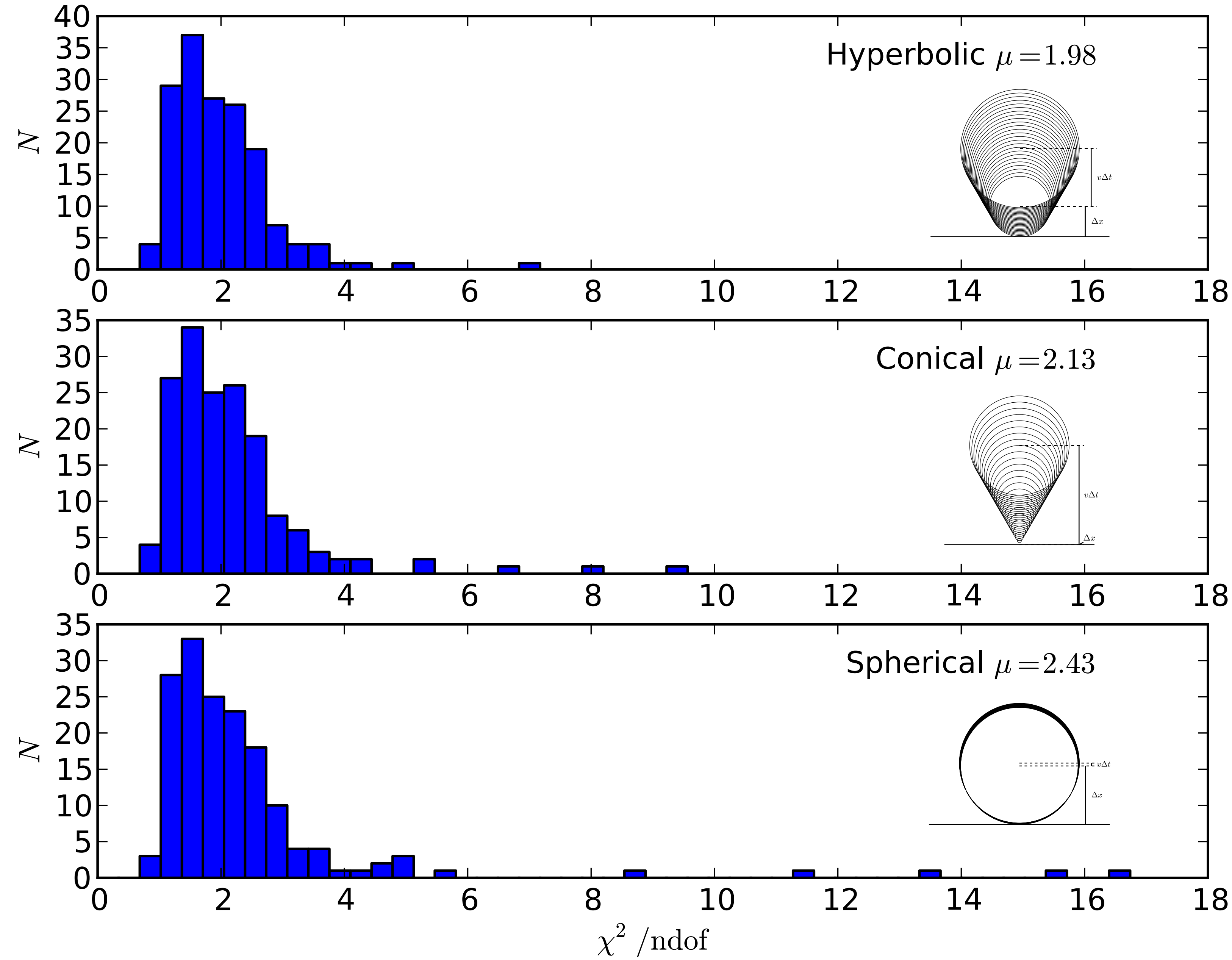
- direction
- energy
- type

Direction

Shape of Shower Front



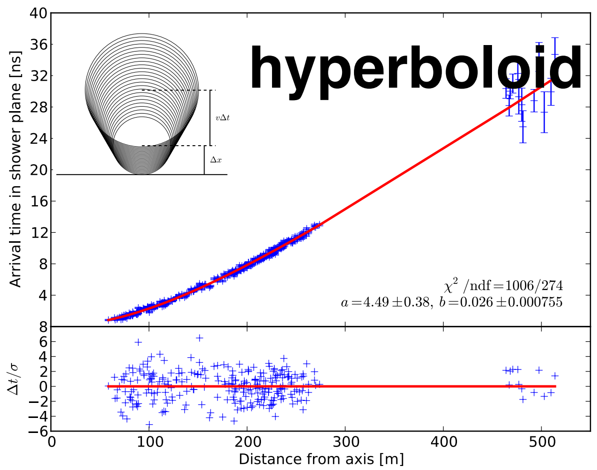
fit quality

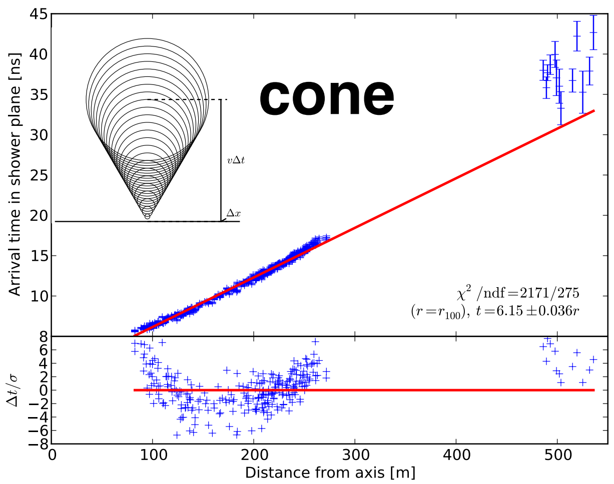


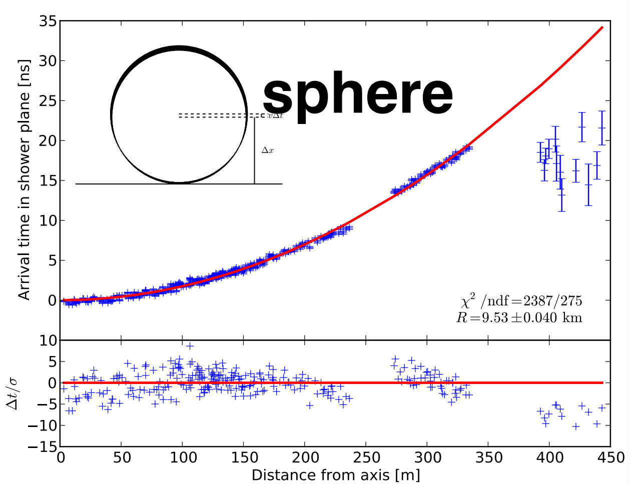
A. Corstanje et al., Astropart. Phys. 61 (2015) 22

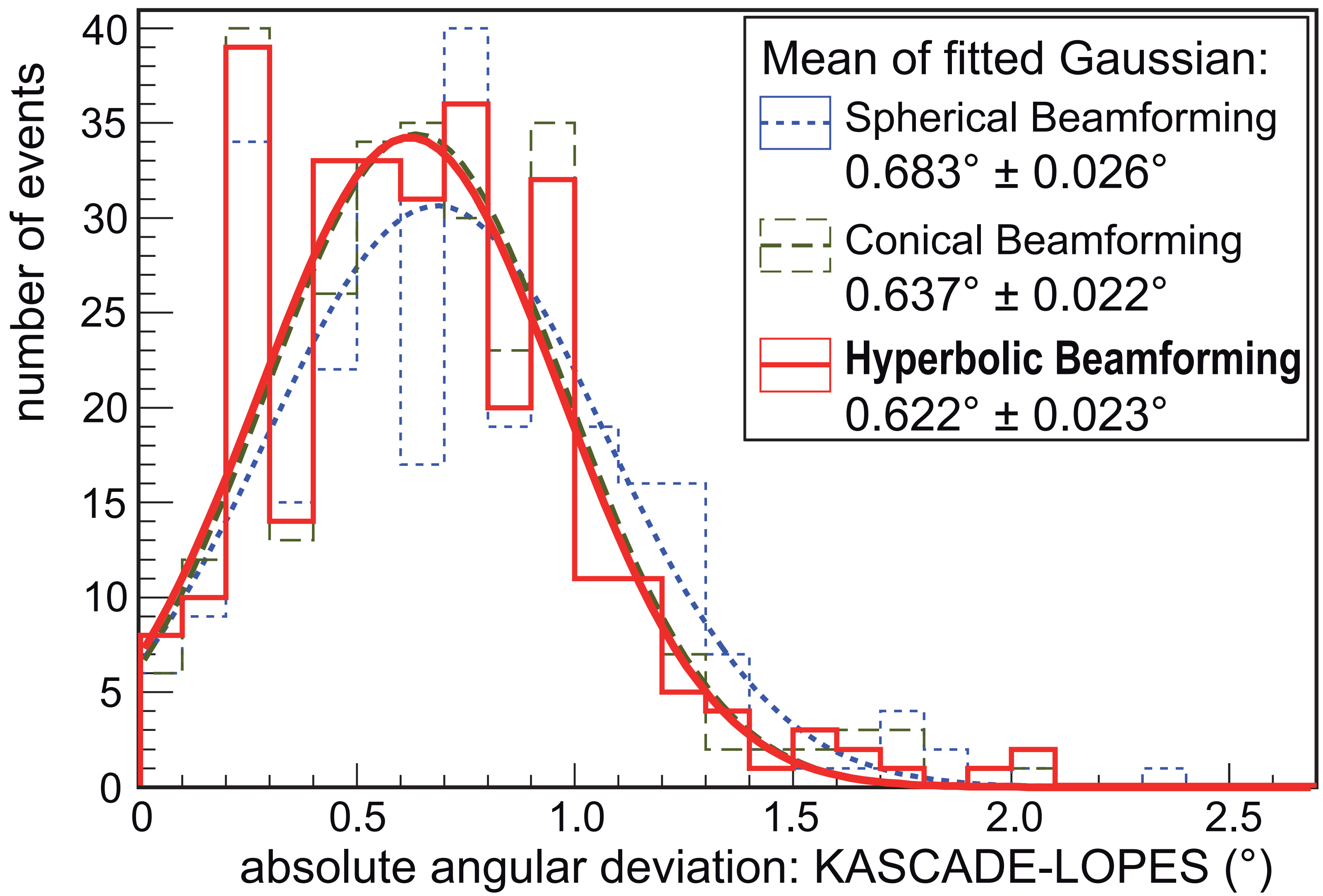
Shape of Shower Front

LOFAR







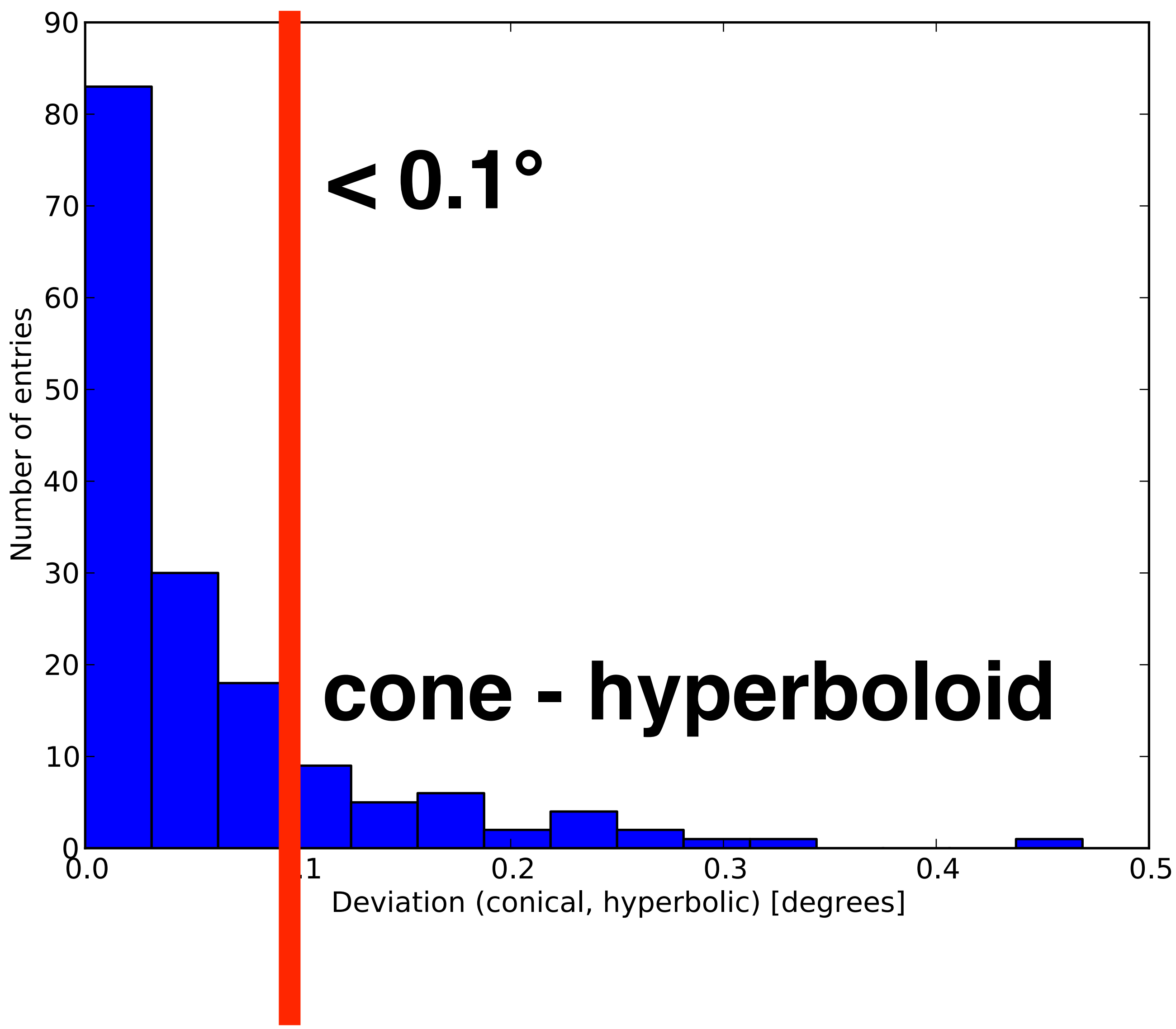


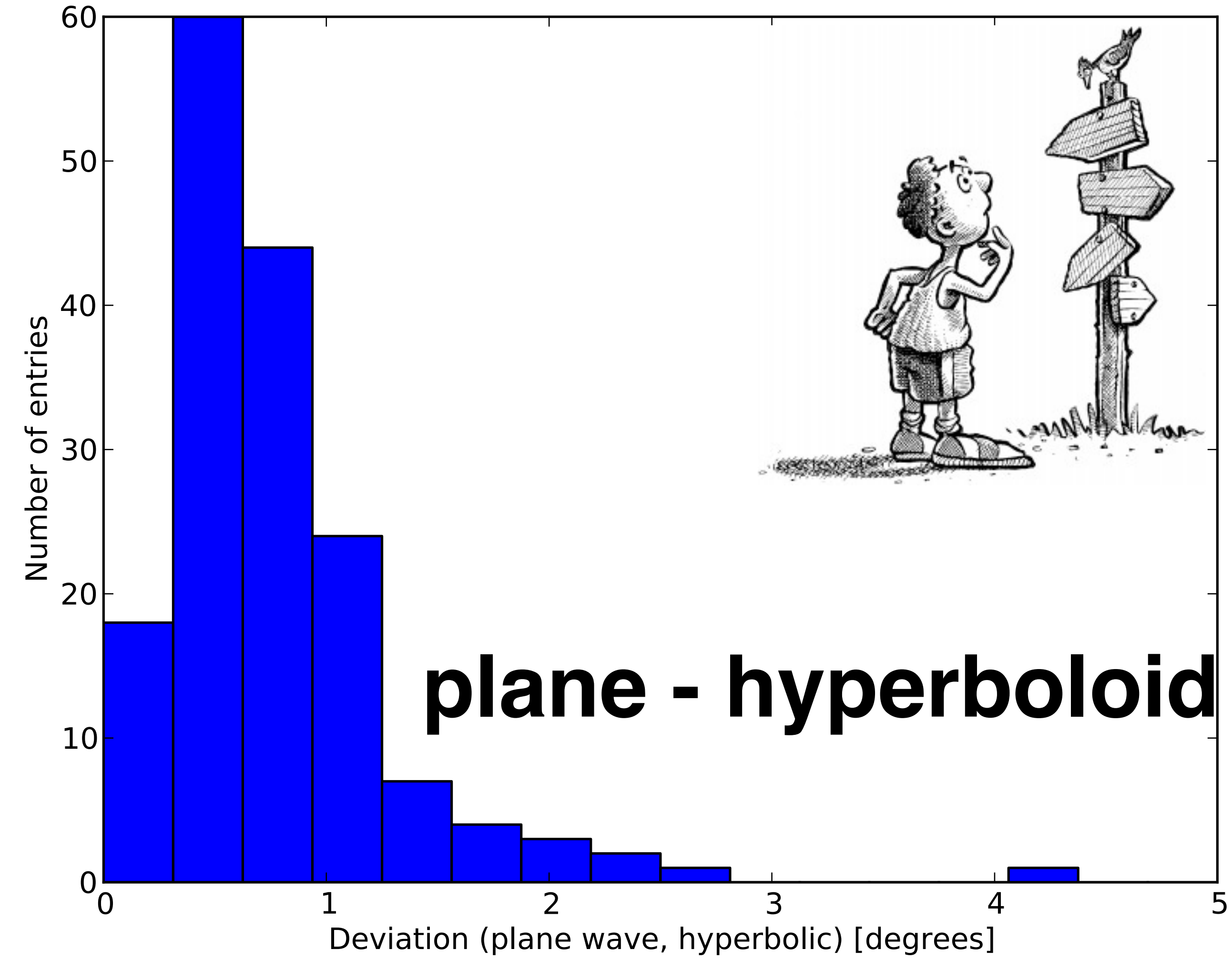
W.D. Apel et al., JCAP 1409 (2014) no.09, 025

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

Accuracy of Shower Direction

angular difference between..





