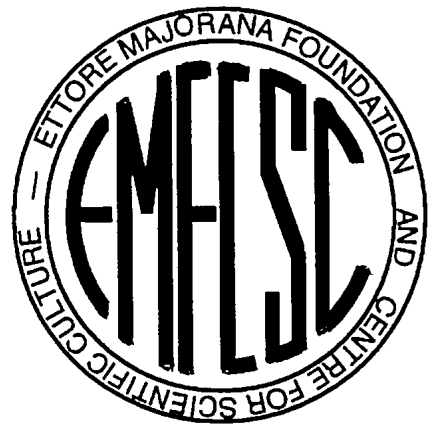


Radio detection of extensive air showers

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»

24th Course: “Particles and the Cosmos – Bridging the infinitesimal and the infinite”
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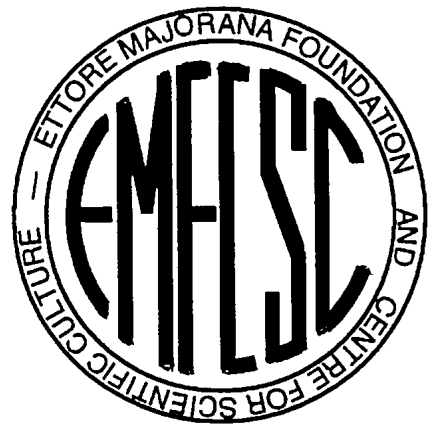


Jörg R. Hörandel

Radboud University, Nijmegen, The Netherlands - Vrije Universiteit Brussel, Belgium - <http://hoerandel.eu>

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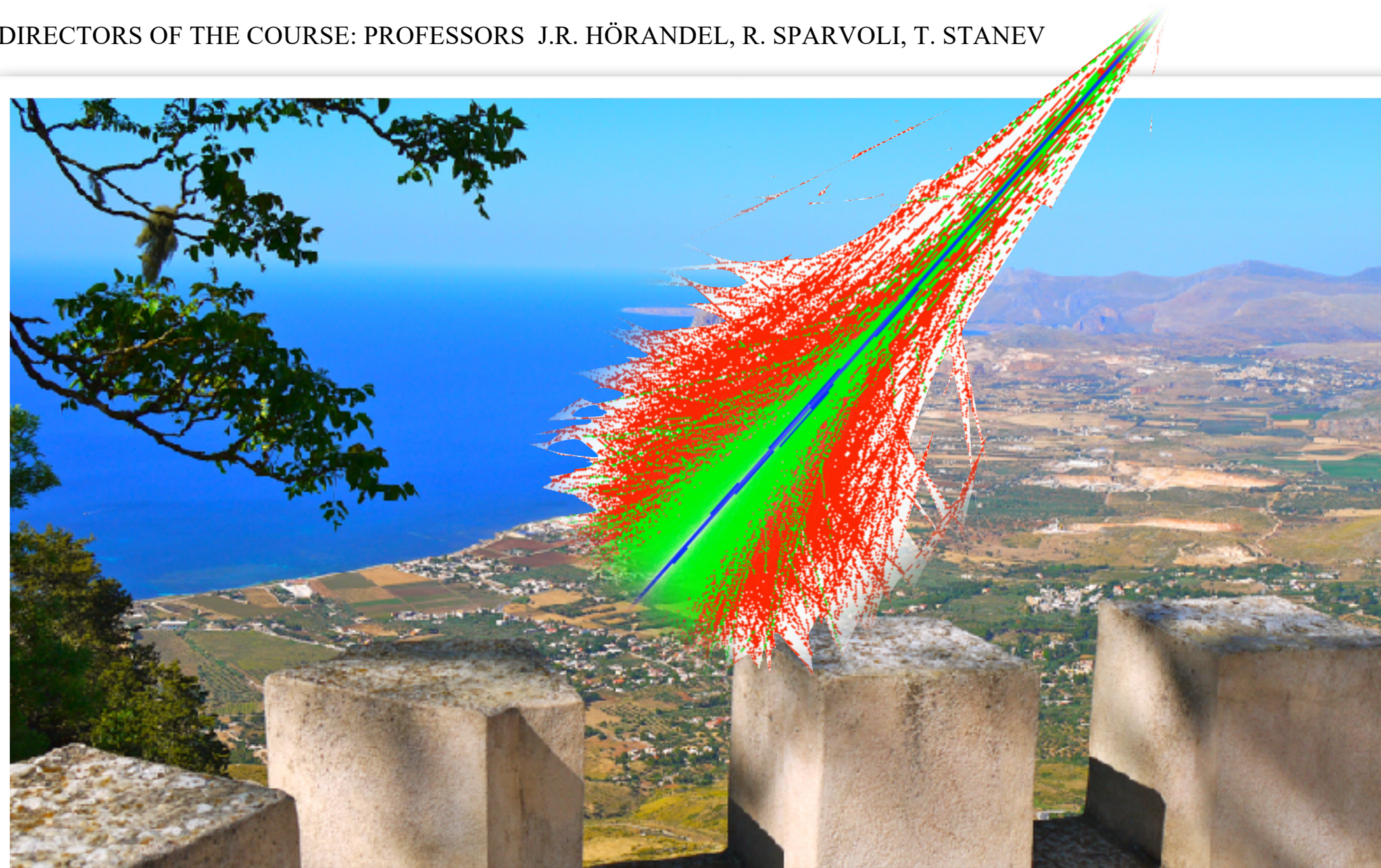
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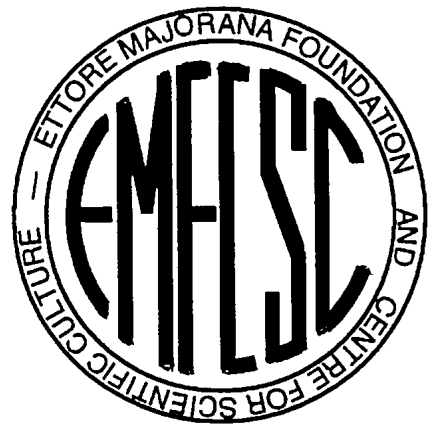


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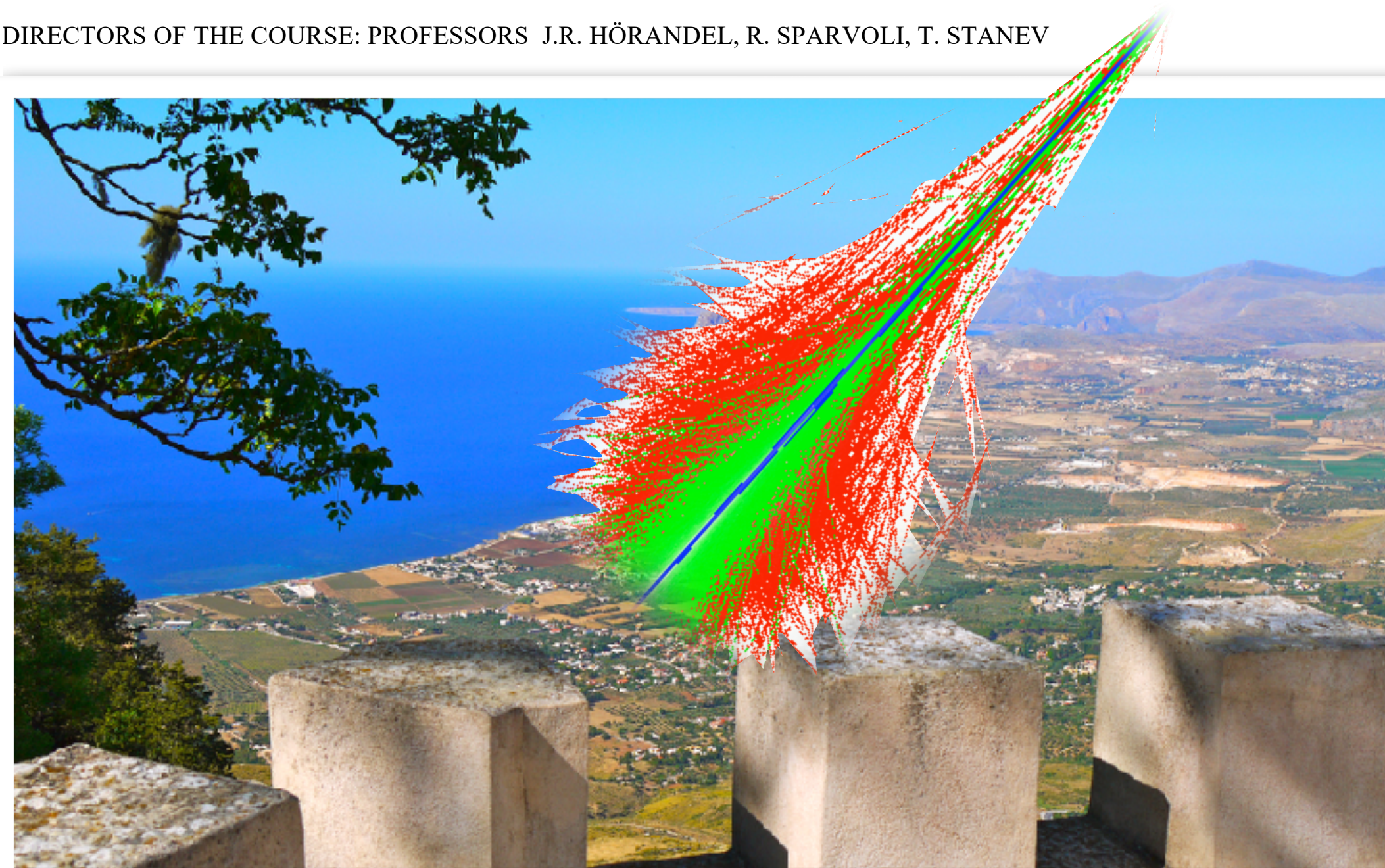
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characterize cosmic rays:

-direction

-energy

-mass

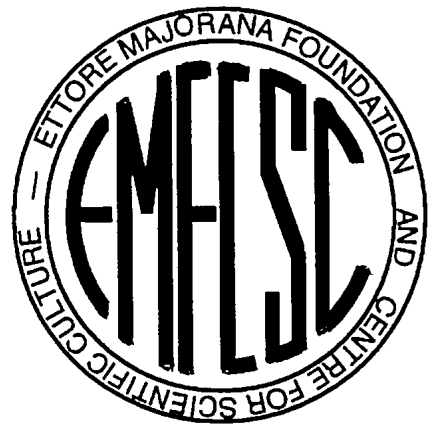
@100% duty cycle

Jörg R. Hörandel

Radboud University, Nijmegen, The Netherlands - Vrije Universiteit Brussel, Belgium - <http://hoerandel.eu>

Radio detection of extensive air showers

Precision measurements of the properties of cosmic rays



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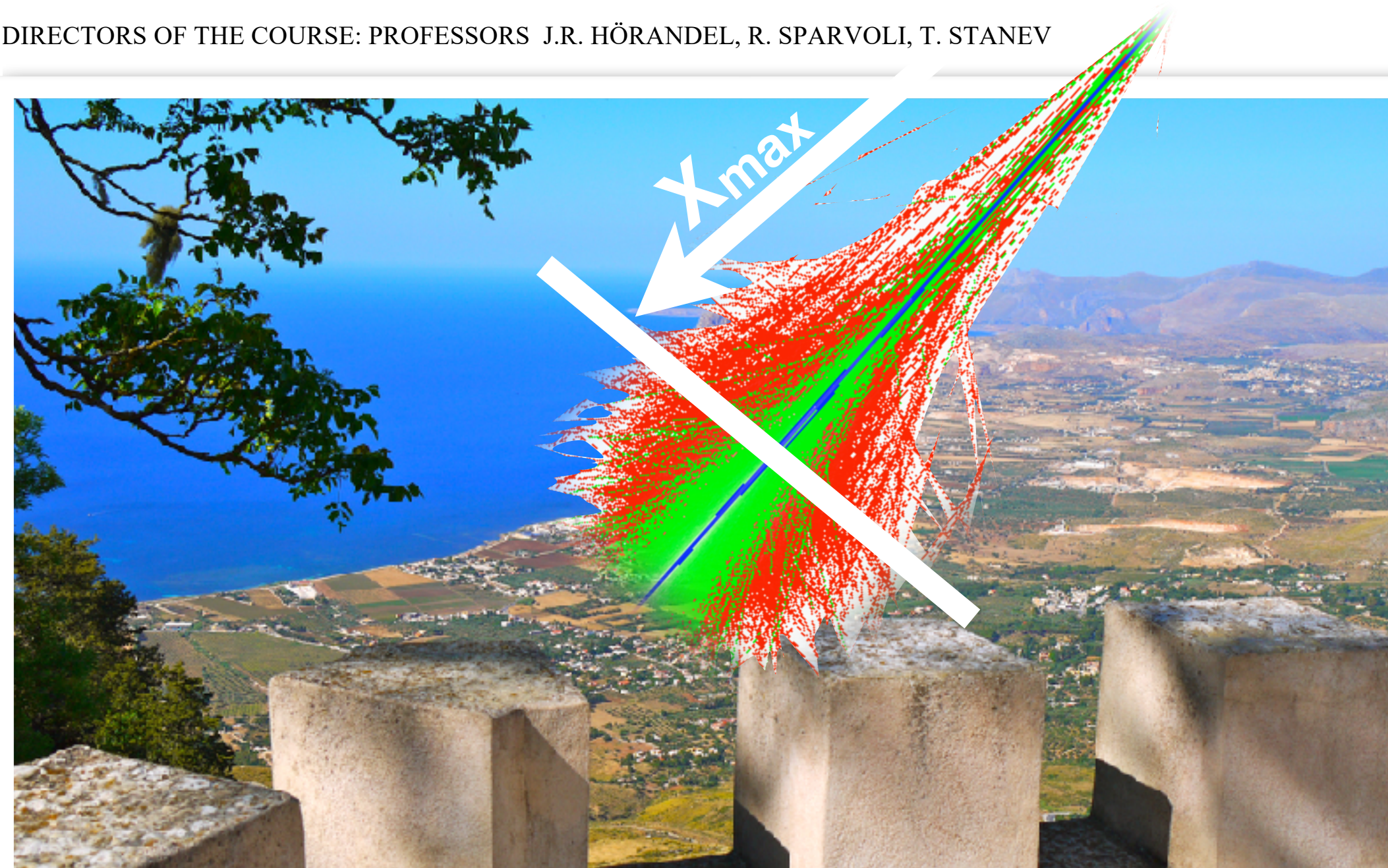
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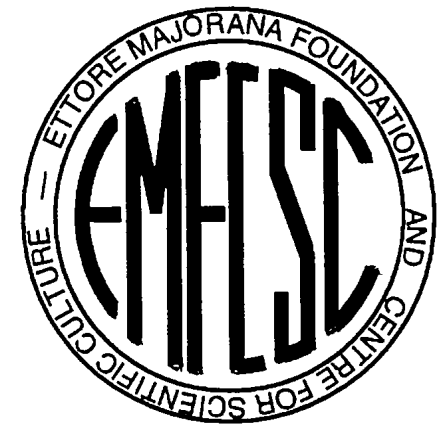
@100% duty cycle

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Radio detection of extensive air showers

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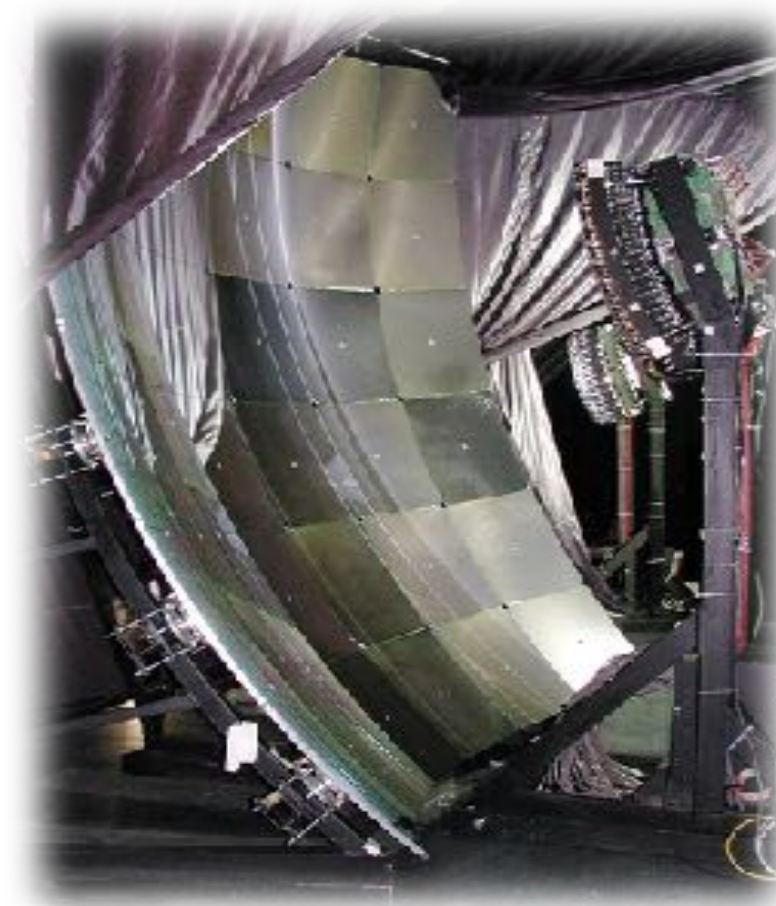
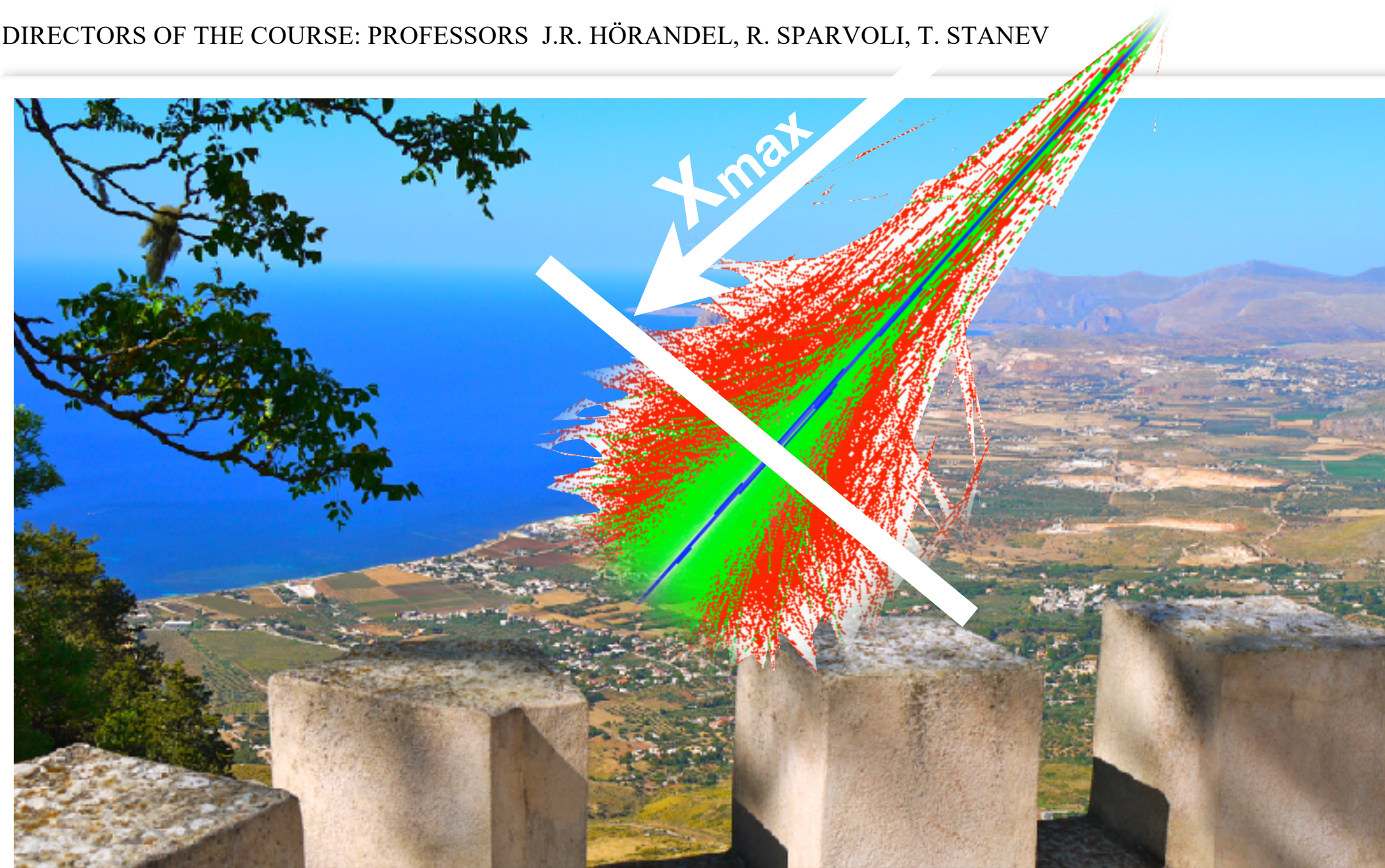
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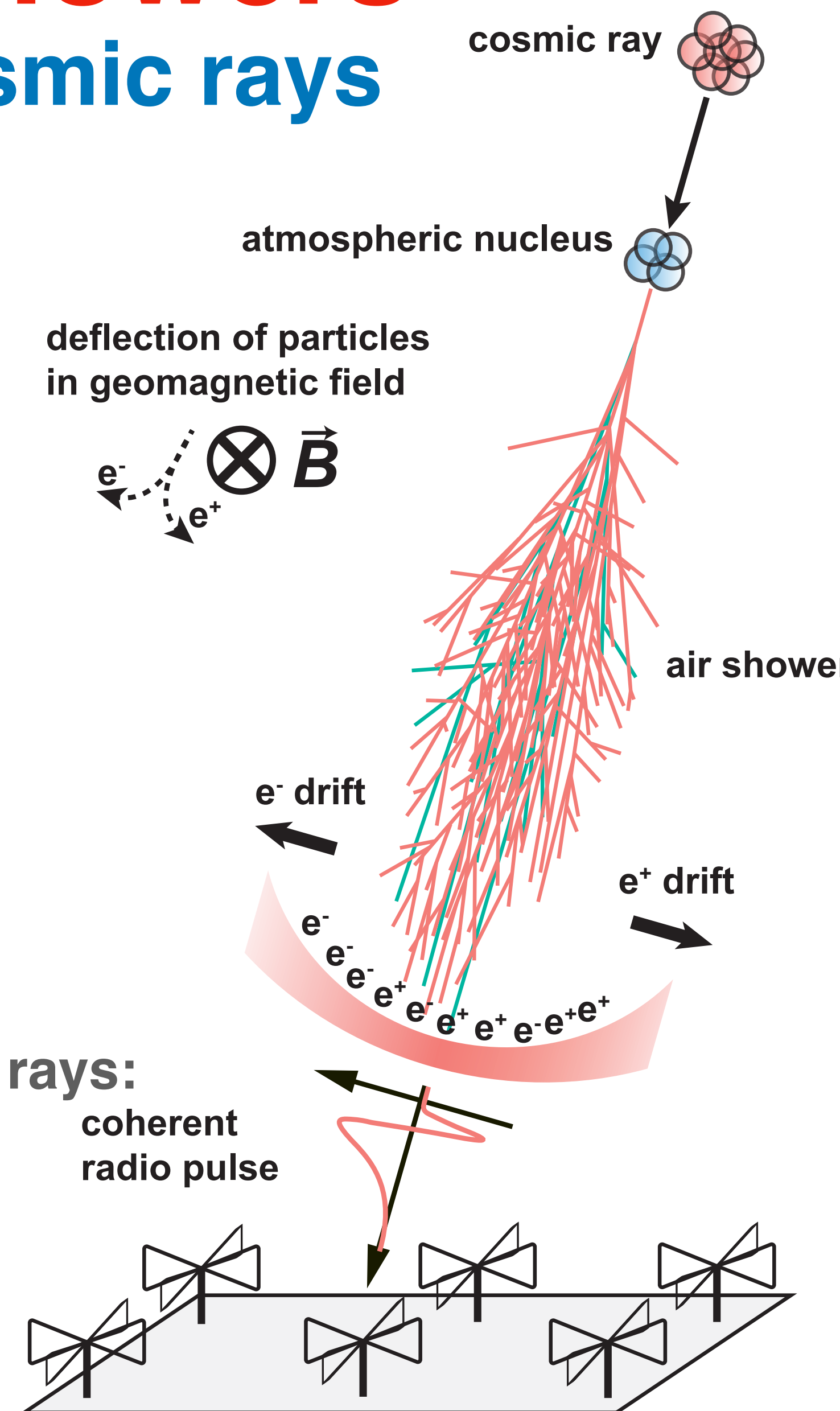
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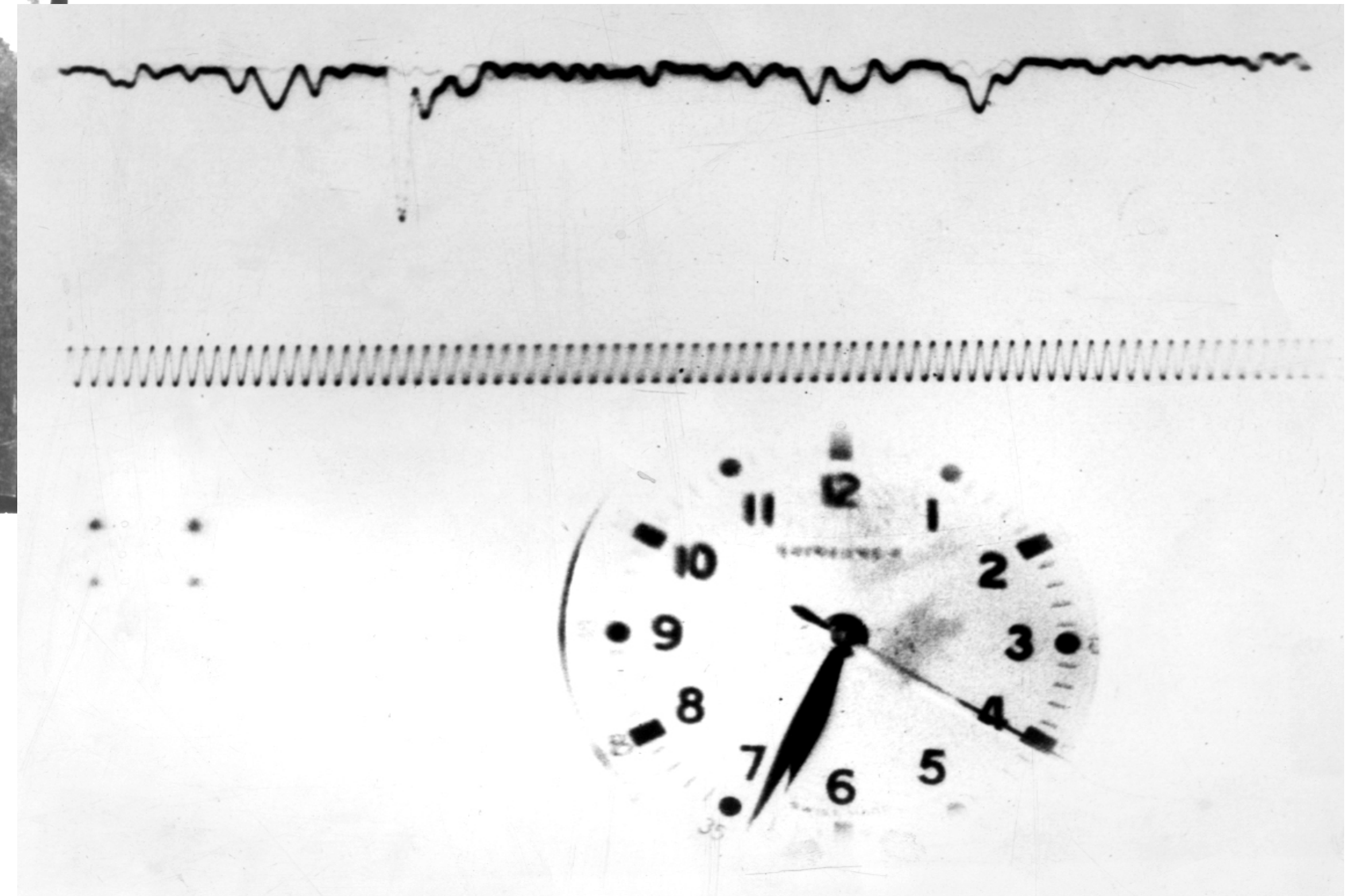