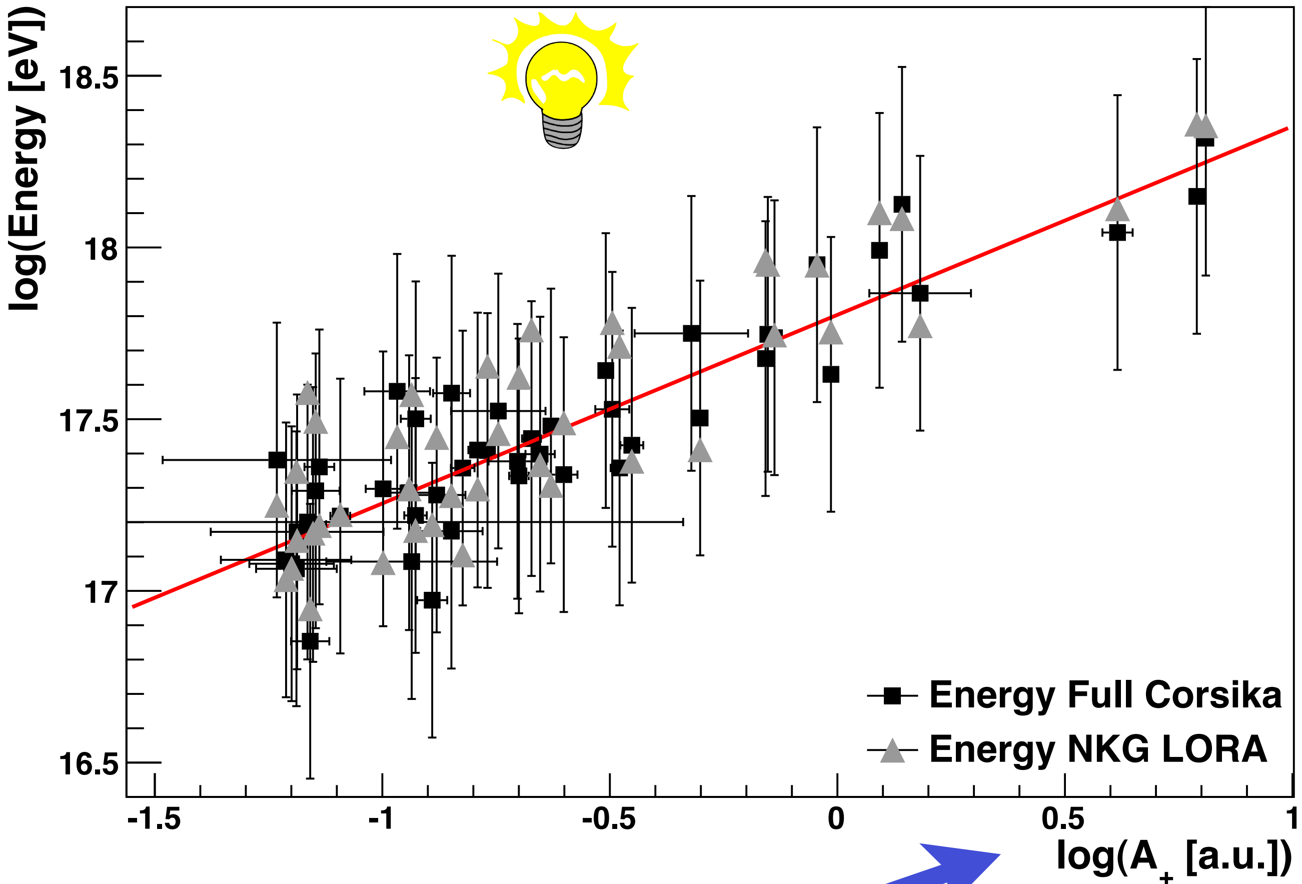
LOFAR

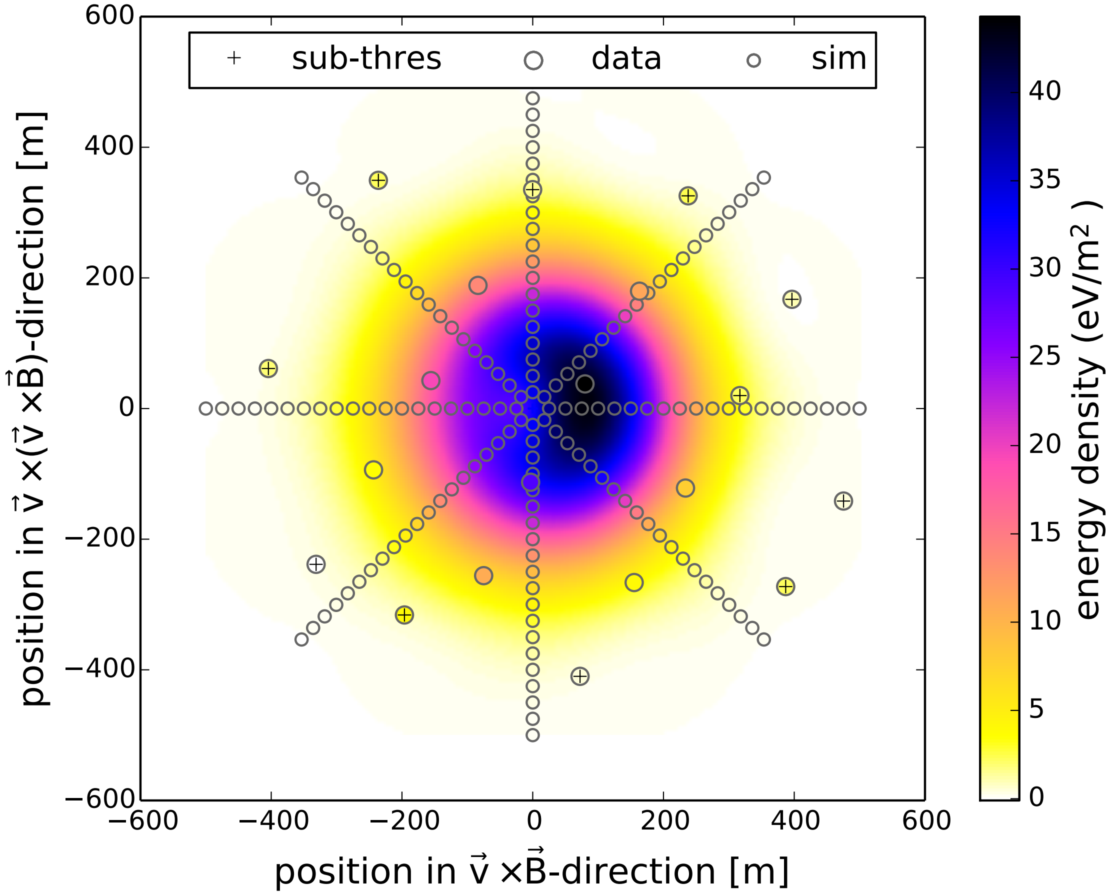
A. Corstanje et al., Astropart. Phys. 61 (2015) 22

Energy

Energy of primary particle

LOFAR

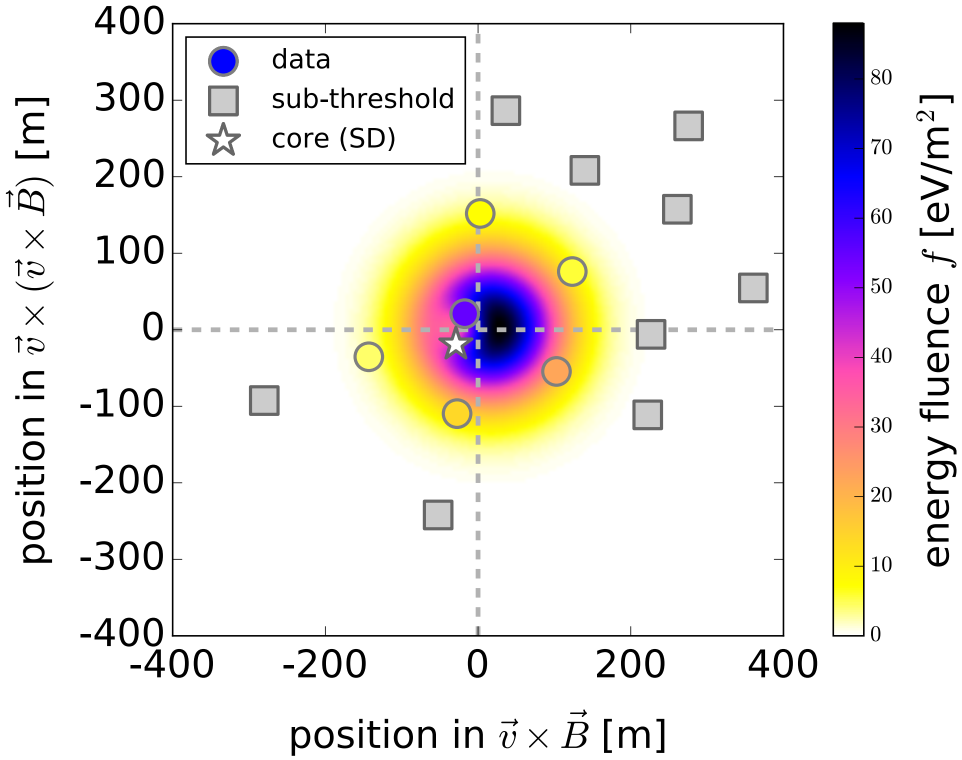




$$P(x', y') = A_+ \cdot \exp\left(\frac{-[(x' - X_+)^2 + (y' - Y_+)^2]}{\sigma_+^2}\right) - A_- \cdot \exp\left(\frac{-[(x' - X_-)^2 + (y' - Y_-)^2]}{\sigma_-^2}\right) + O$$

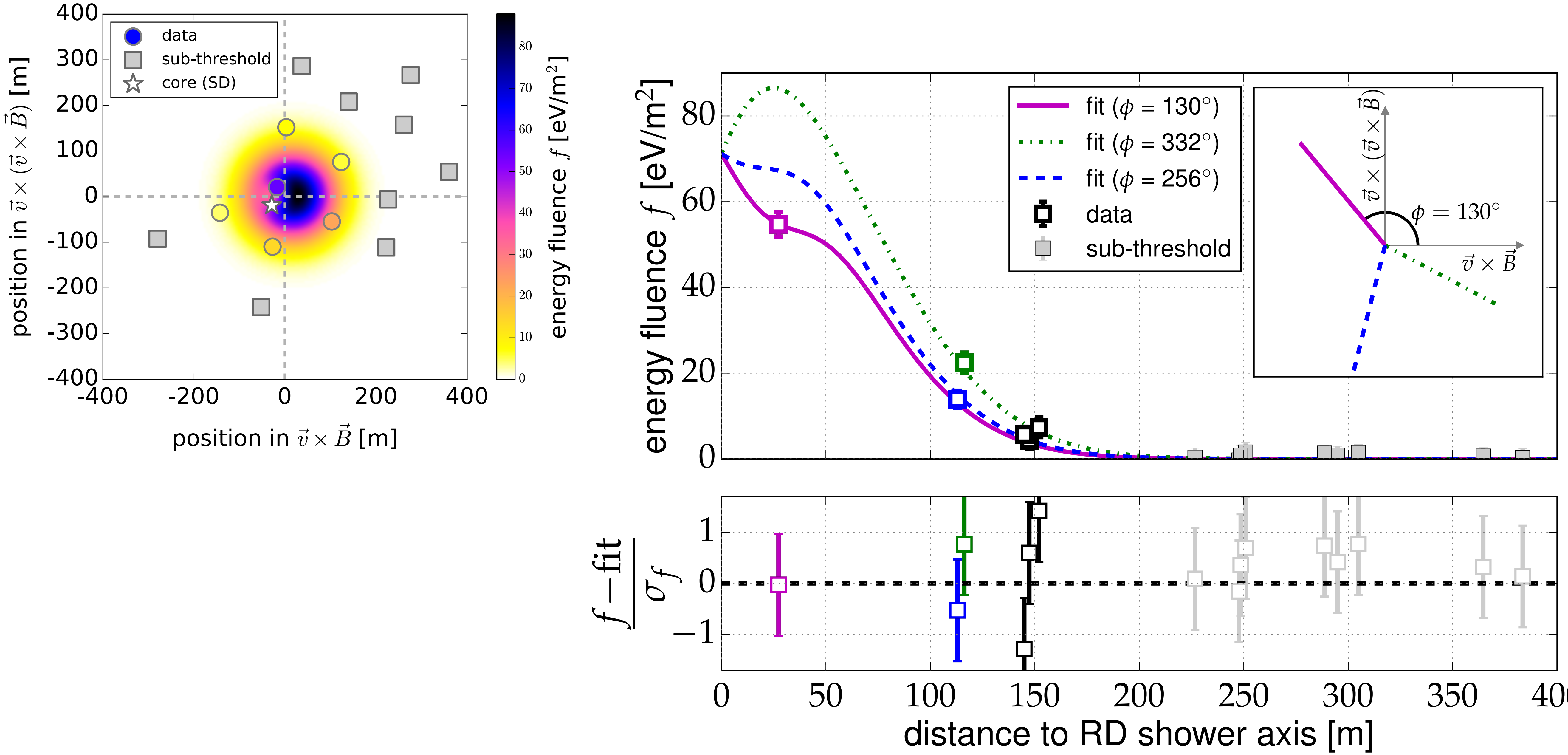
A. Nelles et al., JCAP 05 (2015) 018

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



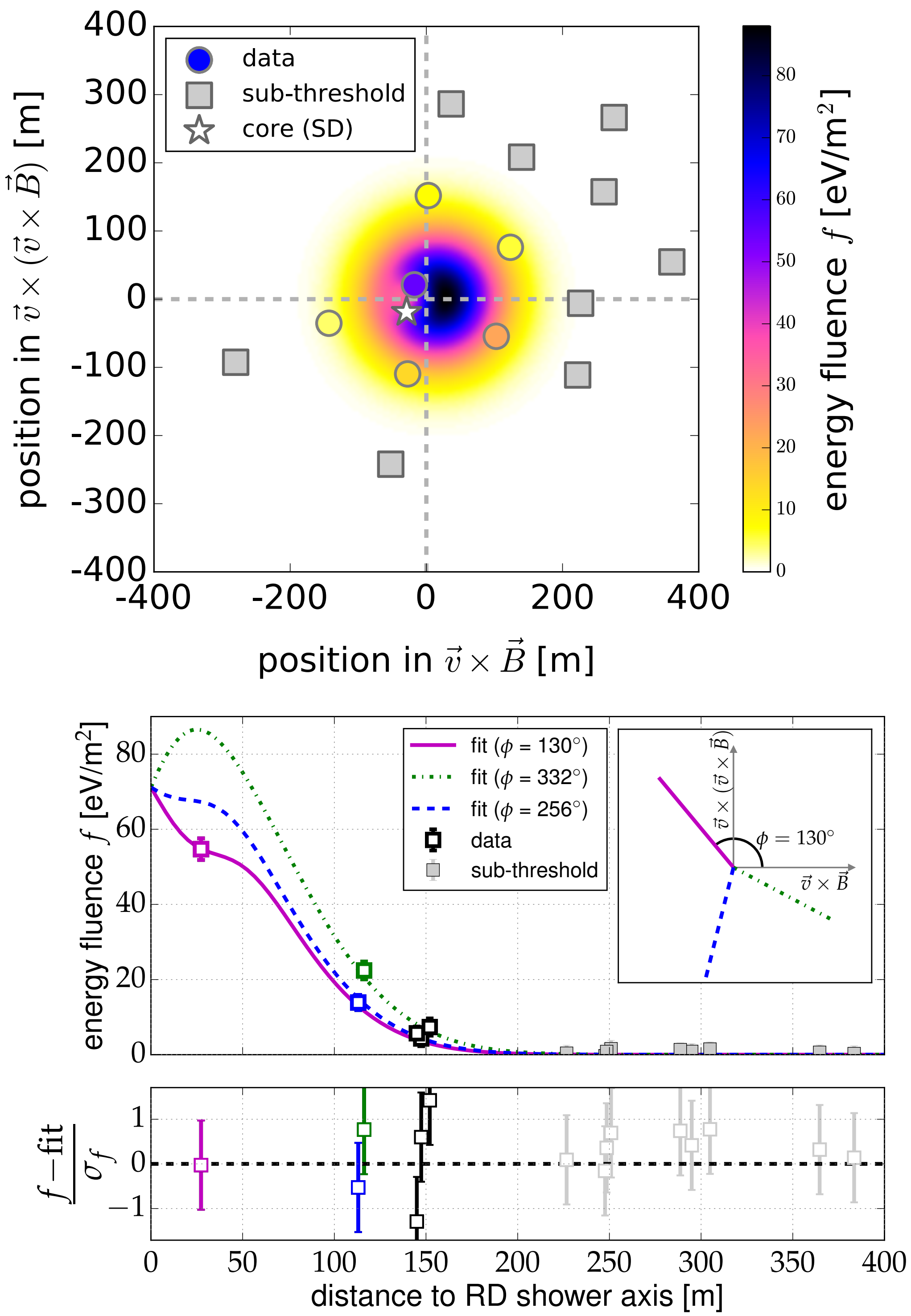
A. Aab et al., PRL 116 (2016) no.24, 241101

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



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

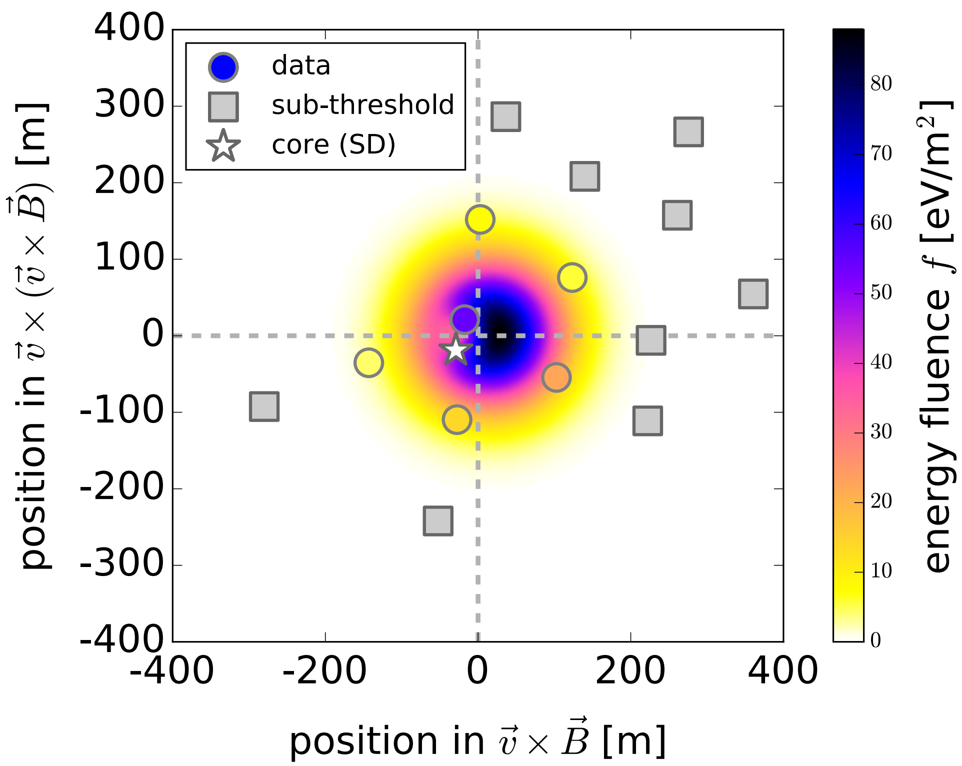
Measurement of the Radiation Energy in the Radio Signal of Extensive Air Showers as a Universal Estimator of Cosmic-Ray Energy



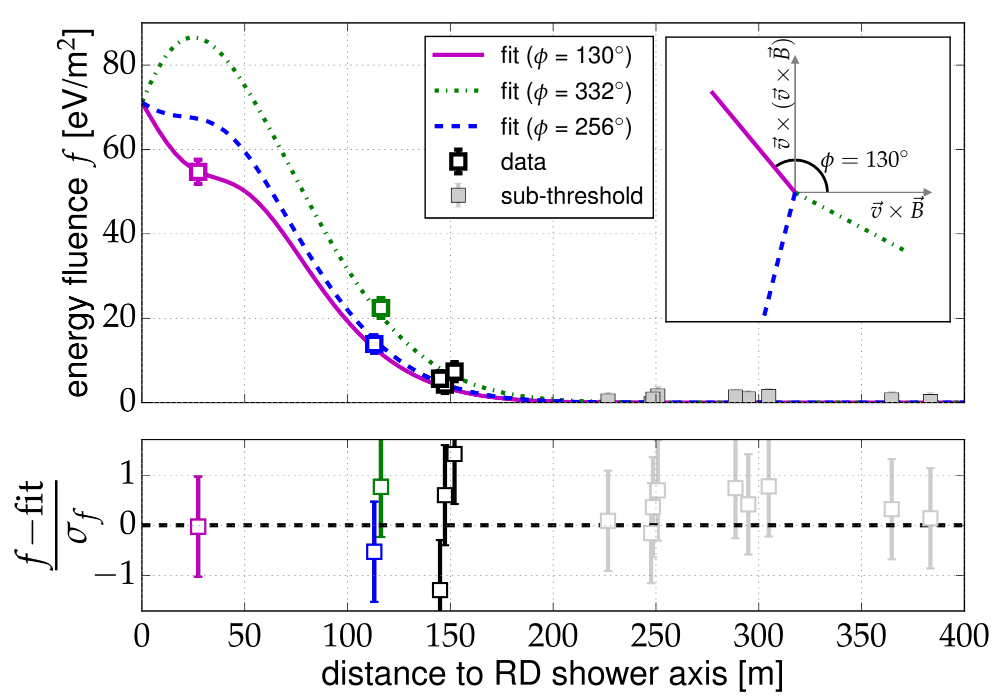
Auger Engineering Radio Array

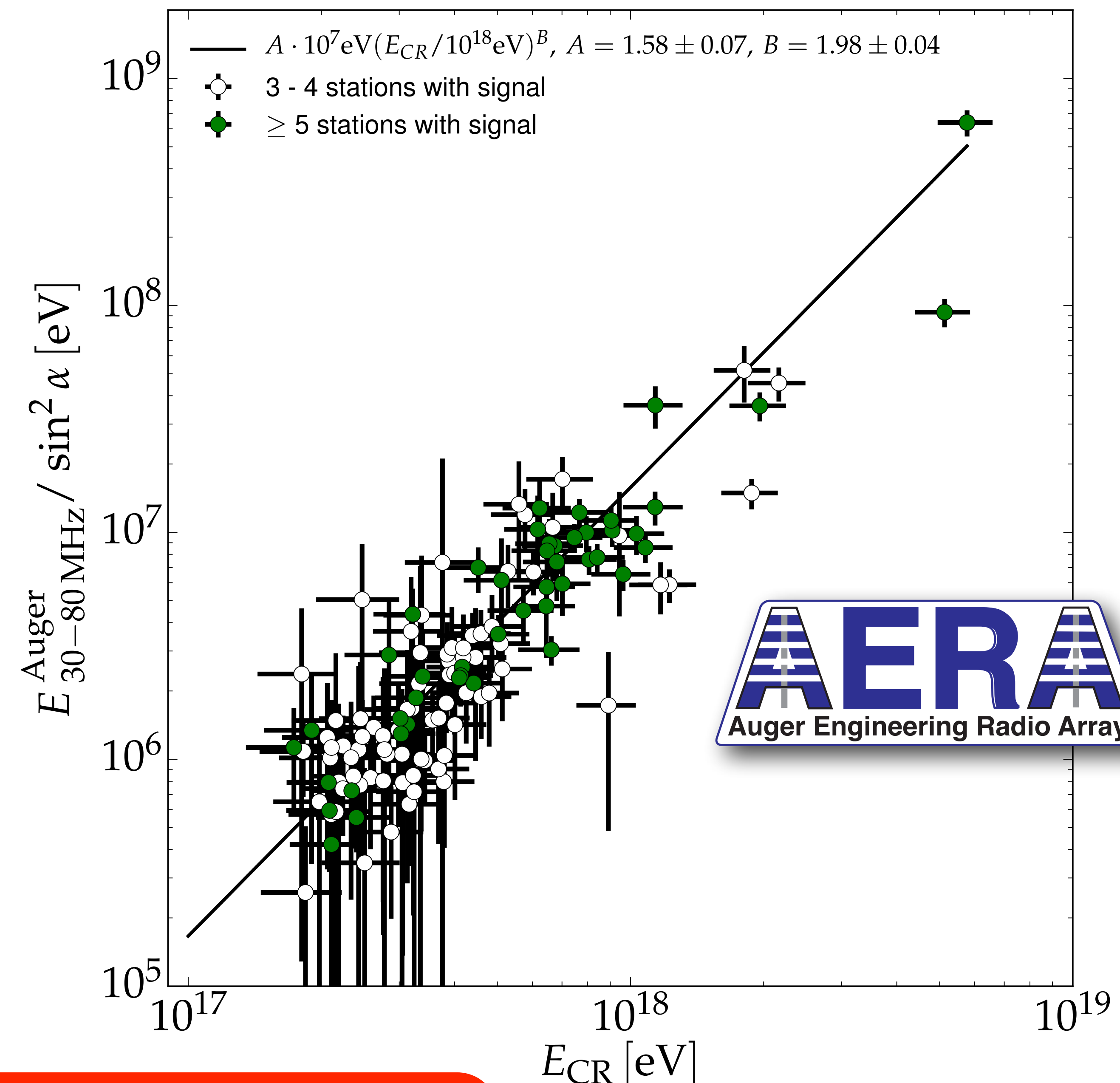
A. Aab et al., PRL 116 (2016) no.24, 241101