Jörg R. Hörandel

Radboud University, Nijmegen, The Netherlands - Vrije Universiteit Brussel, Belgium - <http://hoerandel.eu>

First radio detection of air showers 1965

Blackett's Field ~1967
Porter MSc



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

The renaissance of radio detection of cosmic rays

TIM HUEGE¹

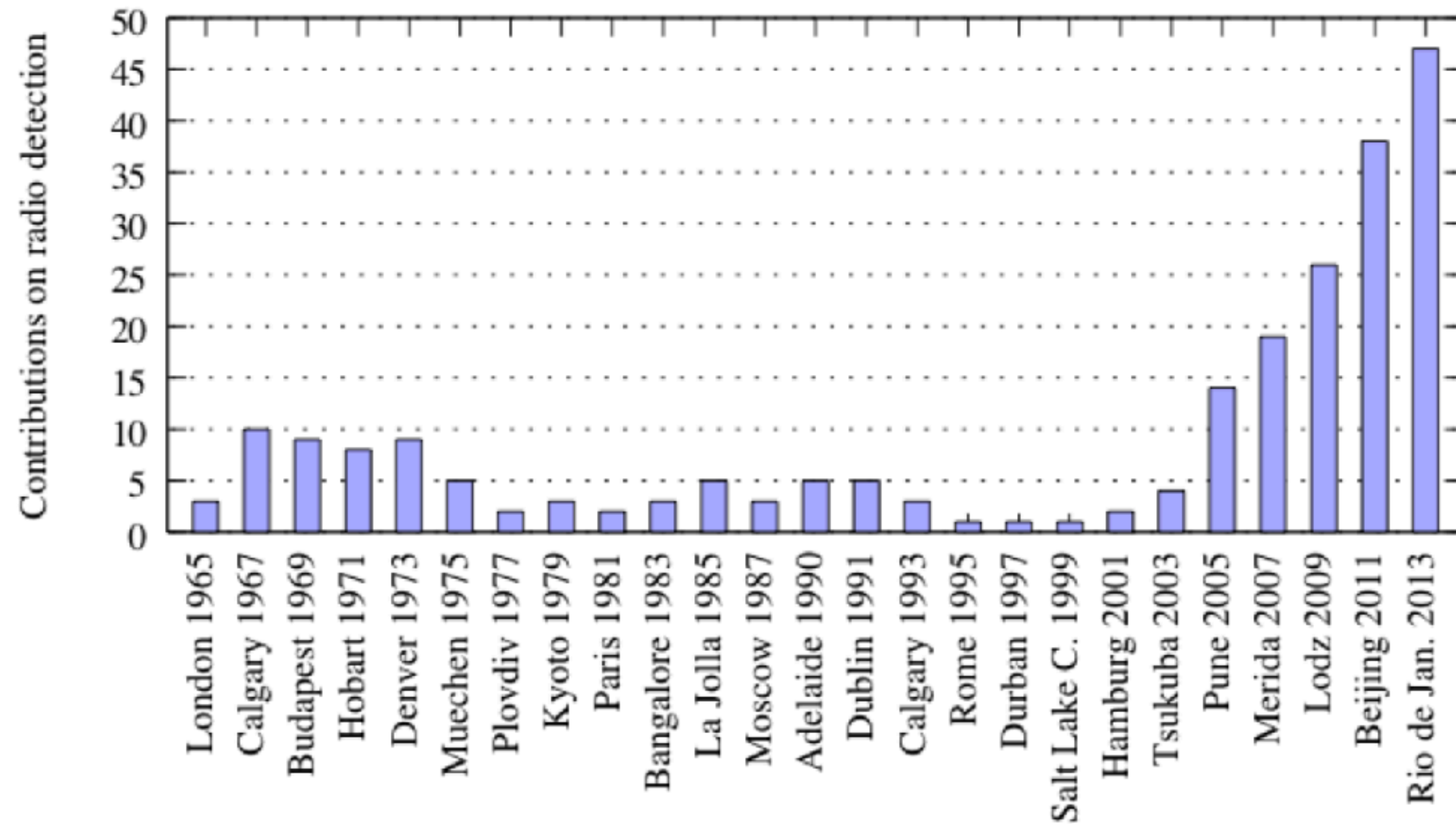


Figure 1: Number of contributions related to radio detection of cosmic rays or neutrinos to the ICRCs since 1965. The field has grown very impressively since the modern activities started around 2003. Data up to 2007 were taken from [11].