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





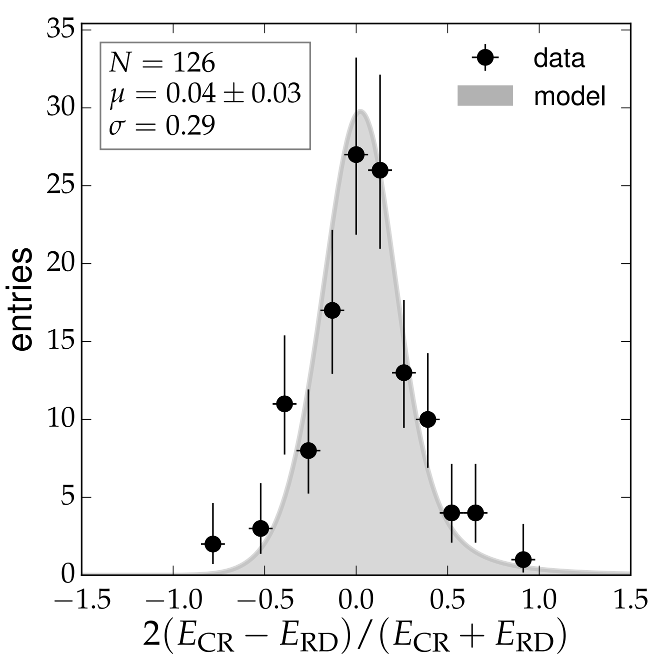
AERA
Auger Engineering Radio Array

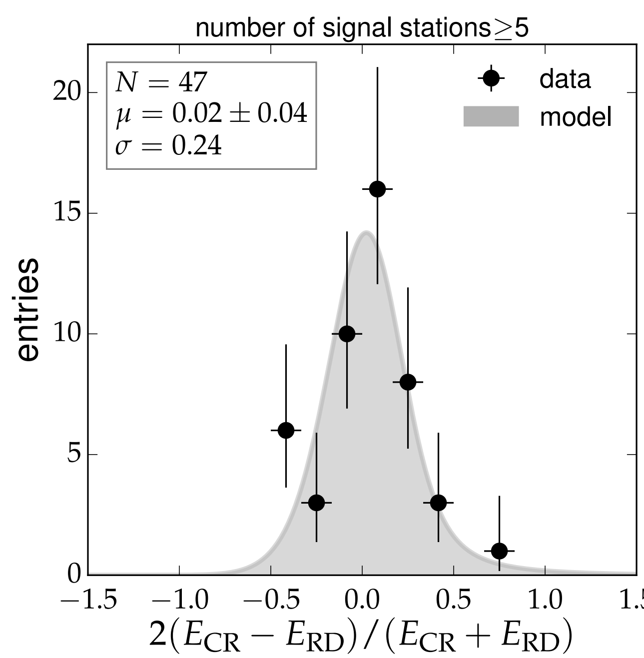
$$E_{30\text{-}80\ \mathrm{MHz}} = (15.8 \pm 0.7(\mathrm{stat}) \pm 6.7(\mathrm{syst})\ \mathrm{MeV}) \times \left(\sin\alpha \frac{E_{CR}}{10^{18}\ \mathrm{eV}} \frac{B_{Earth}}{0.24\ \mathrm{G}}\right)^2$$

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

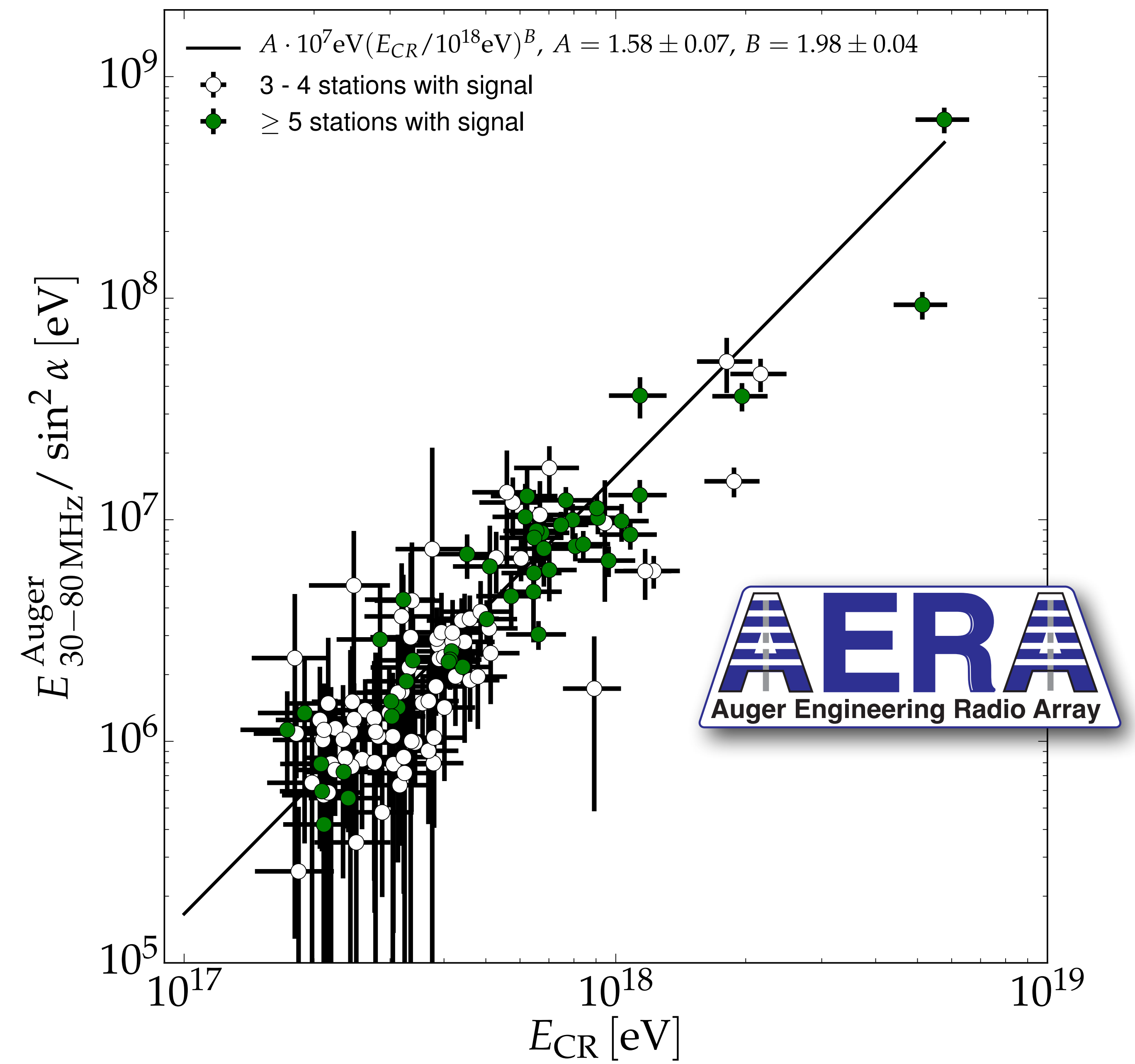
Energy Estimation of Cosmic Rays with the Engineering Radio Array of the Pierre Auger Observatory

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



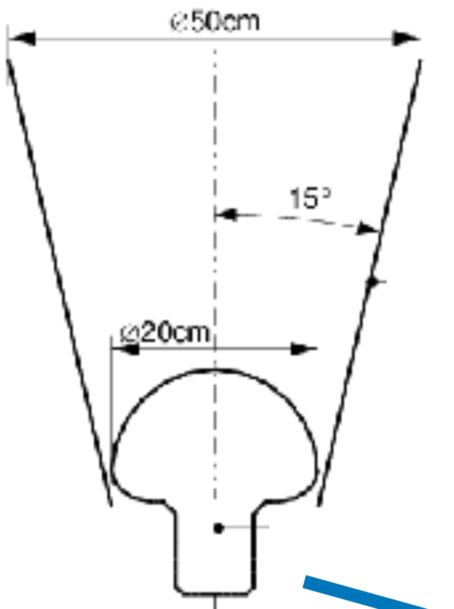


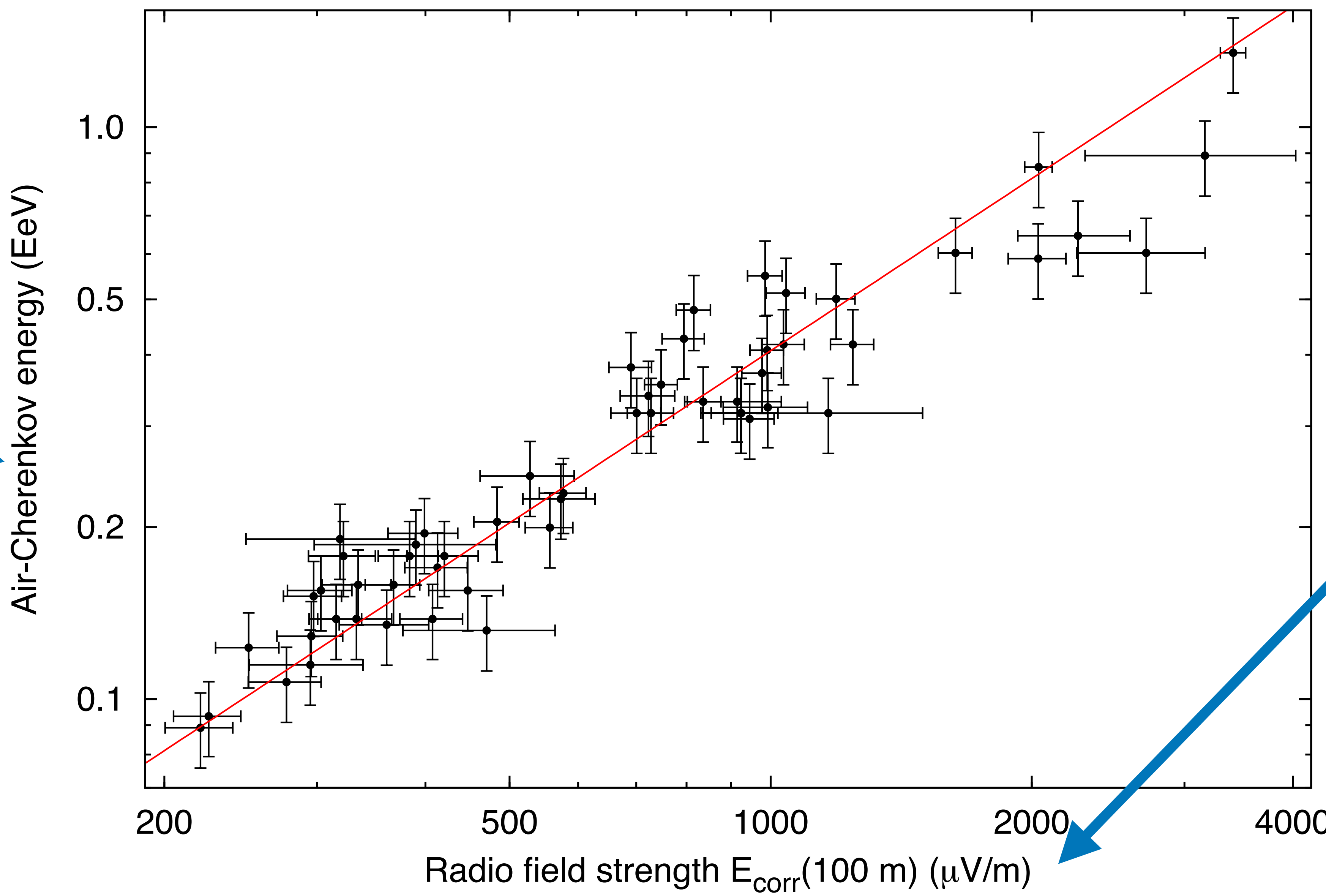
$$\sigma \approx 24\%$$



A. Aab et al., PRD 93 (2016) no.12, 122005
A. Aab et al., PRL 116 (2016) no.24, 241101

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.

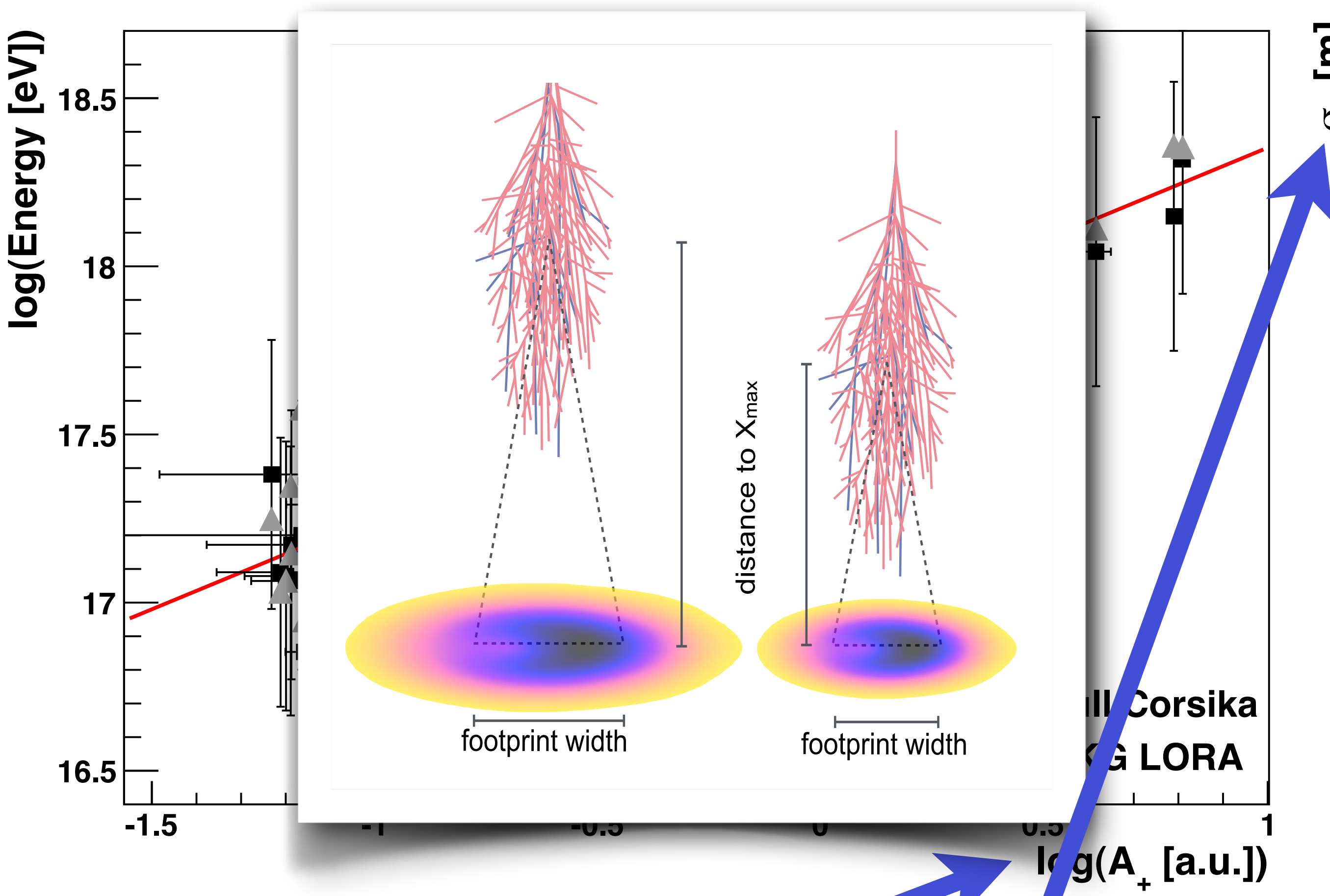
F.G. Schröder et al., JPS Conf. Proc. 9 (2016) 010008

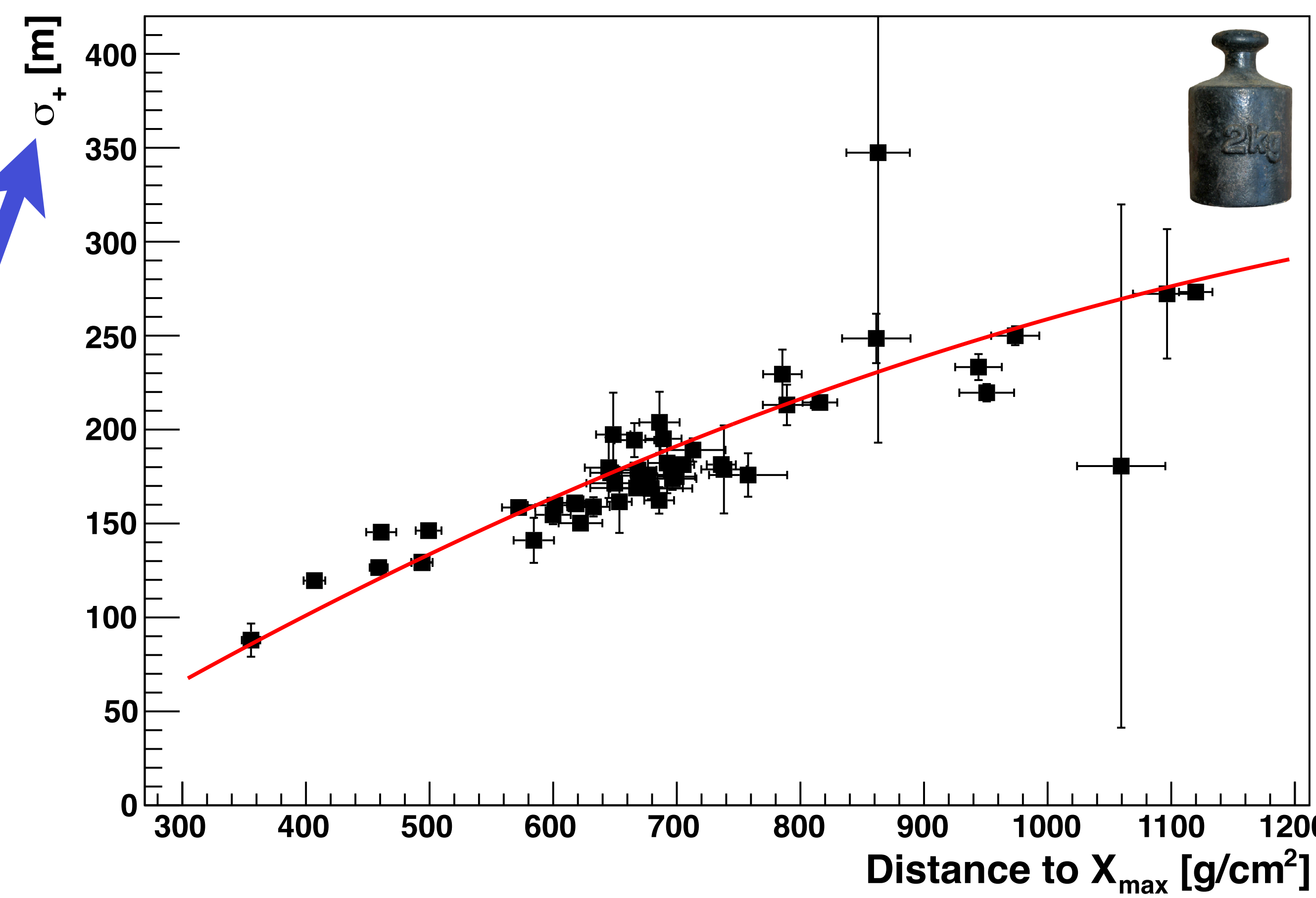
Mass

Properties of primary particle

energy

distance to Xmax



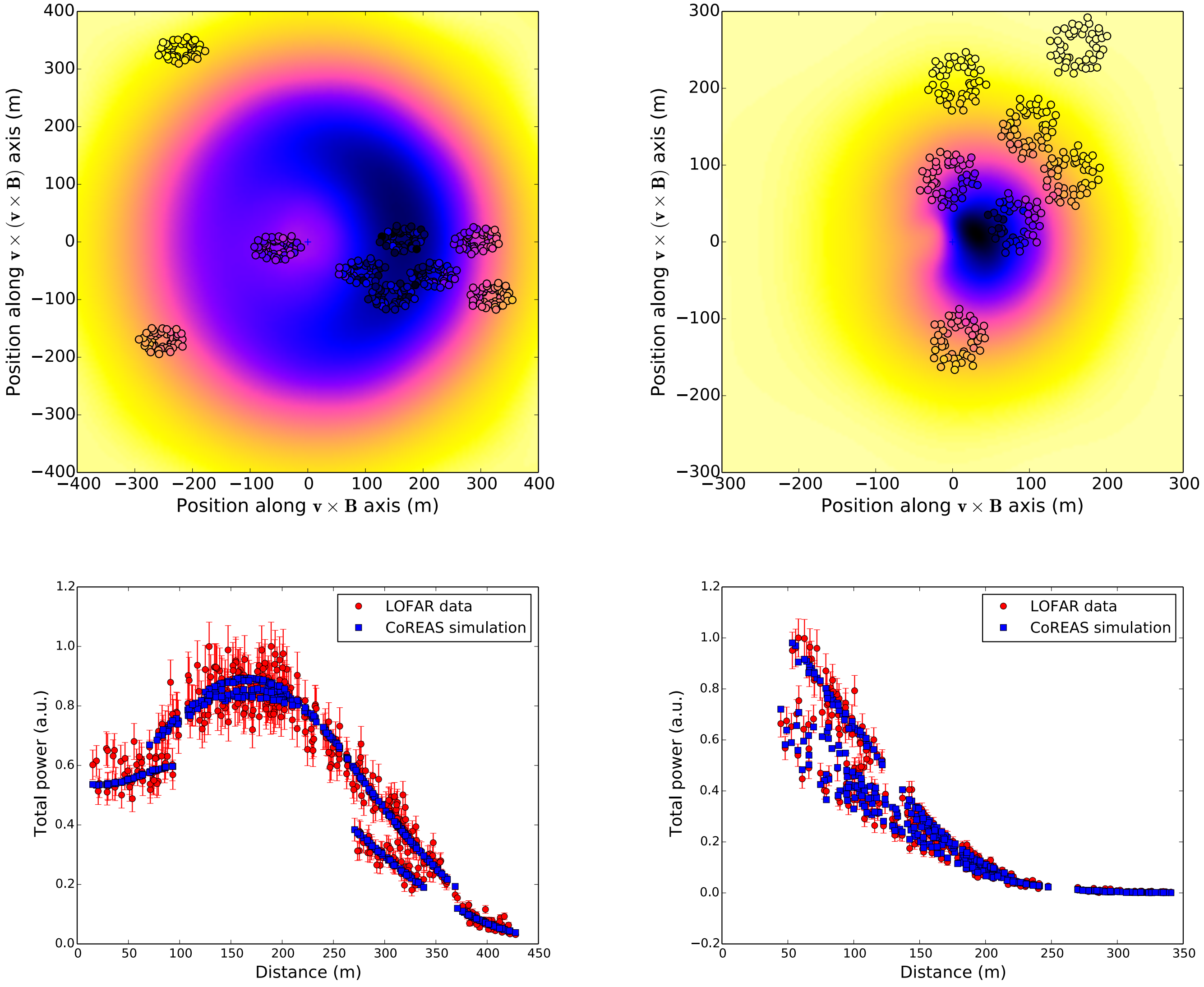


$$P(x', y') = A_+ \cdot \exp\left(\frac{-[(x'-X_+)^2 + (y'-Y_+)^2]}{\sigma_+^2}\right) - A_- \cdot \exp\left(\frac{-[(x'-X_-)^2 + (y'-Y_-)^2]}{\sigma_-^2}\right) + O$$

LOFAR

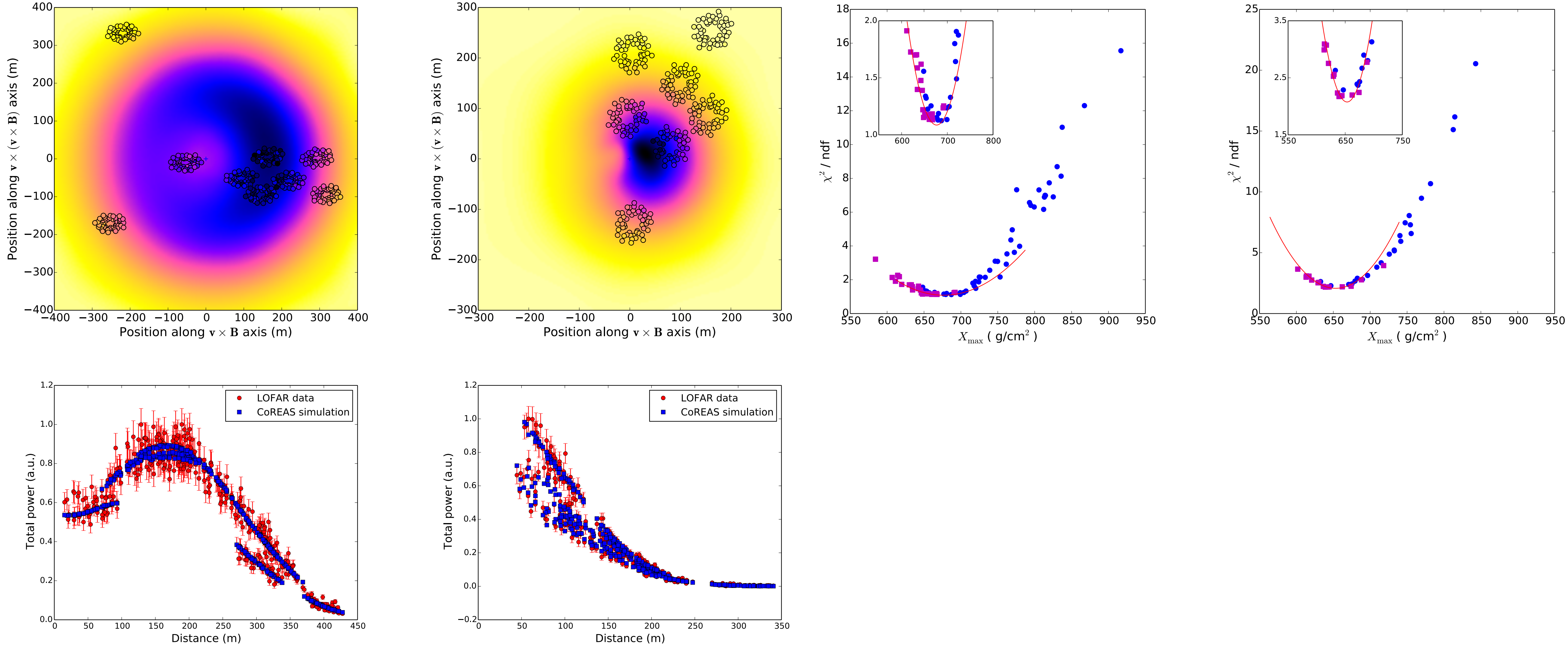
A. Nelles et al., JCAP 05 (2015) 018

Measurement of particle mass



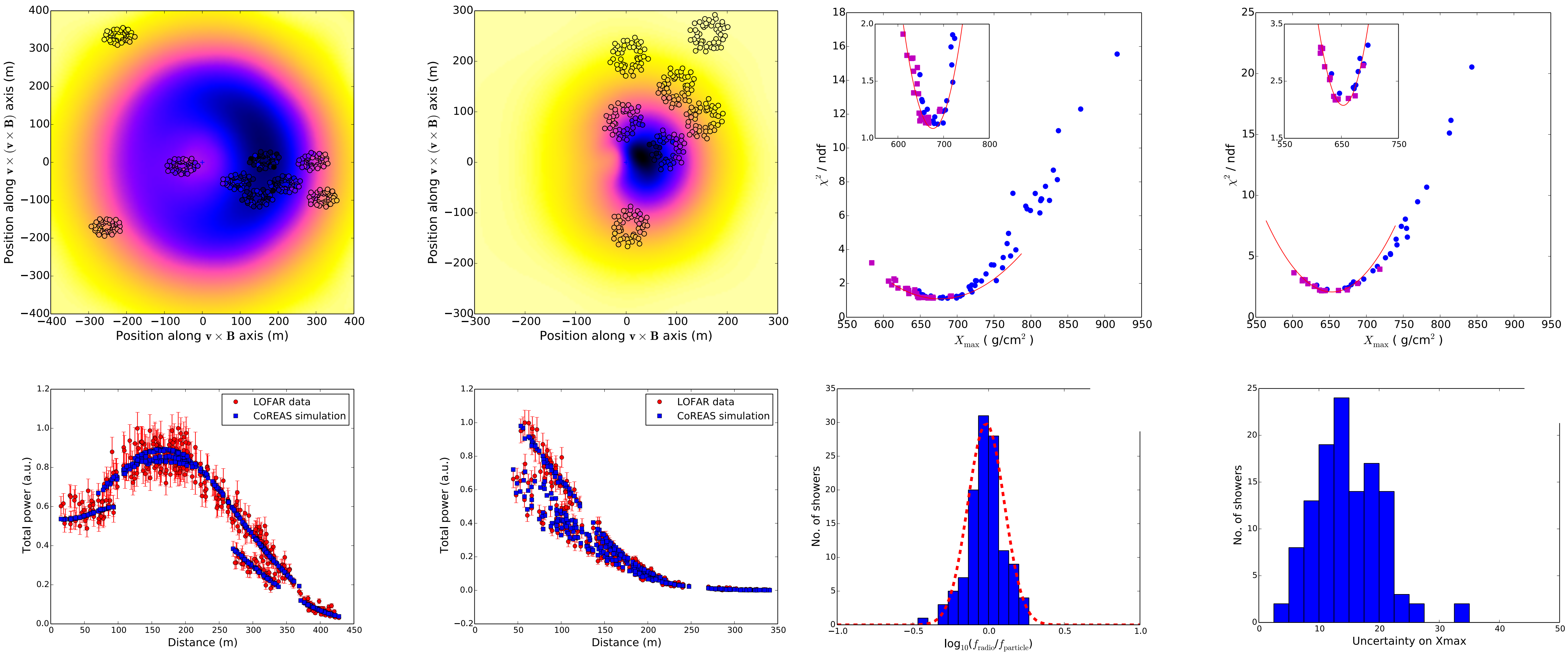
S. Buitink et al., PRD 90 (2014) 082003

Measurement of particle mass



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

Measurement of particle mass

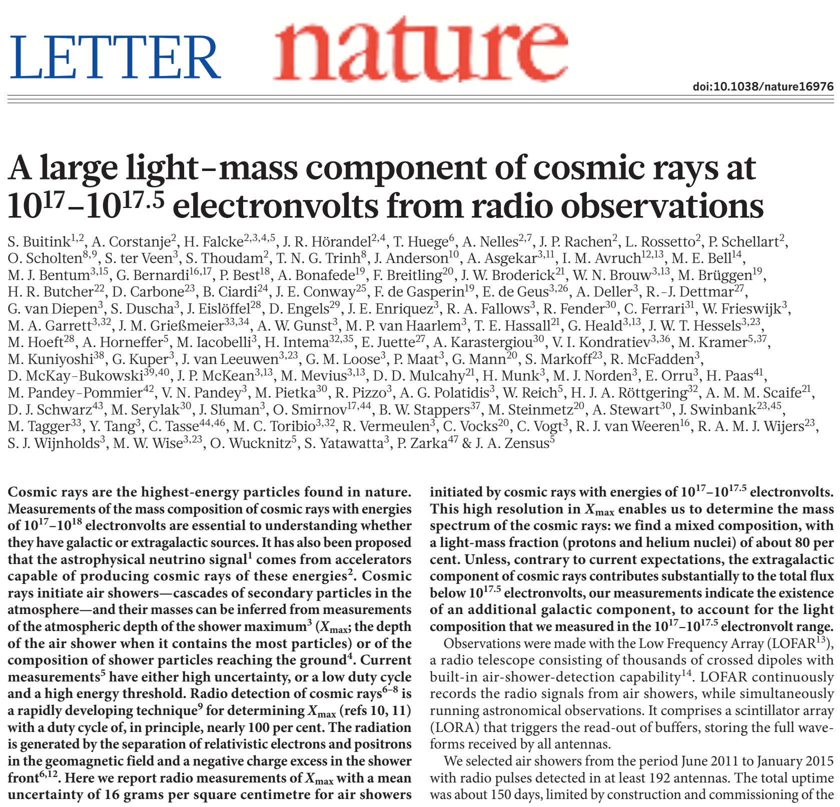


$\sigma_E \approx 32\%$

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

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

Depth of the shower maximum



LETTER nature

doi:10.1038/nature16976

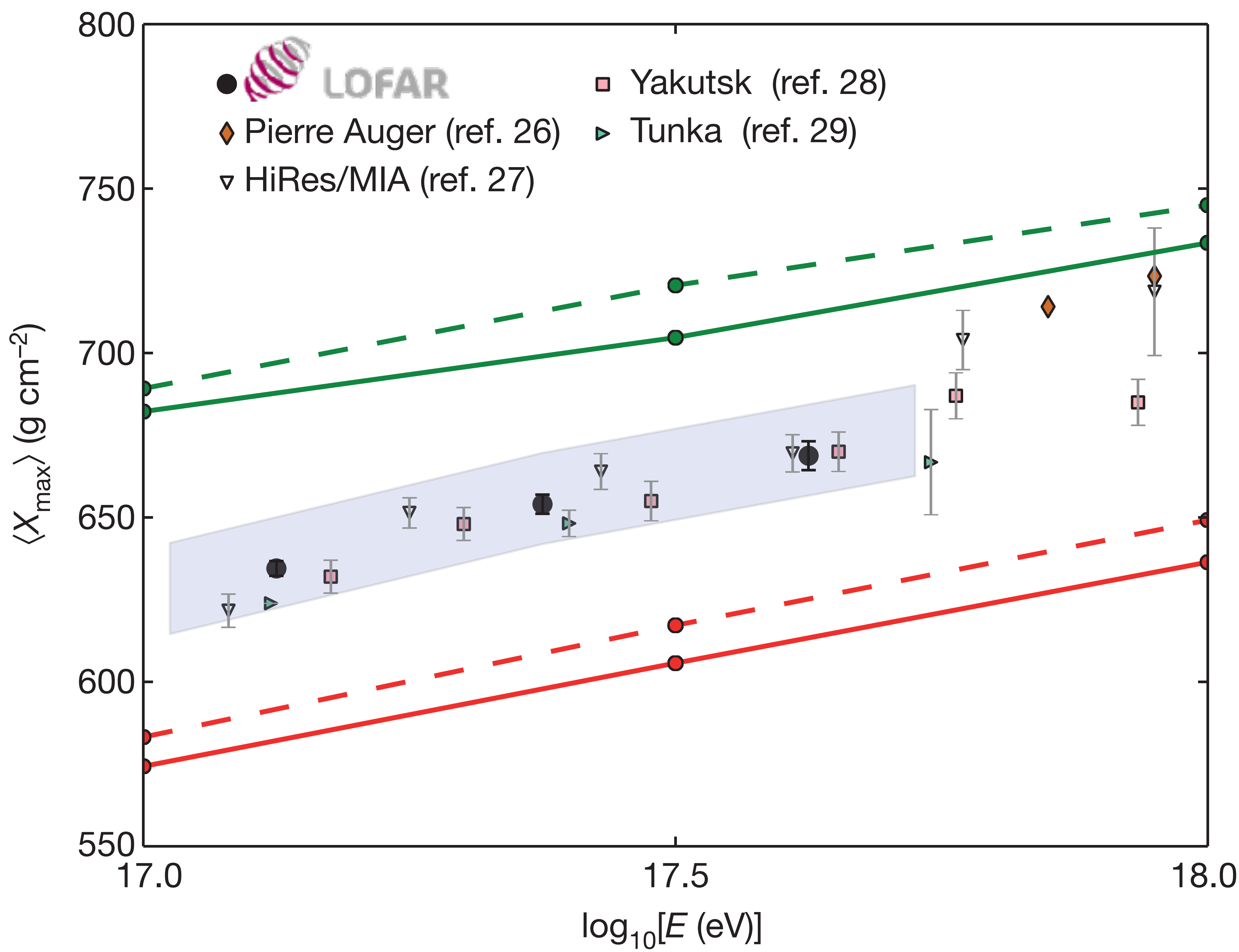
A large light-mass component of cosmic rays at 10^{17}–$10^{17.5}$ electronvolts from radio observations

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 wave-forms 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