The renaissance of radio detection of cosmic rays

TIM HUEGE¹

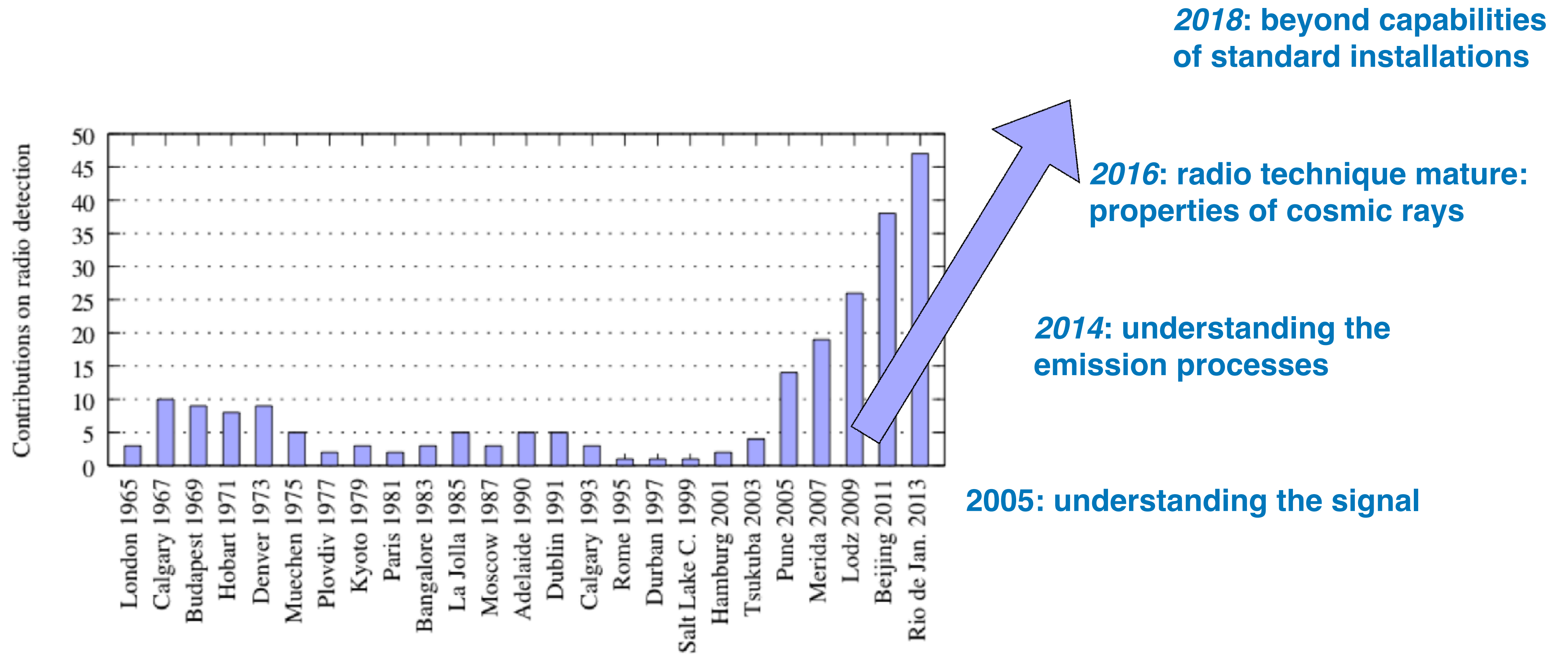
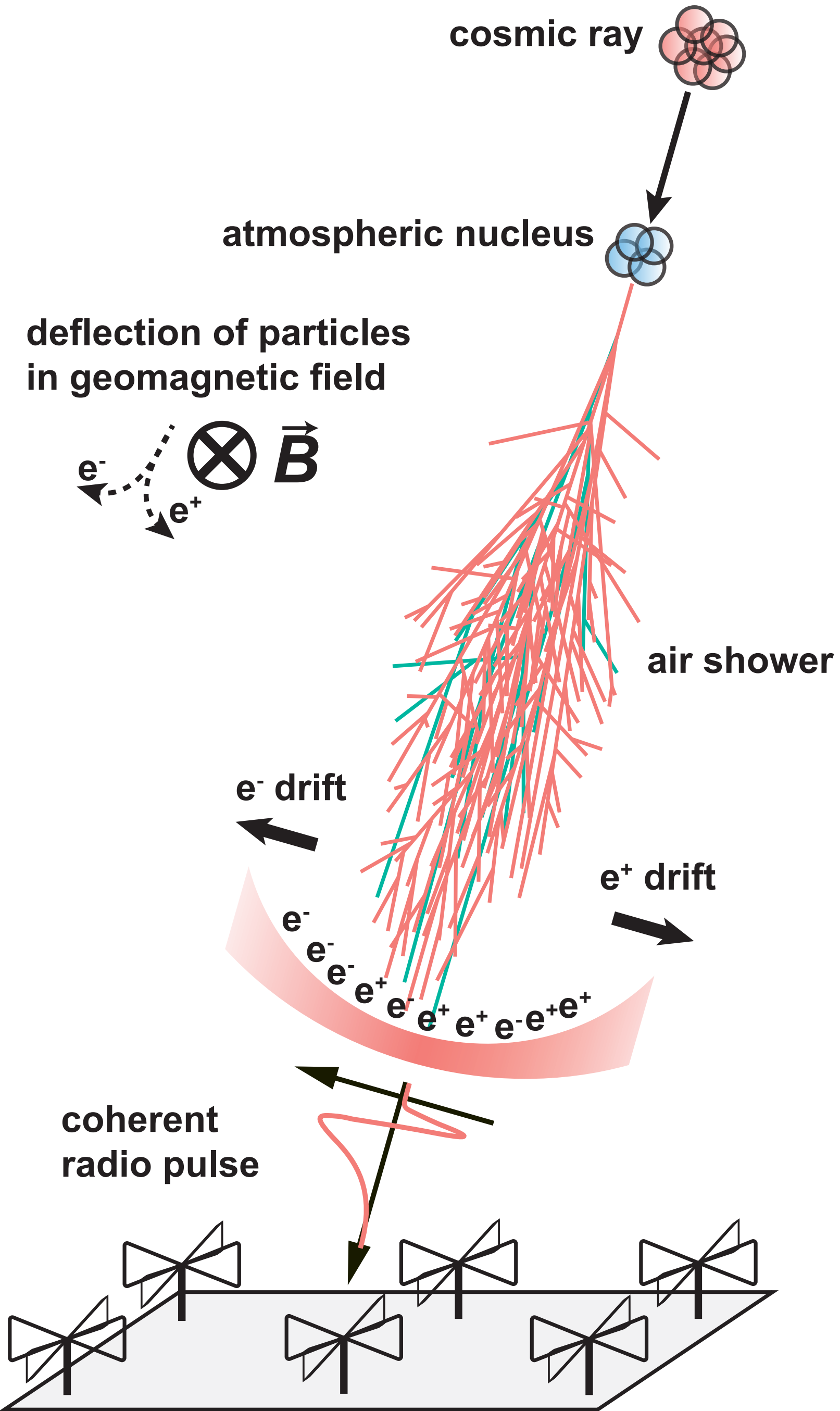
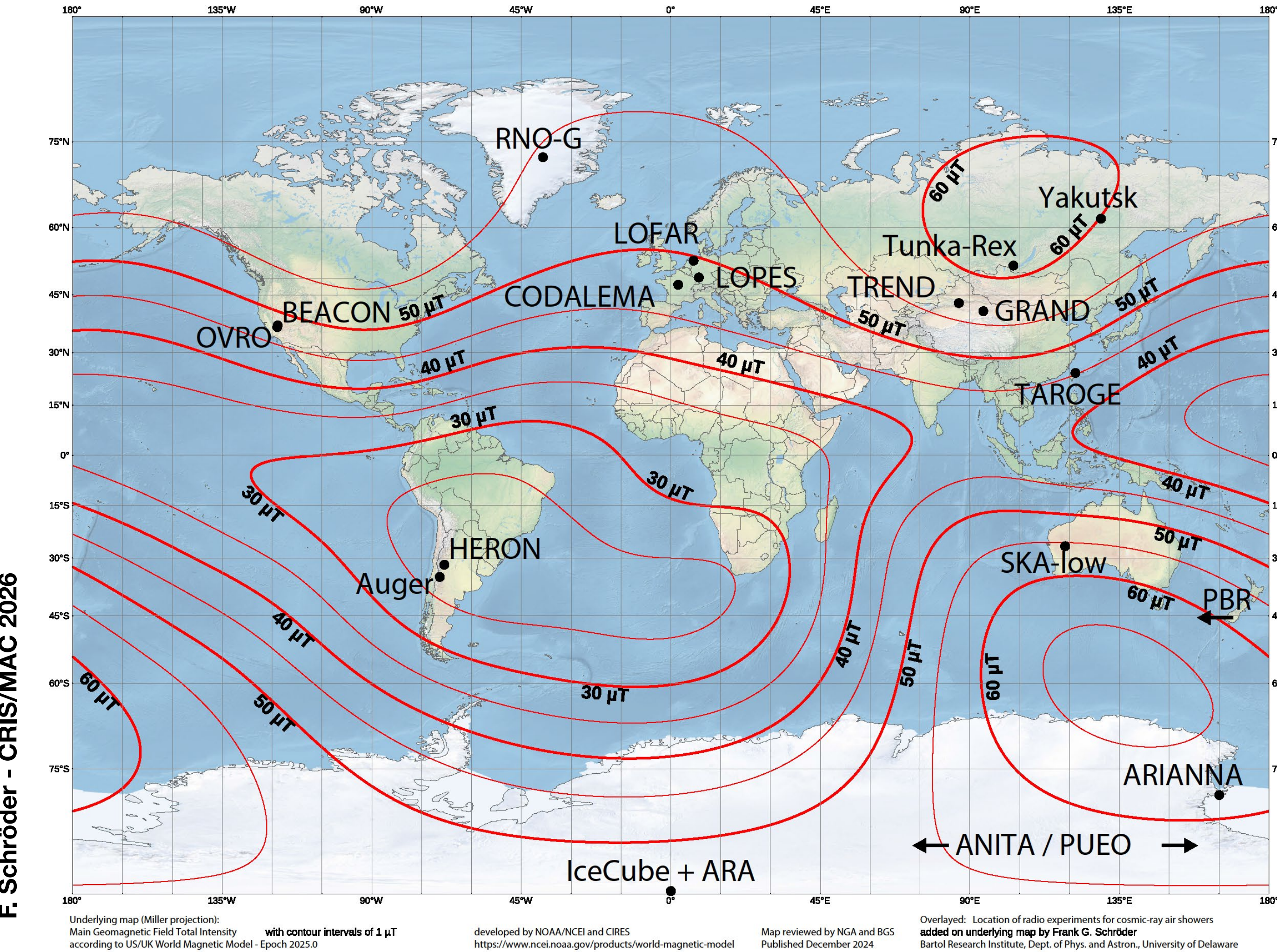