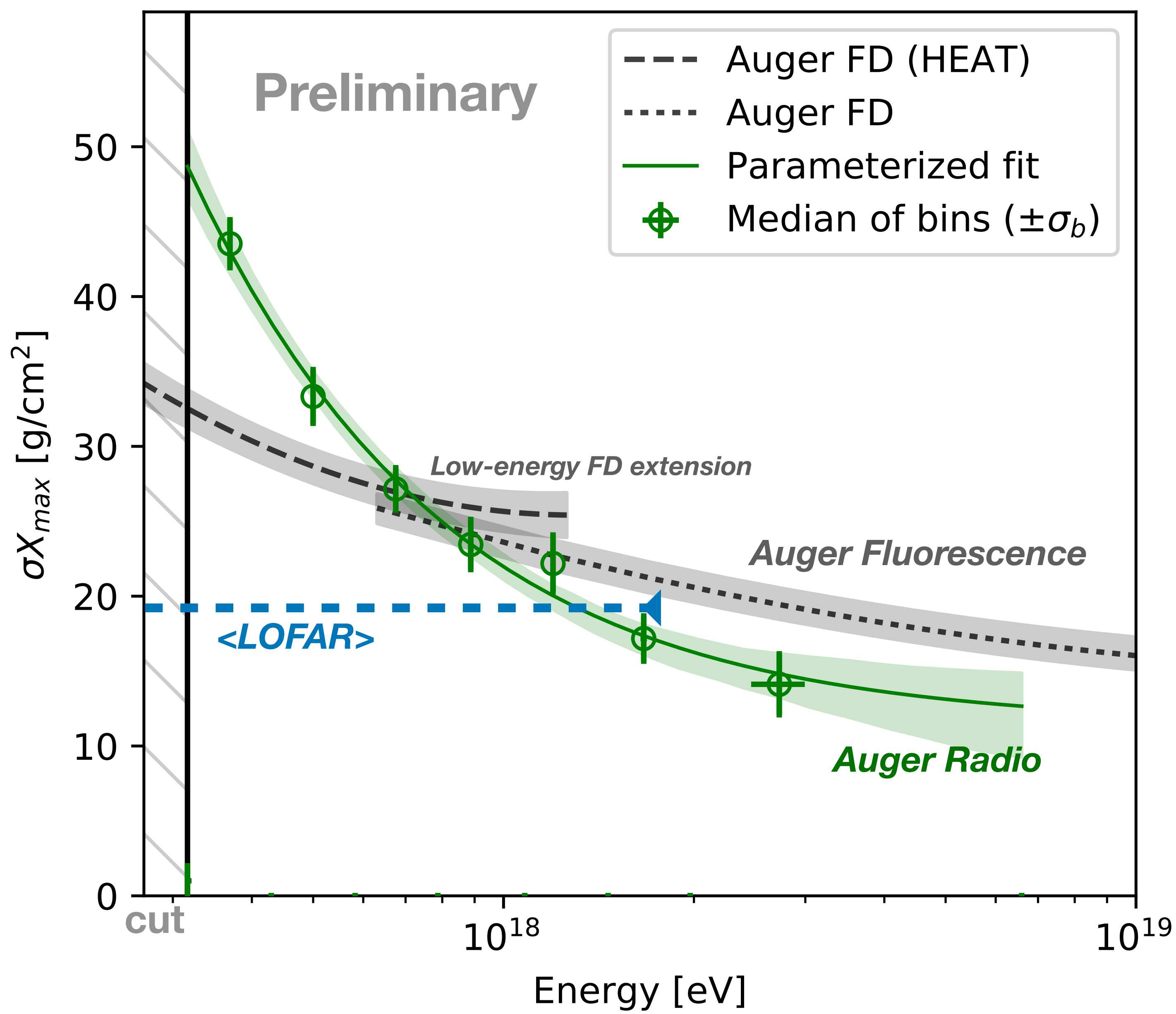


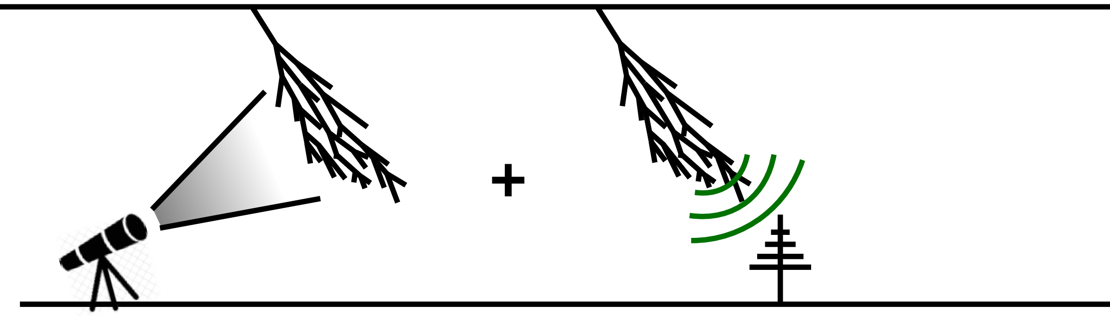
S. Buitink et al., Nature 531 (2016) 70

Results: Resolution of AERA X_{max} method

Radboud University

Radio X_{max} resolution





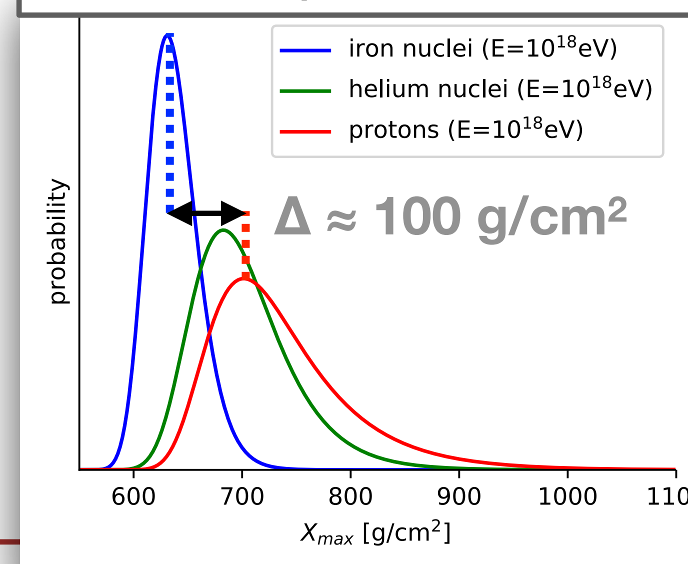
Resolution improves with energy.

- Up to 'better than 15 g/cm² '
- Trend driven by low SNR at low energy.

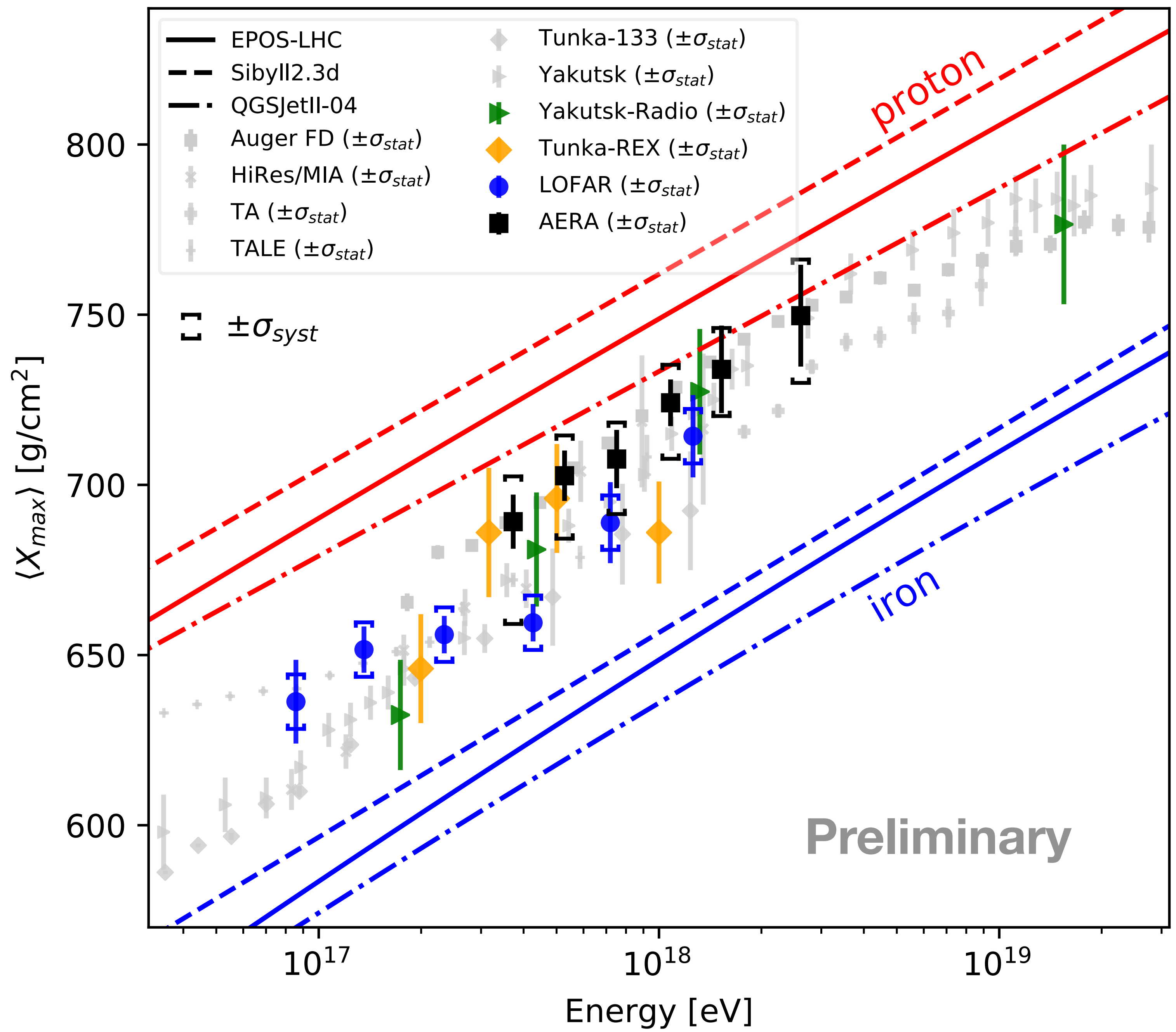
Resolution competitive with e.g.:

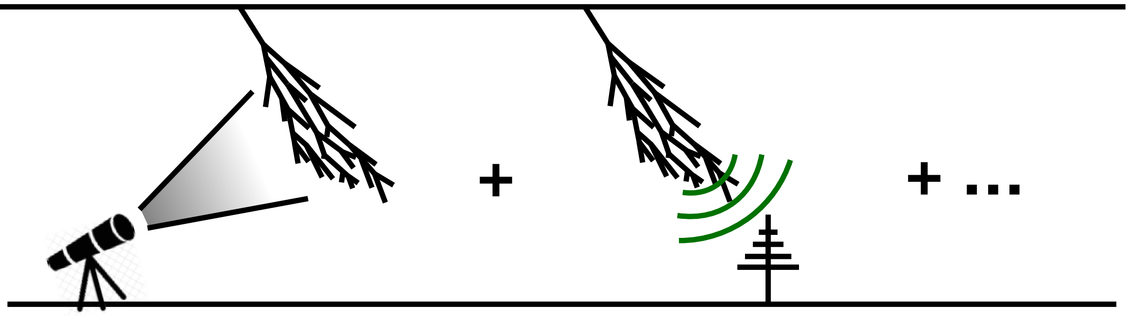
- Auger fluorescence [arXiv:1409.4809]
- LOFAR radio (E=$10^{16.8\ldots18.3}$eV) [arXiv:2103.12549v2]

Side note:
High resolution is crucial for mass composition studies.



Results: AERA vs other (radio) experiments

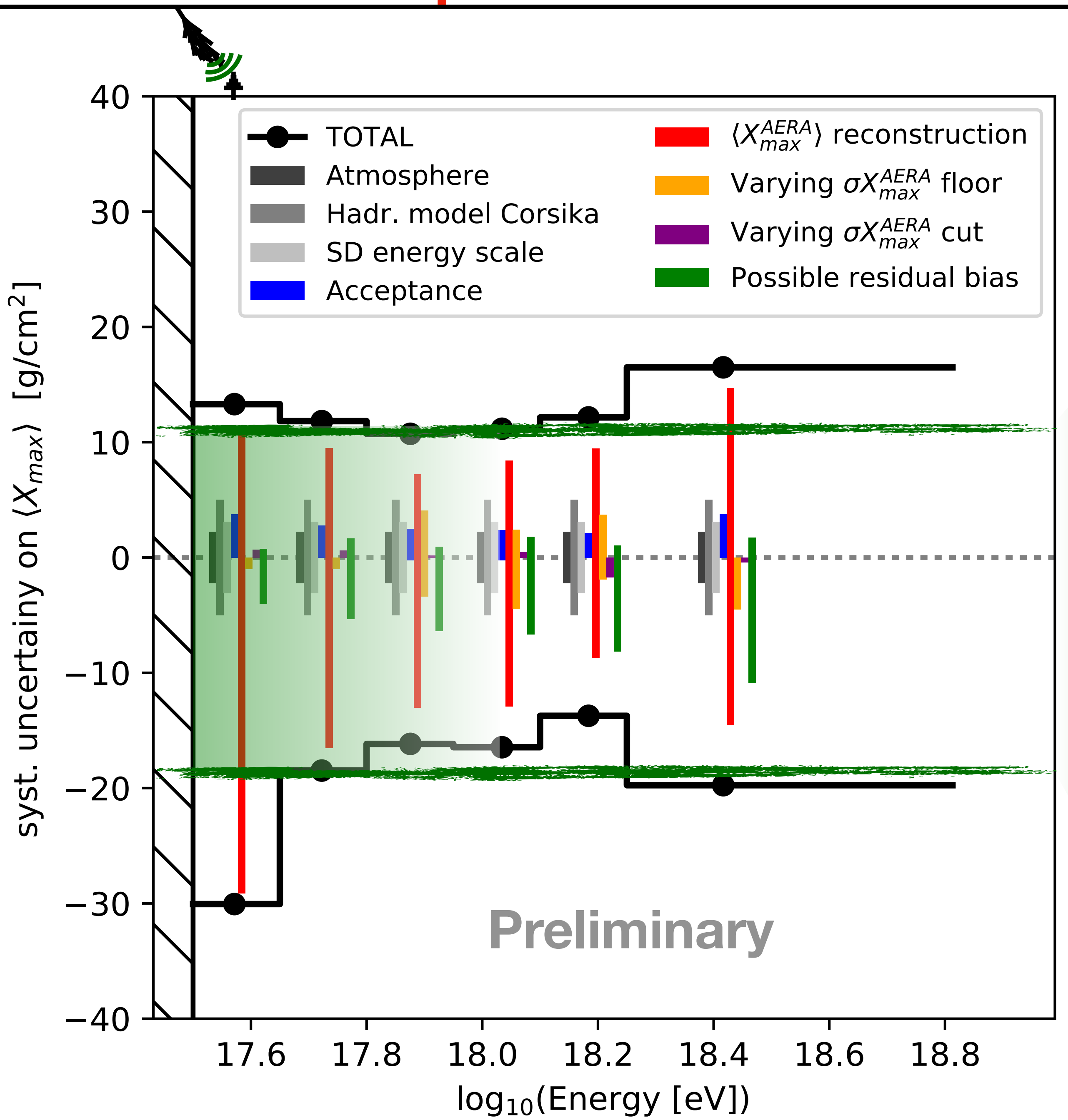




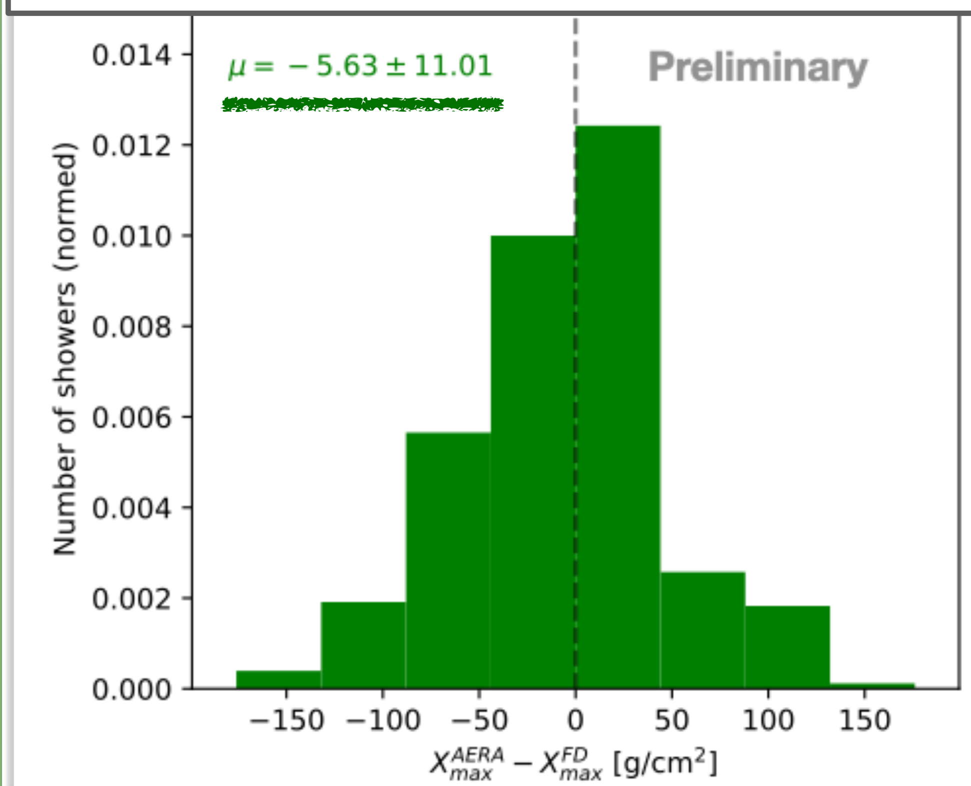
- No general radio-bias w.r.t other techniques (within uncertainties).
- Highlights that systematic uncertainties are key to interpret and compare.
- **LOFAR-AERA** differences are being investigated in a working group

—> come talk to us during coffee and lunch!

Two independent estimates of systematic uncertainties



Independent constrained from AERA-FD dataset (most lower E)



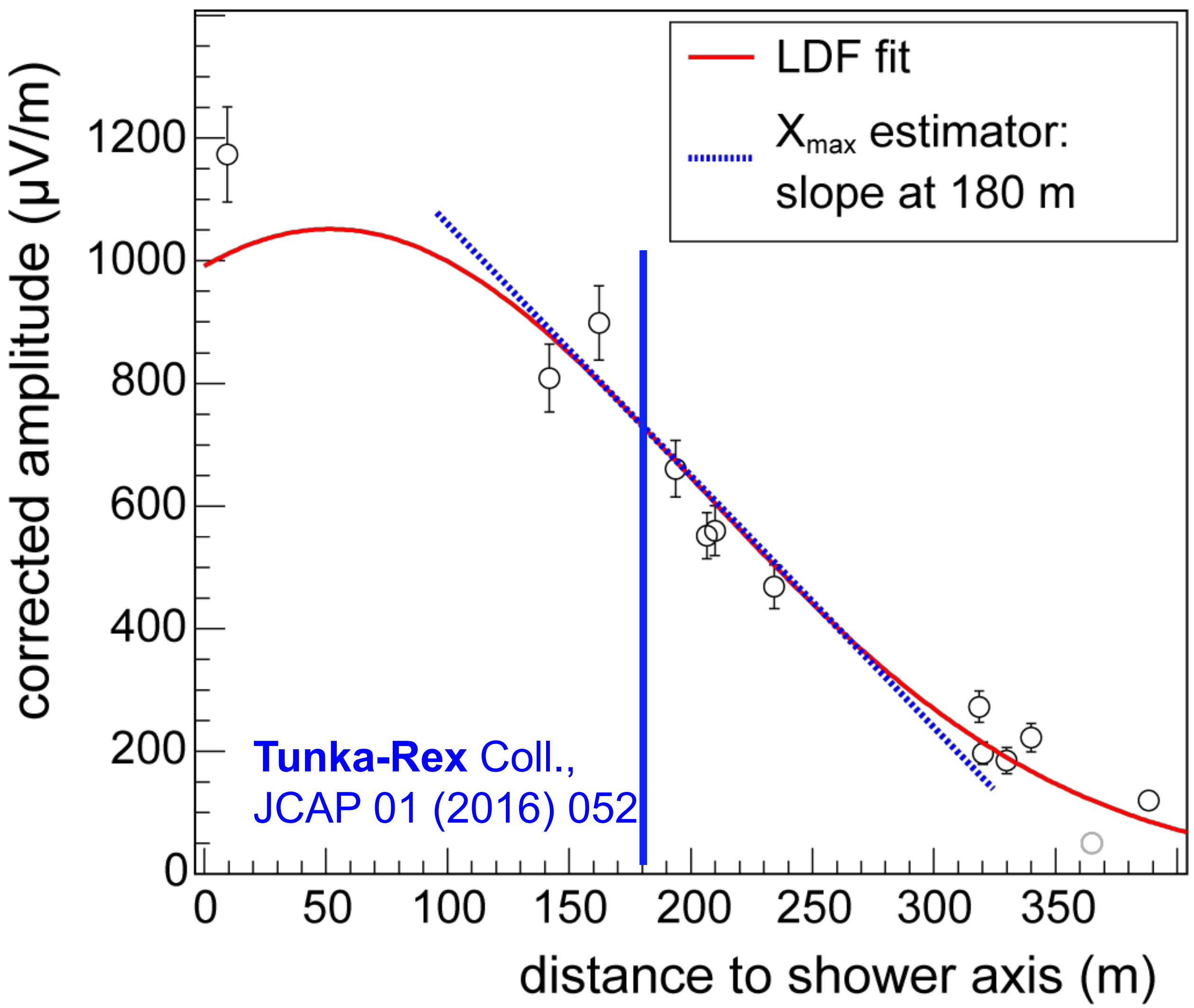
+

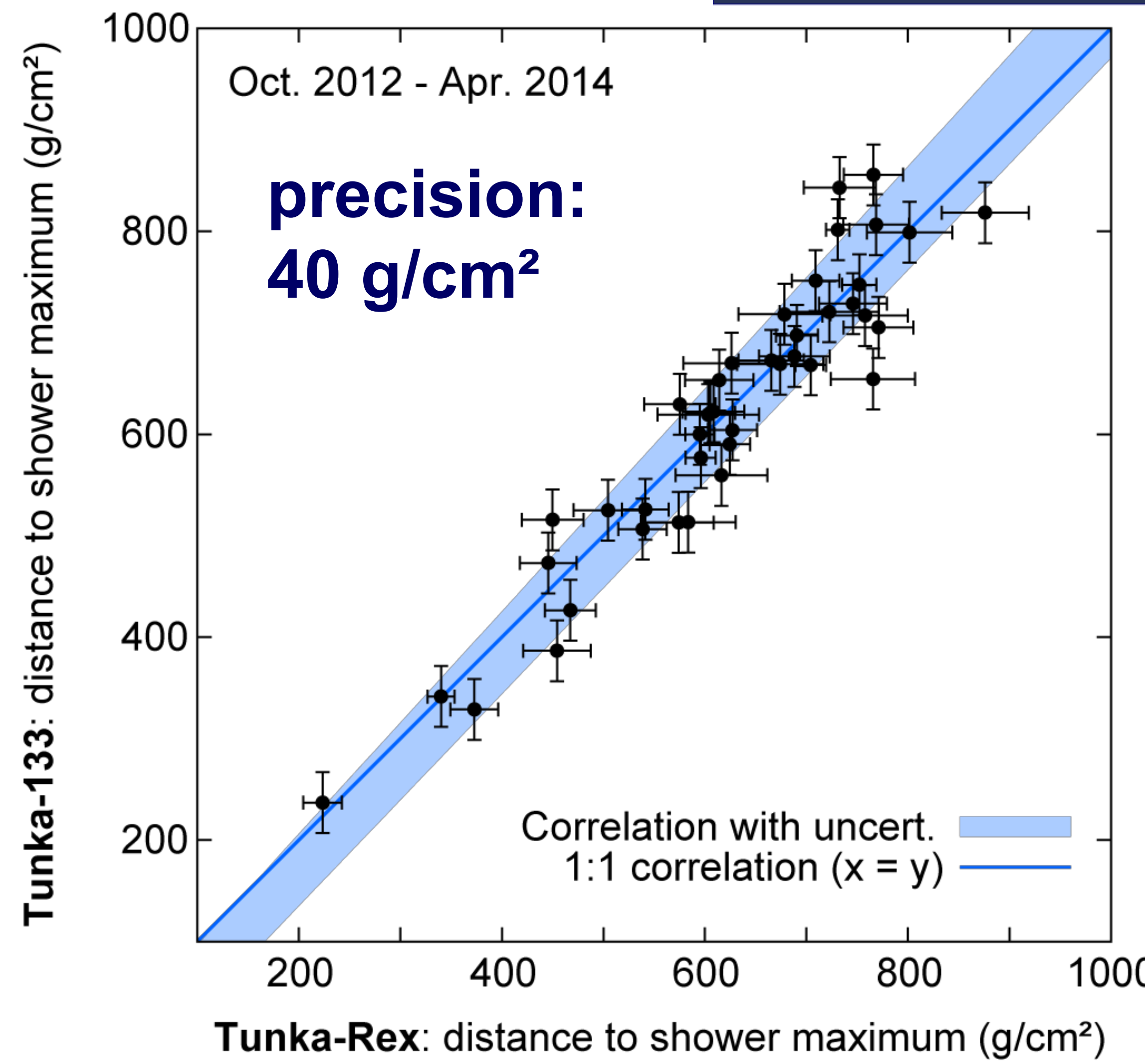
FD syst. unc. ~ 10 g/cm²

- **Cross check:** two independent estimates for total systematic uncertainties are in agreement.
  —> suggests systematic uncertainties are well-understood and no significant contribution is missing.

Shower maximum: proof by Tunka-Rex

- One of several methods: slope of lateral distribution





frank.schroeder@kit.edu
Institut für Kernphysik

Determine the properties of the incoming particle with the radio technique

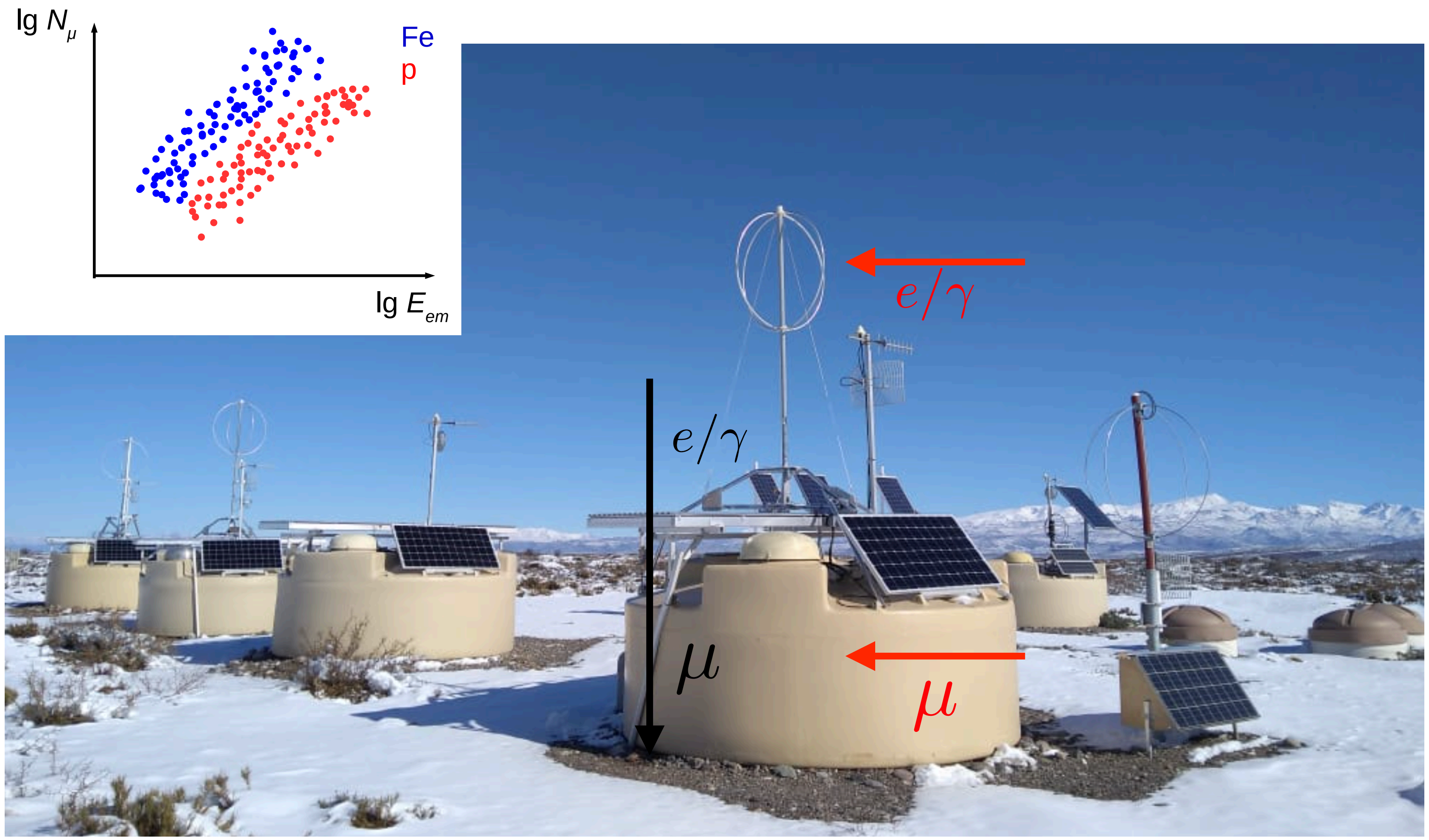
- direction ~ 0.1° - 0.5°
- energy ~ 15% - 30%
- type (X_{max}) ~ 20 - 30 g/cm²

(depending on energy, detector spacing, …)

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


The Future
NEXT EXIT

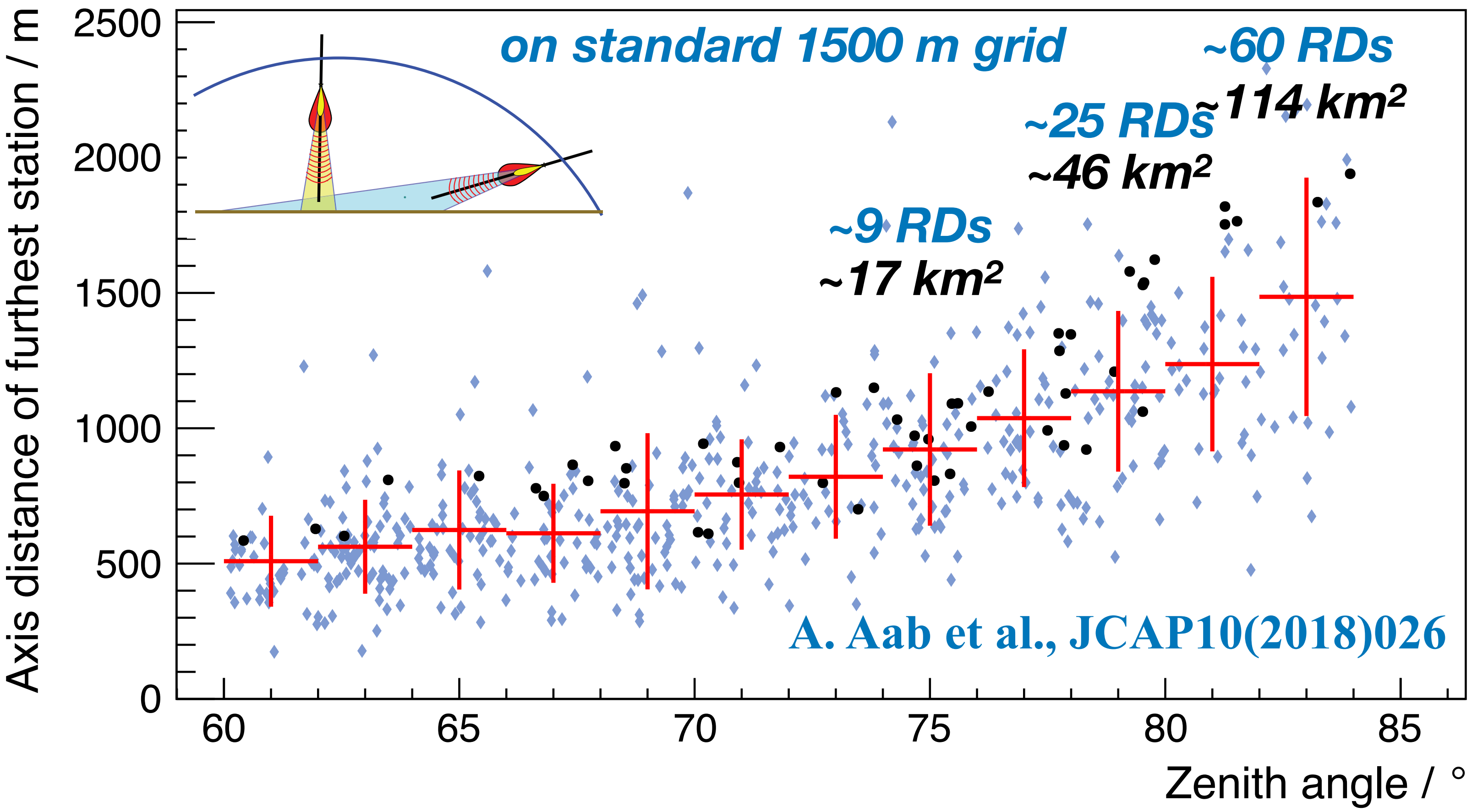
The Radio Detector of the Pierre Auger Observatory



Key science questions

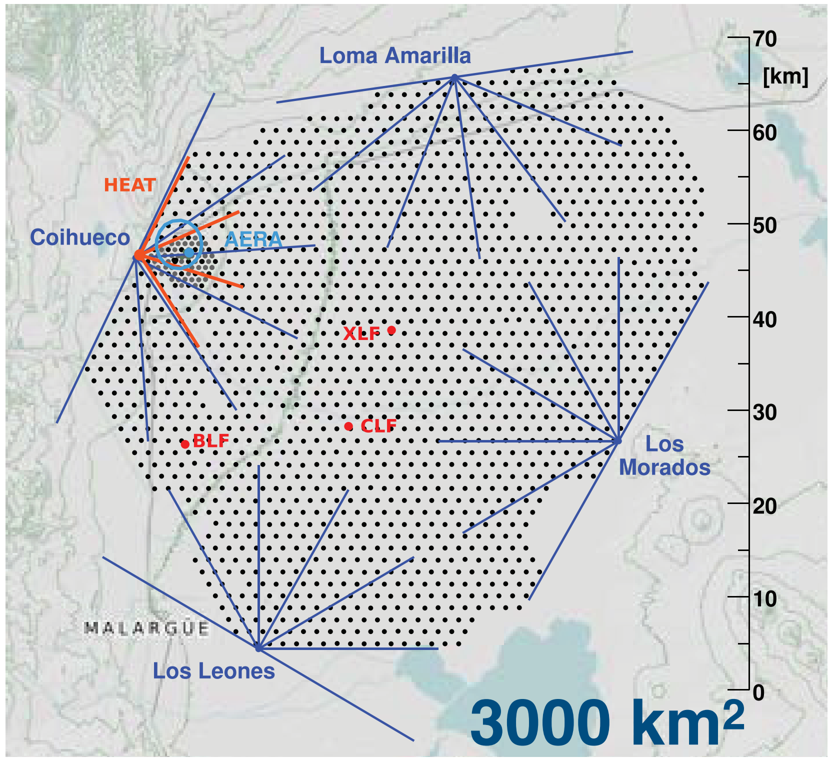
- What are the **sources** and **acceleration** mechanisms of ultra-high-energy cosmic rays (UHECRs)?
- Do we understand **particle** acceleration and **physics** at energies well beyond the LHC (Large Hadron Collider) scale?
- What is the fraction of **protons**, **photons**, and **neutrinos** in cosmic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

Horizontal air showers have large footprints in radio emission



this is MEASURED with the *small* 17km² AERA

Pierre Auger Observatory

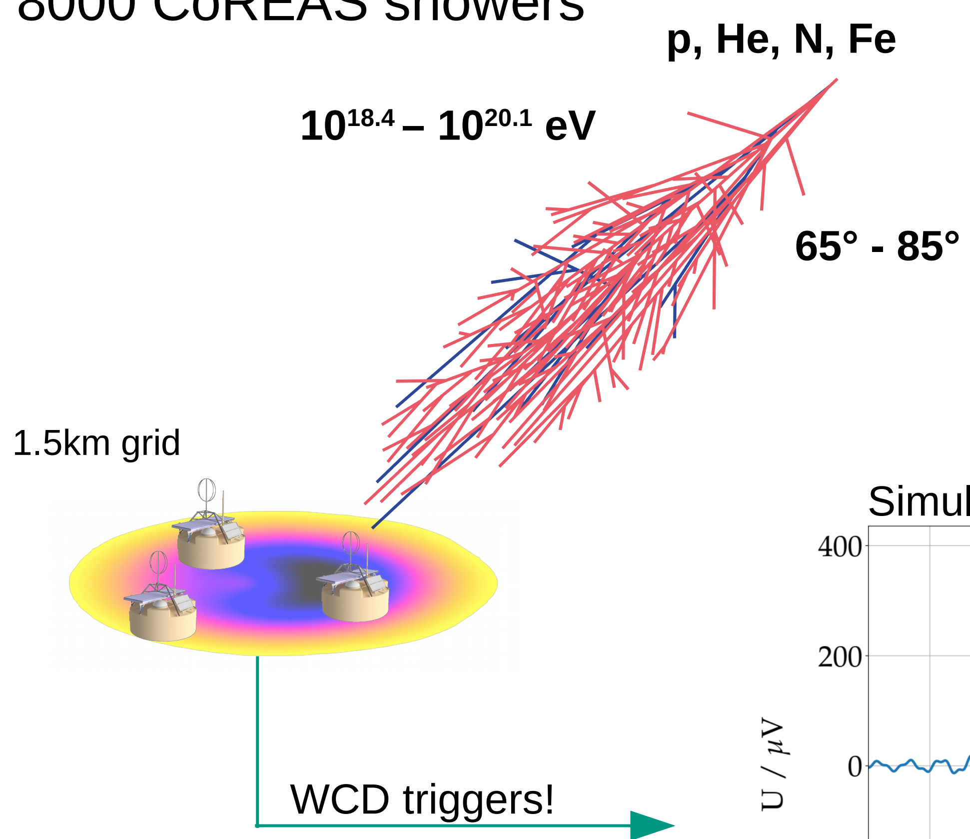


Surface Detector array:
Water Cherenkov Detector,
Surface Scintillator Detector,
Radio Detector
1600 stations on 1500 m grid
61 stations on 750 m grid

Expected Performance

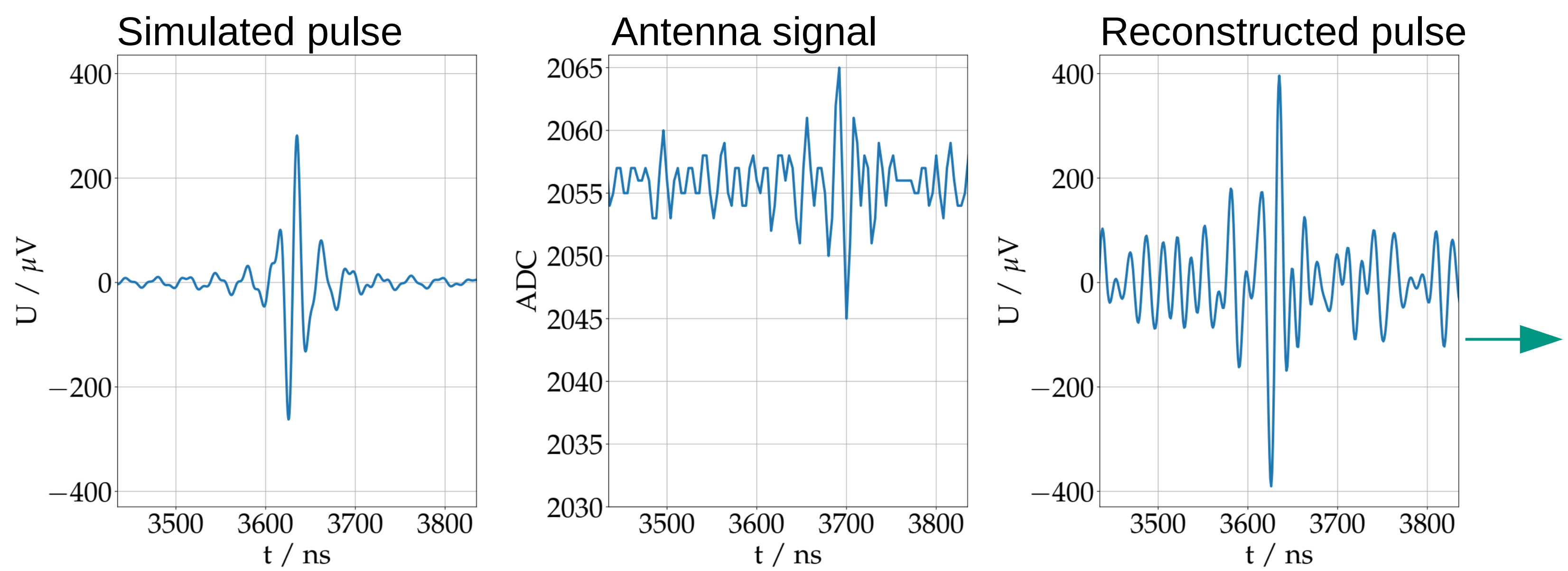
End-to-end simulation

8000 CoREAS showers



Simulate instrumental response
(directional response, analog gain, digitization, …..)