Figure 1: Number of contributions related to radio detection of cosmic rays or neutrinos to the ICRCs since 1965. The field has grown very impressively since the modern activities started around 2003. Data up to 2007 were taken from [11].

Radio Emission in Air Showers

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



Geomagnetic effect

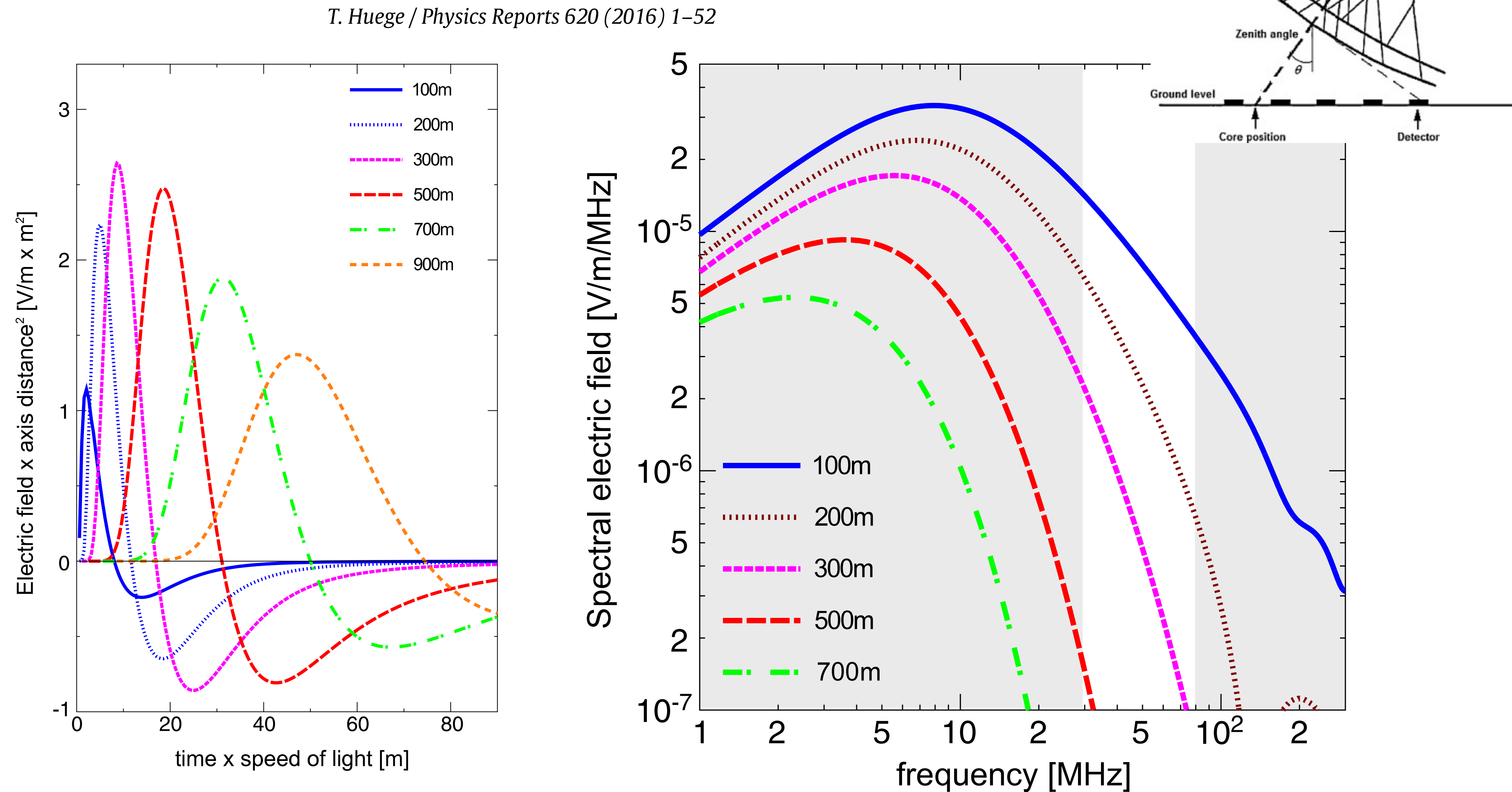


Fig. 4. Radio pulses (top) arising from the time-variation of the geomagnetically induced transverse currents in a 10^{17} eV air shower as observed at various observer distances from the shower axis and their corresponding frequency spectra (bottom). Refractive index effects are not included.
Source: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

Radio Emission in Air Showers

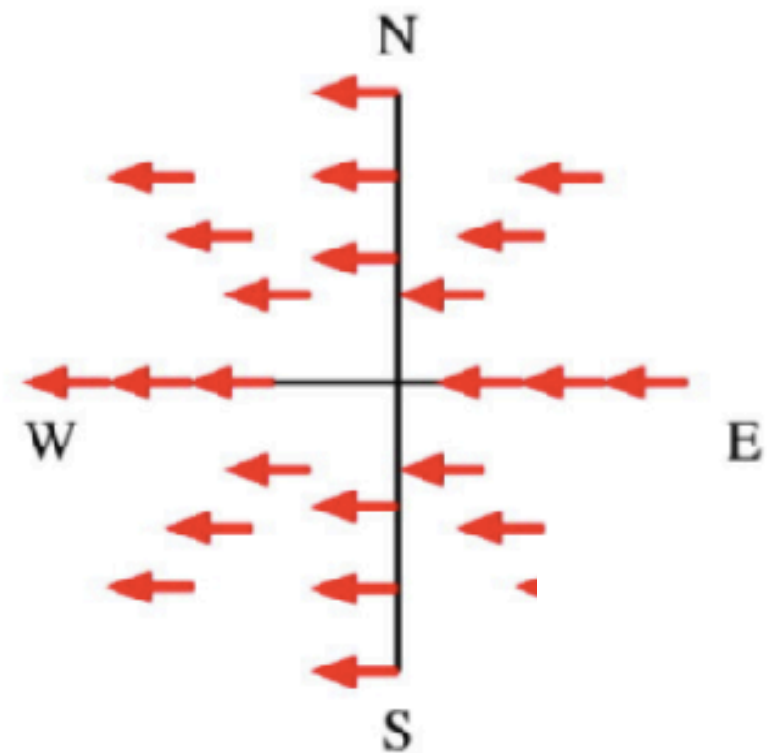
- Mainly: Charge separation in **geomagnetic field** $\vec{E} \propto \vec{v} \times \vec{B}$