- Including uncertainties (σ_A = 5%)
- Measured noise

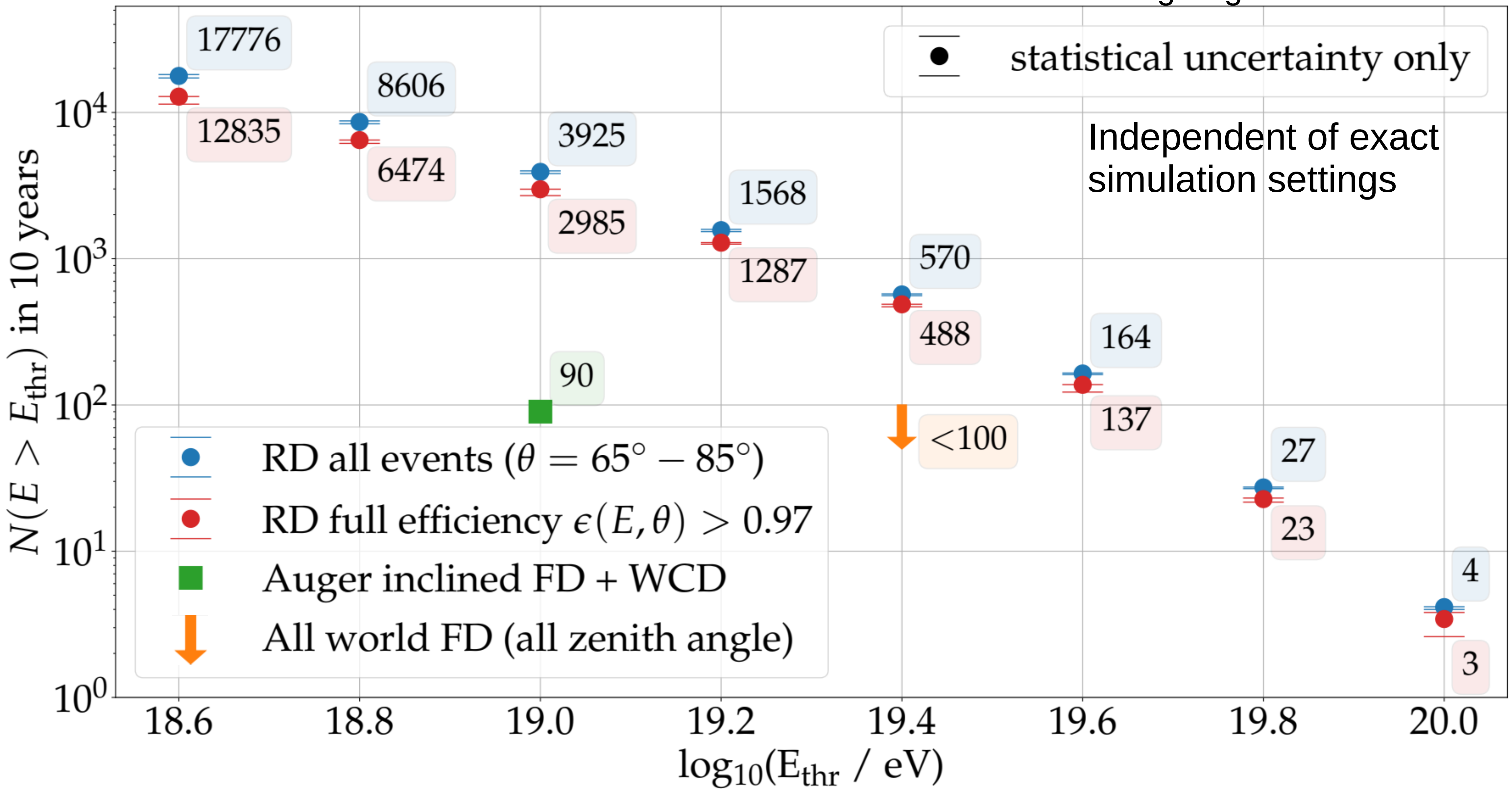


see Felix Schlüter, ARENA 2022

see talk by Felix Schlüter on Thursday

Expected number of cosmic rays after 10 years

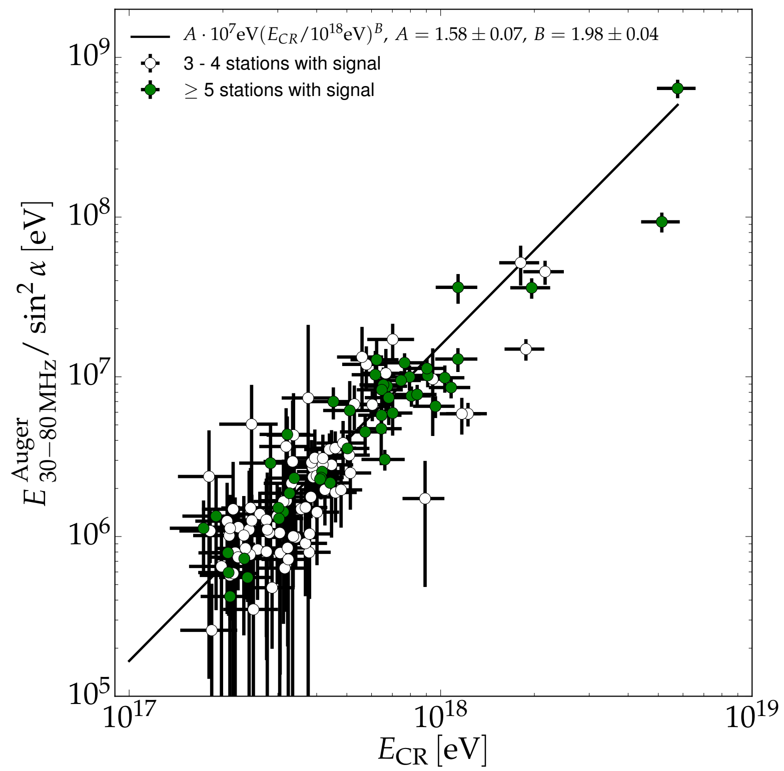
Using Auger-measured flux

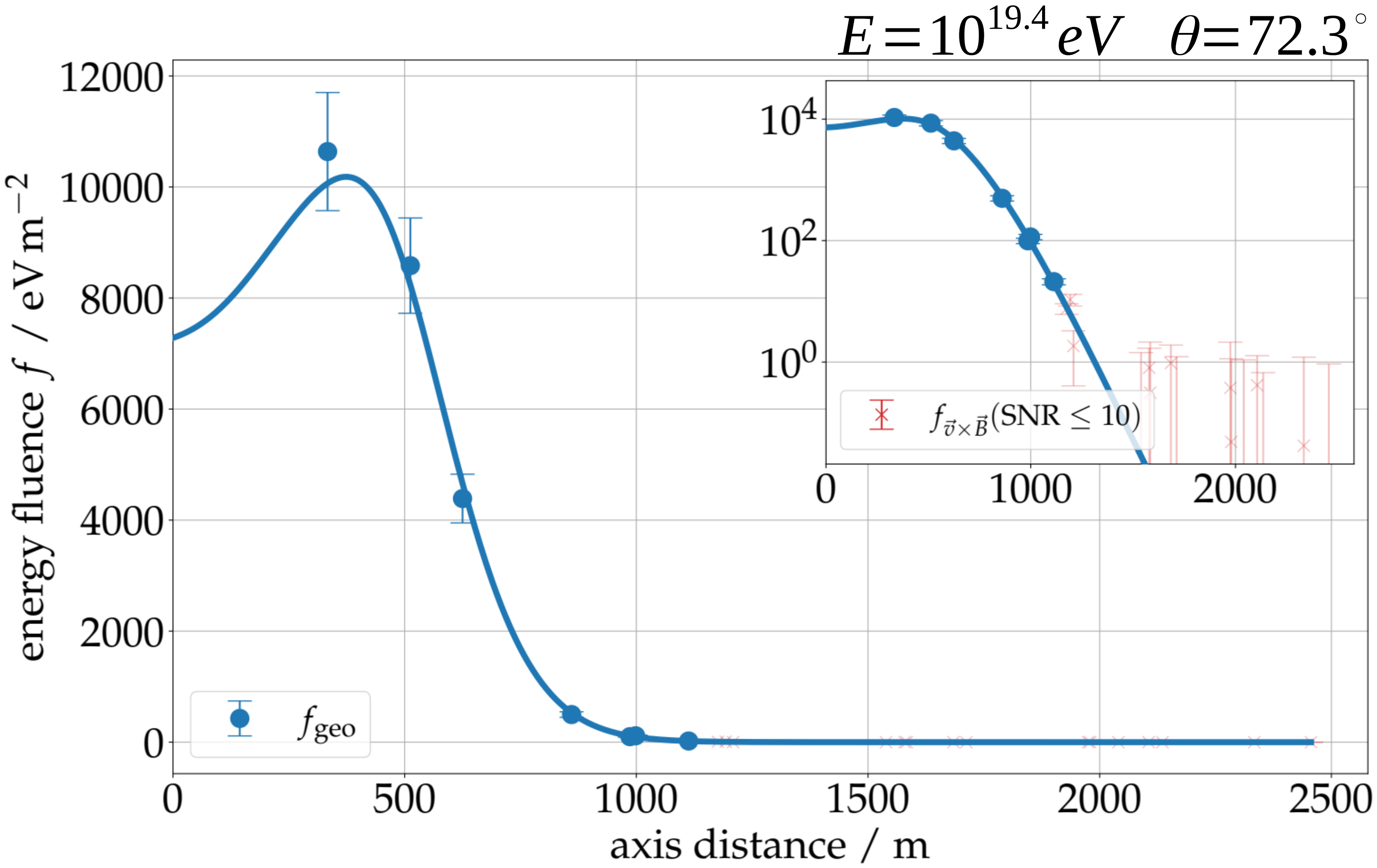


Lateral signal distribution

new model for LDF

- 2 parameter + core coordinates
- derive start values from WCD (use RD arrival direction)
- integral -> energy estimator

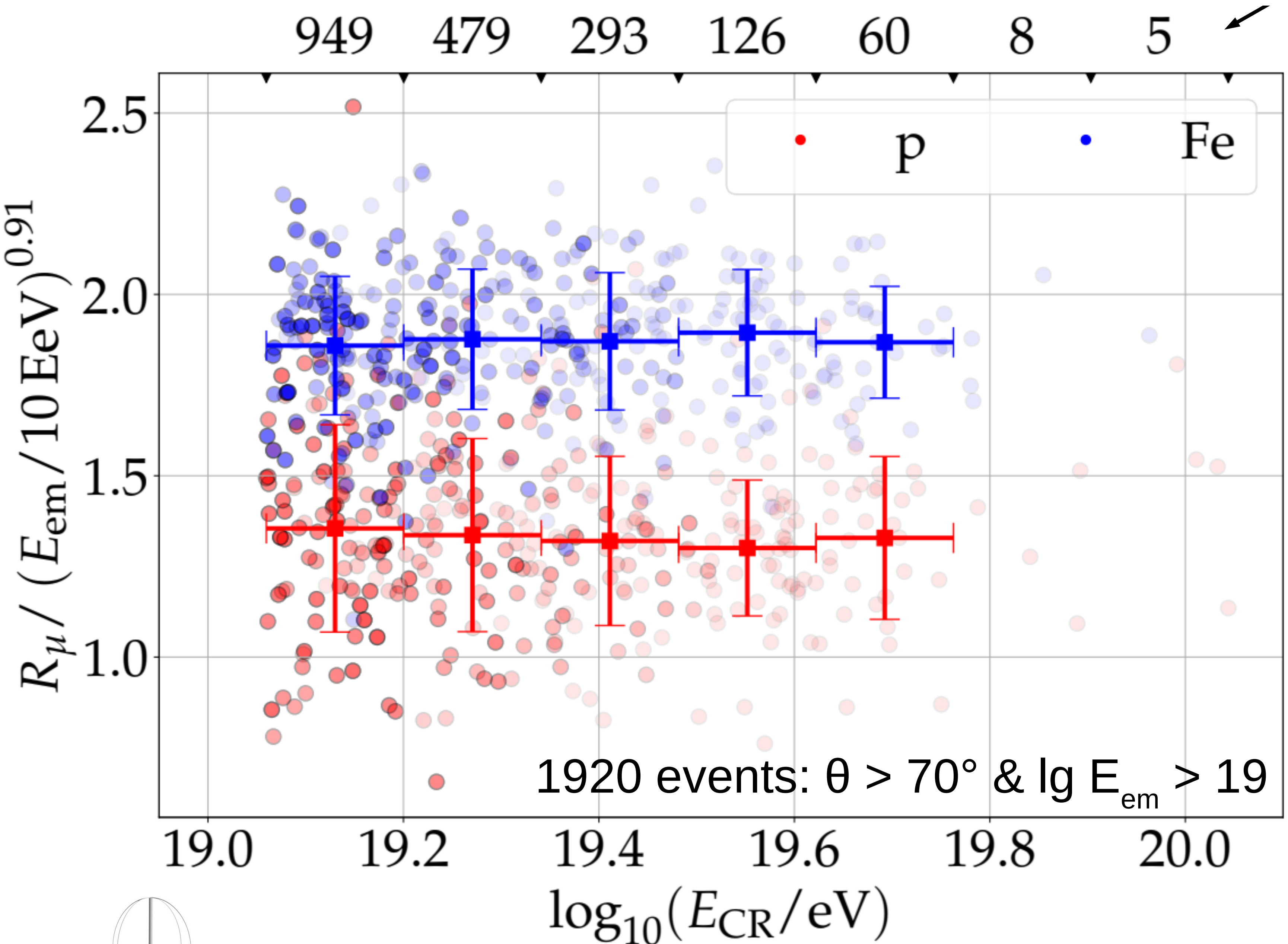




A. Aab et al., PRL 116 (2016) no.24, 241101
A. Aab et al., PRD 93 (2016) no.12, 122005

see Felix Schlüter, ARENA 2022

Particle type for each cosmic ray



50/50 p-Fe composition with 10 yr RD measurements

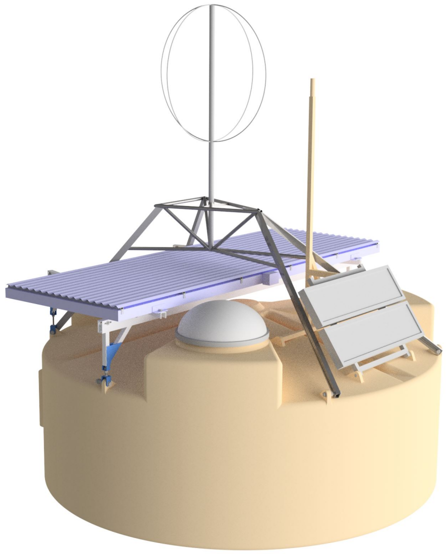
figure of Merit:

$$\mathrm{FOM} = \frac{|\langle r_p \rangle - \langle r_{Fe} \rangle|}{\sqrt{\sigma^2_{r_p} + \sigma^2_{r_{Fe}}}}$$

FOM = 1.61 ± 0.04

equal to X_{max} with perfect resolution

goal for the upgrade: 1.5



since November 2019
10 prototype stations installed

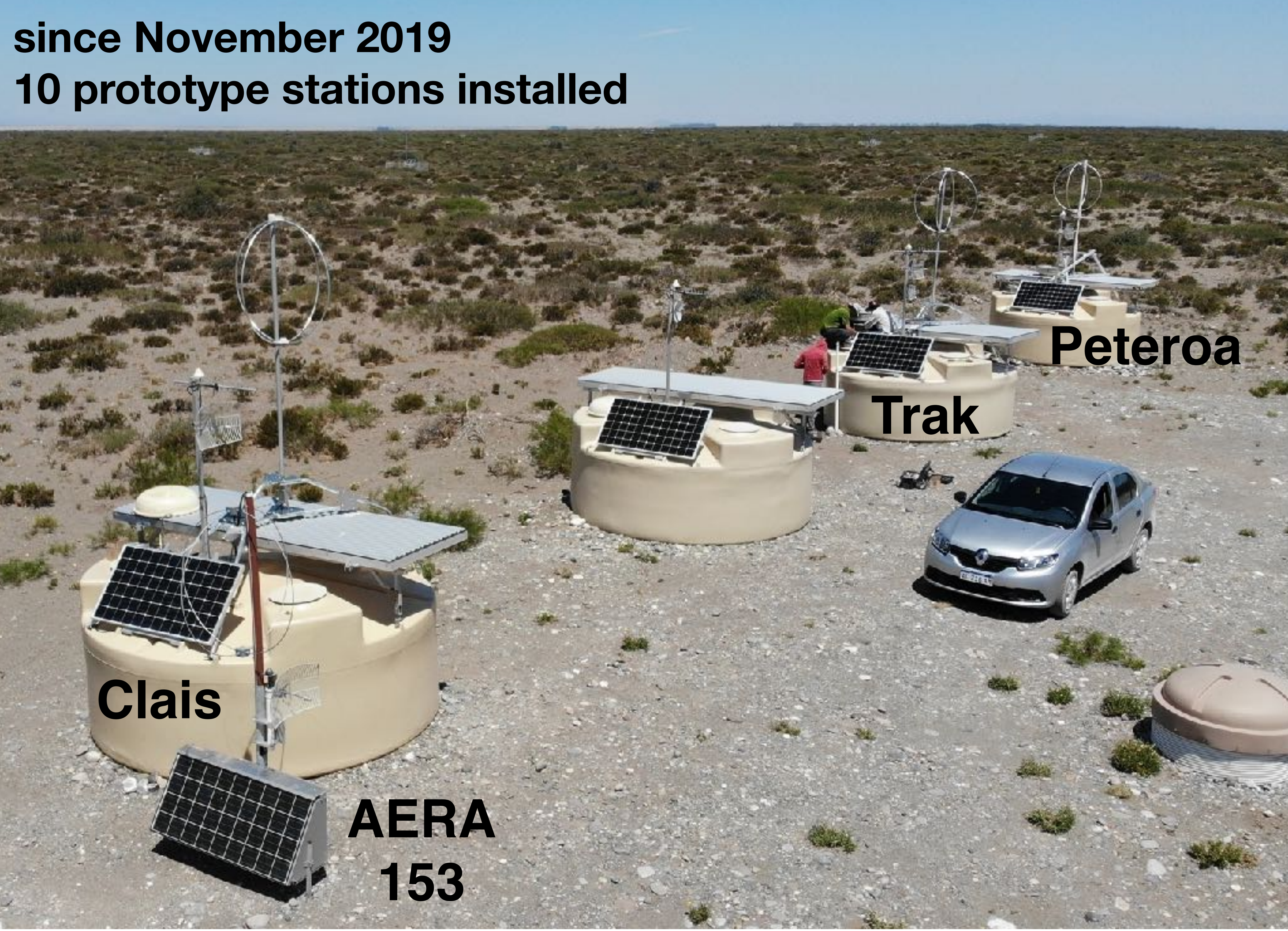
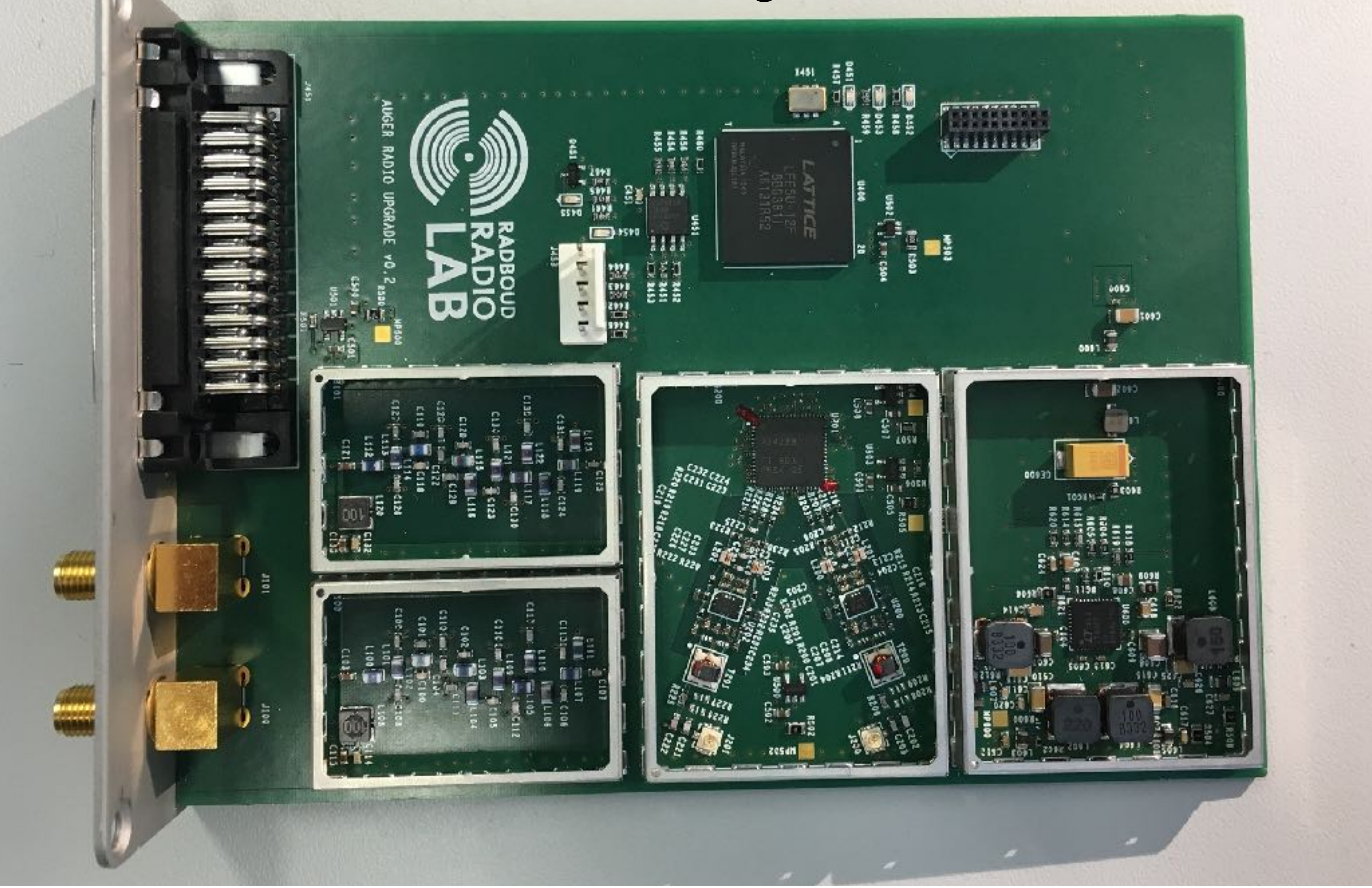
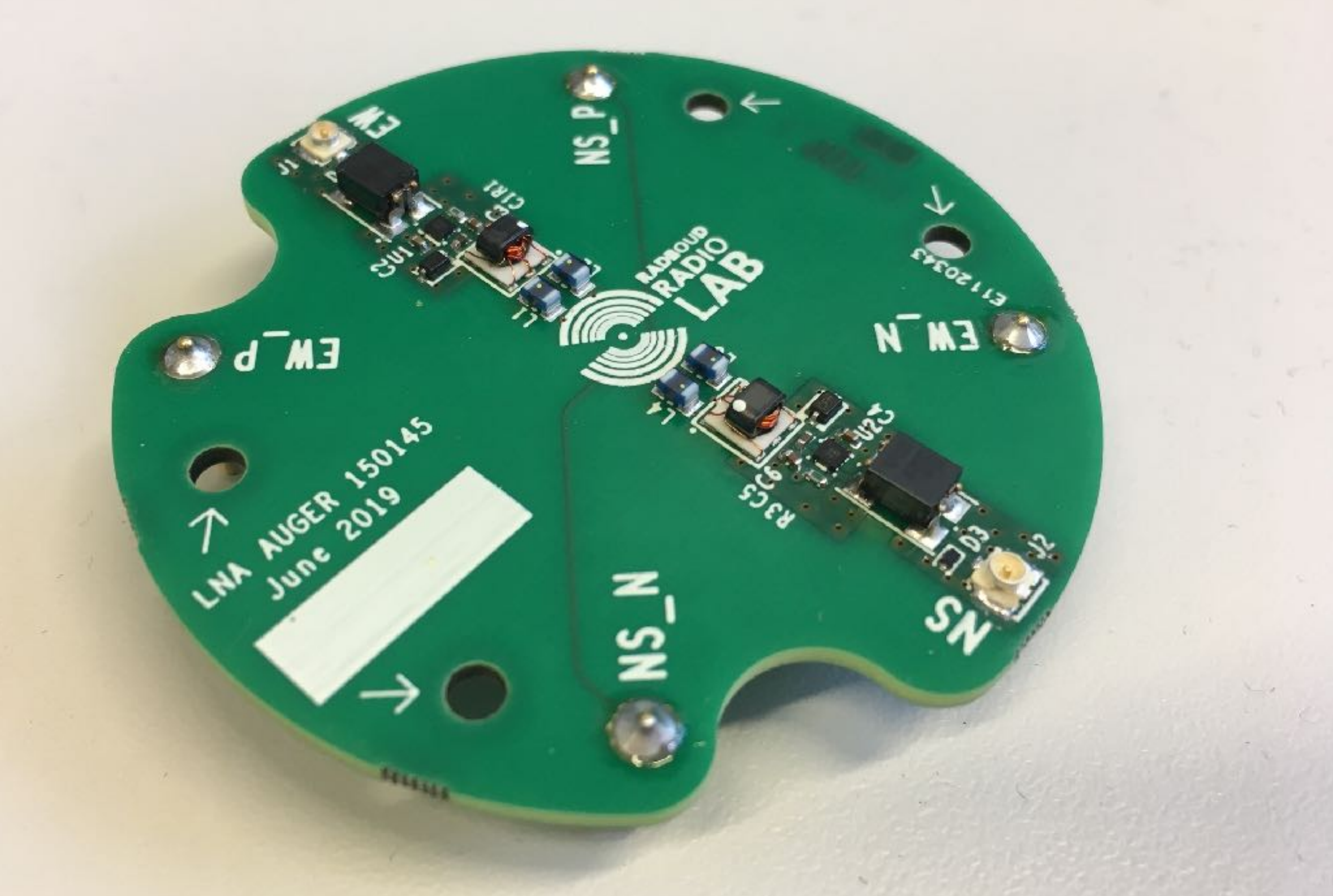