Theory predicts additional mechanisms:

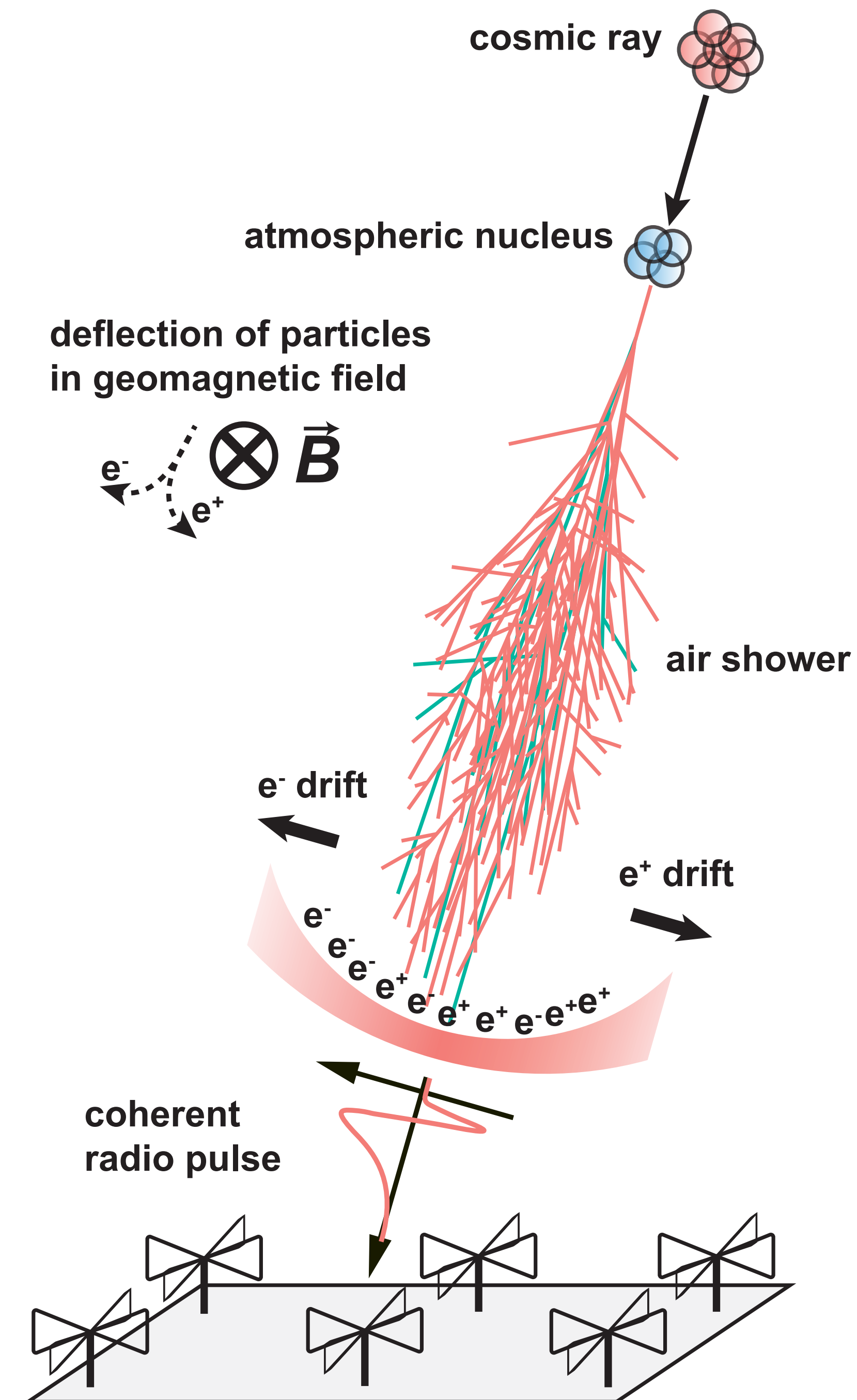
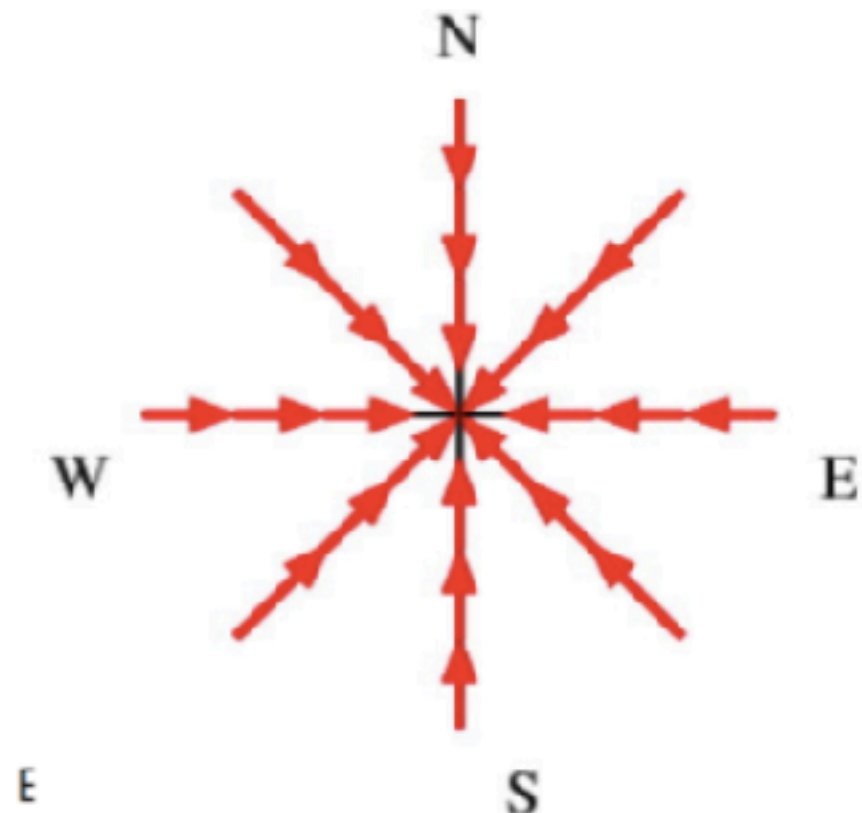
- excess of electrons in shower: **charge excess**
- superposition of emission due to **Cherenkov** effects in atmosphere