photo: Tim Huege

radio digitizer



developed at RU Nijmegen

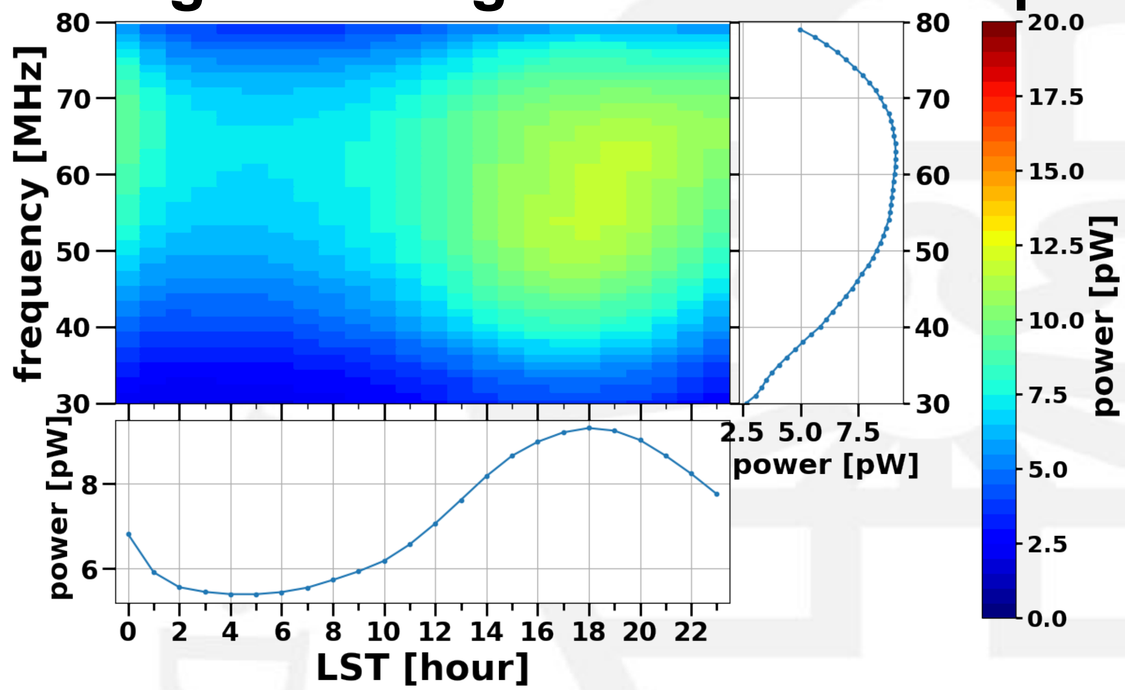


final version of LNA, RU Nijmegen, June 2019

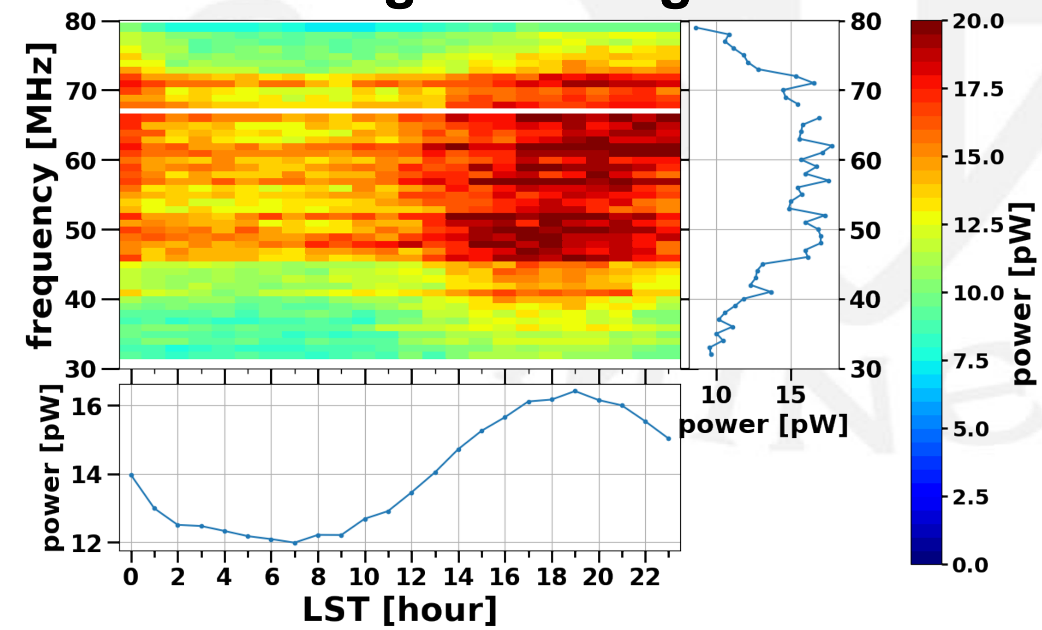
Calibration with Galactic signal

siderial modulation of Galactic signal

Simulated galactic signal in the EW loop



Measured noise & galactic signal in the EW loop

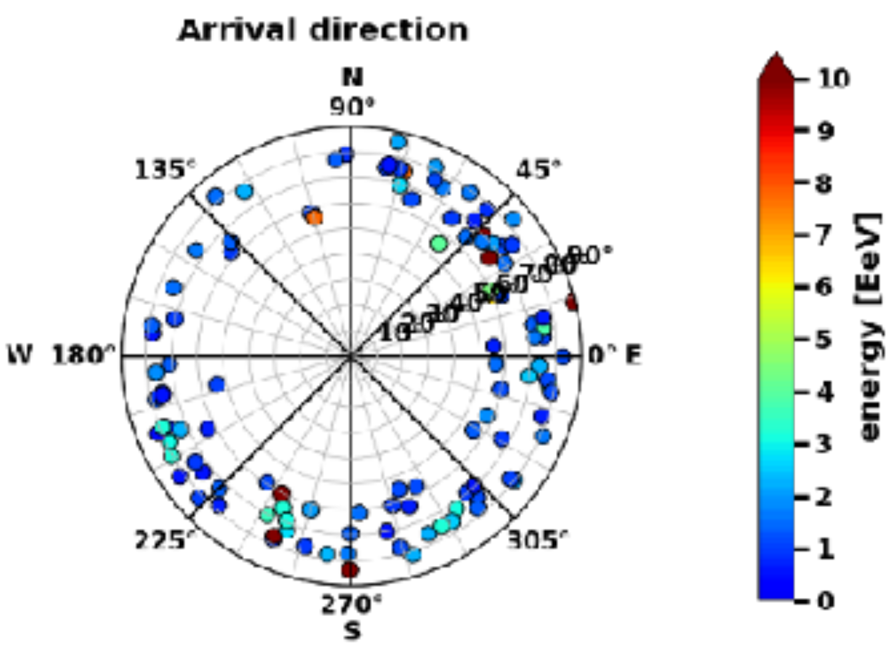


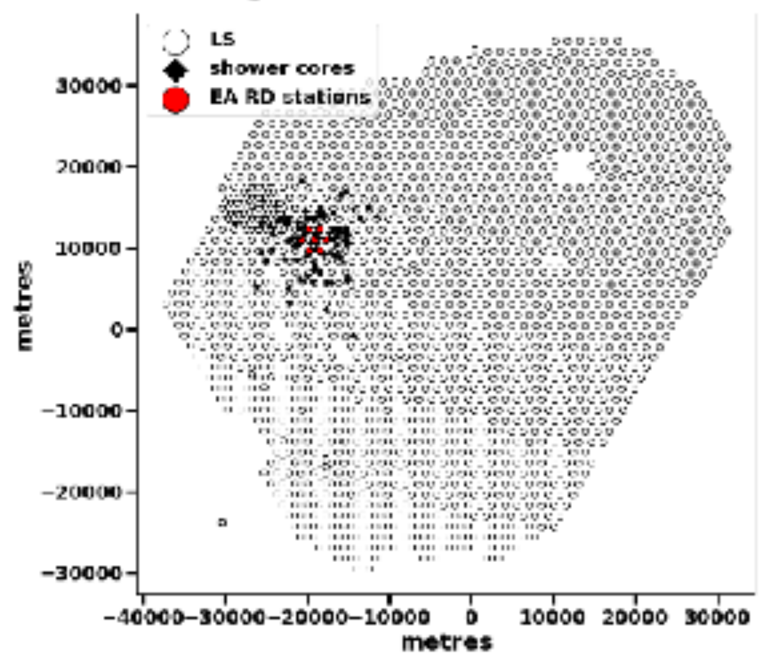
- **EW calibration constant: 1.03 ± 9.6% ± 2%**
- **NS calibration constant: 0.96 ± 9.7% ± 2%**
- **Uncertainty caused by the Antenna model: max 1.5%**
- **For more details see this proceeding: https://pos.sissa.it/395/**

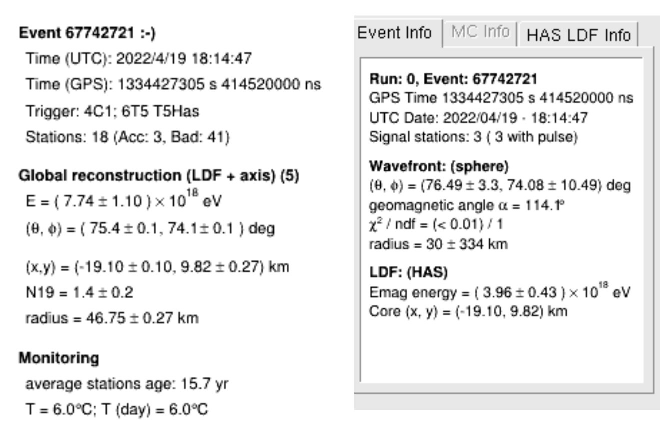
see Tomas Fodran, ARENA 2022

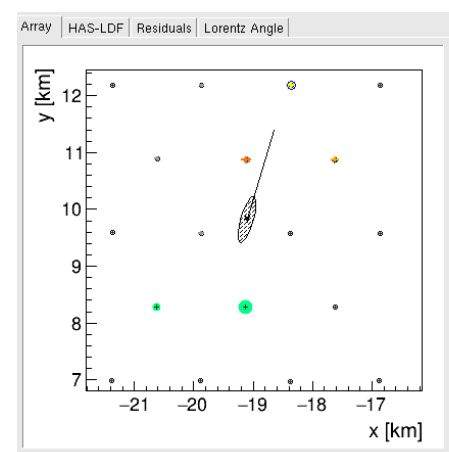
Air showers measured with engineering array

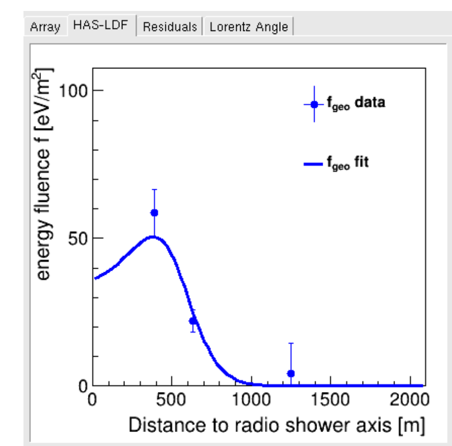
Nice 3-fold event above lg(18.4/eV)

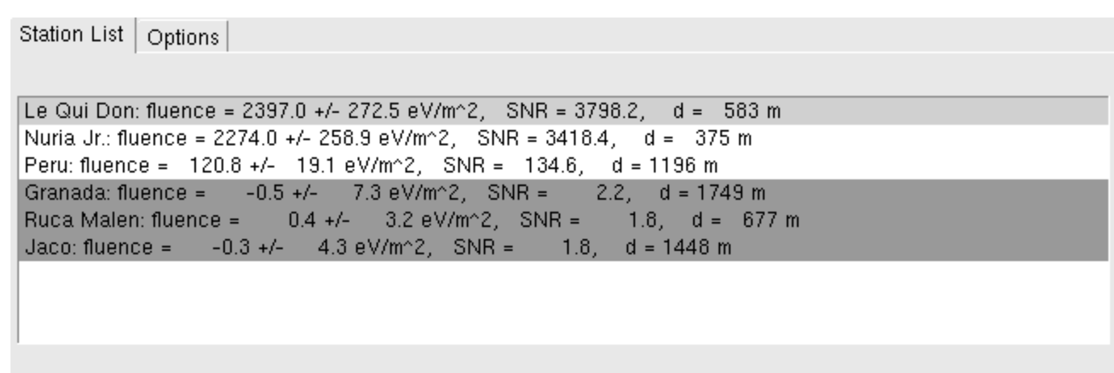


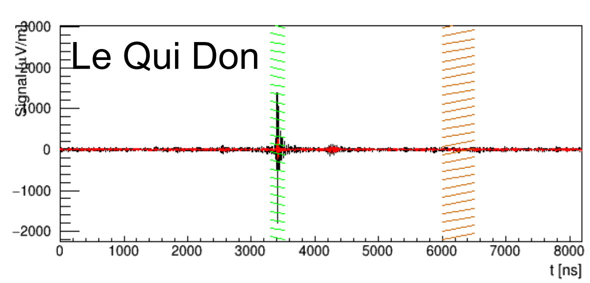


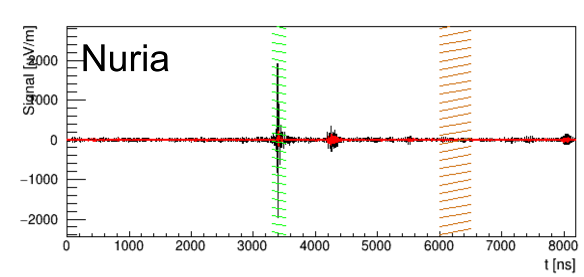


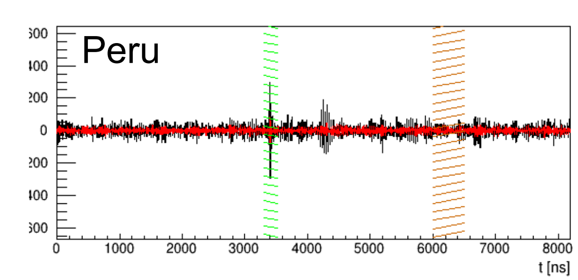




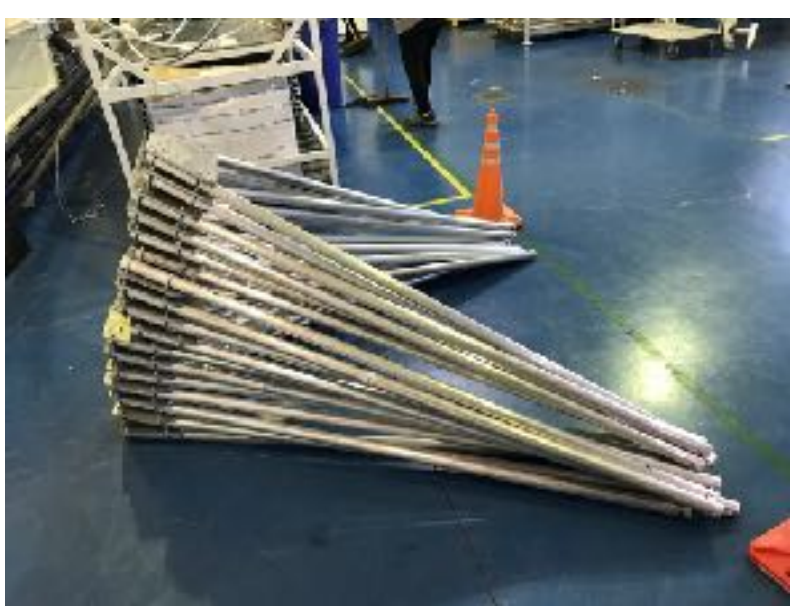


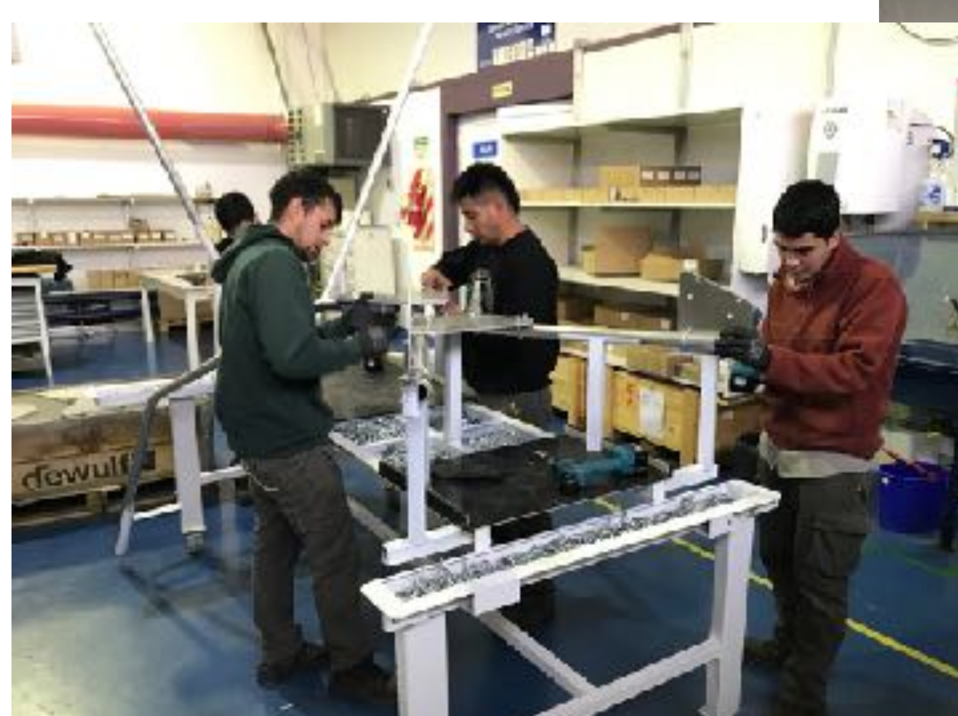






Mass production of RD started at Observatory





Radio detection of extensive air showers

Precision measurements of the properties of cosmic rays

The radio technique is now able to characterize cosmic rays:
- -direction ✓
- -energy ✓
- -mass ✓

@100% duty cycle

—> application on largest scales at Pierre Auger observatory