polarization of radio signal

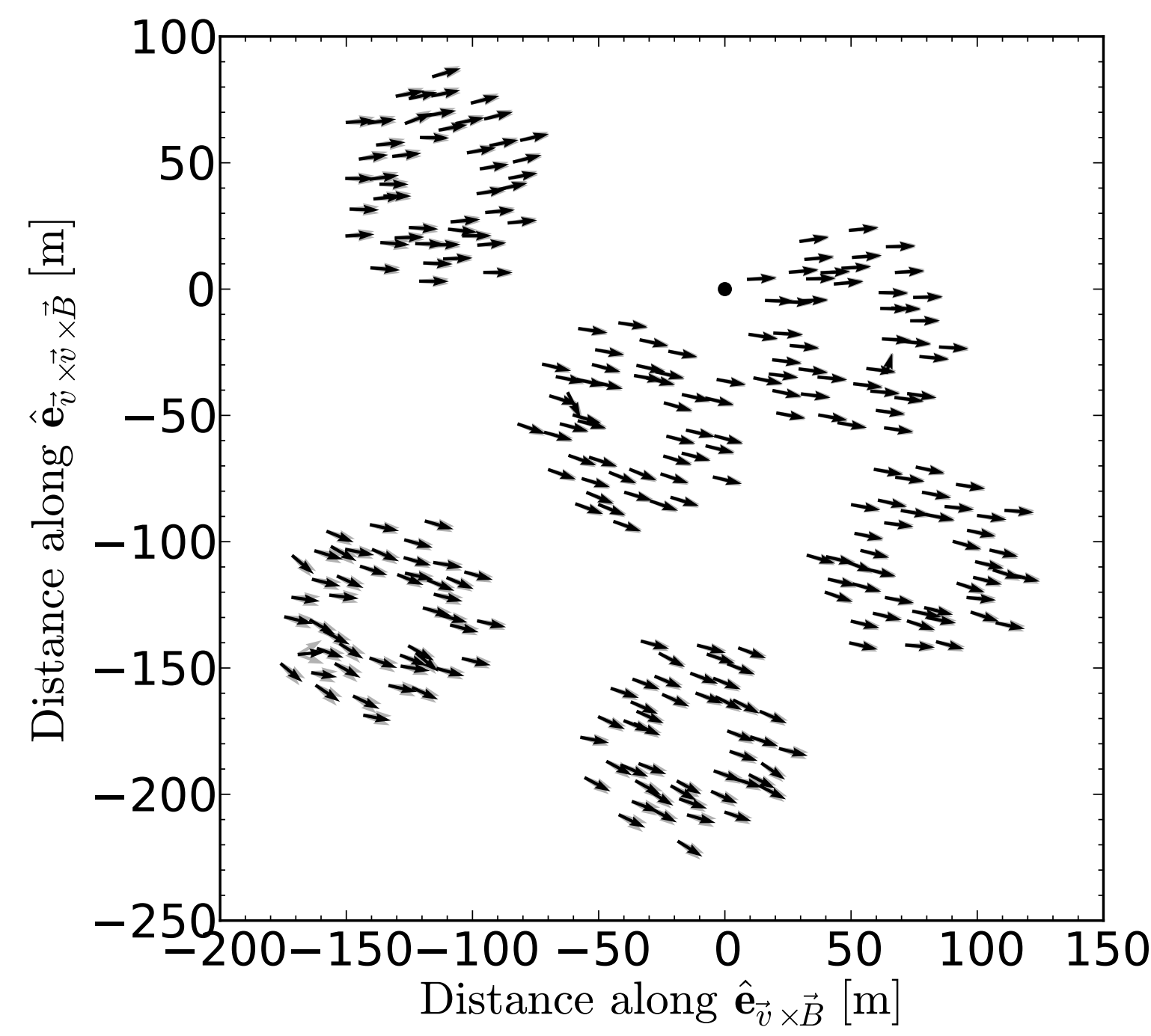
geomagnetic



Askaryan



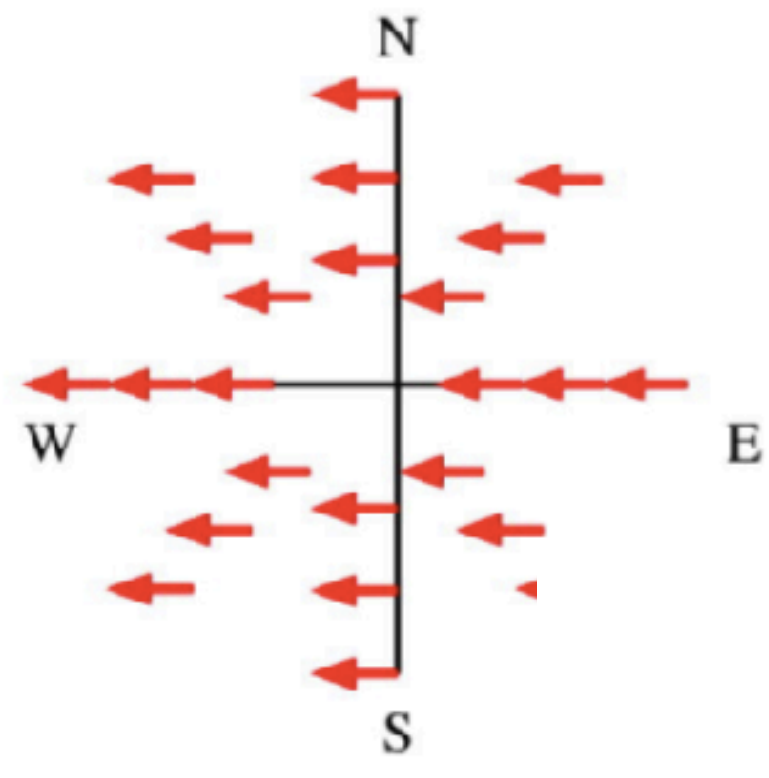
Charge excess fraction



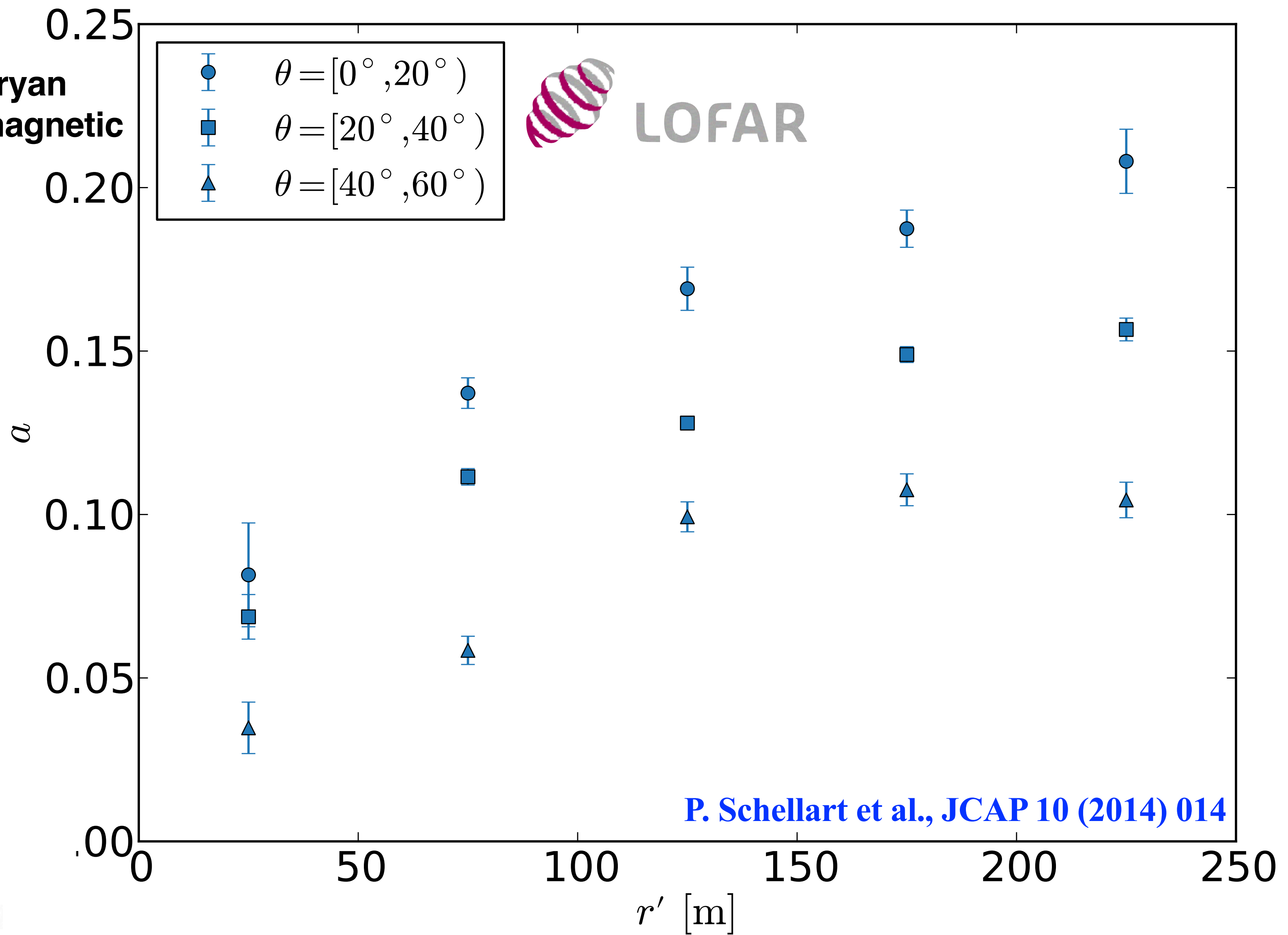
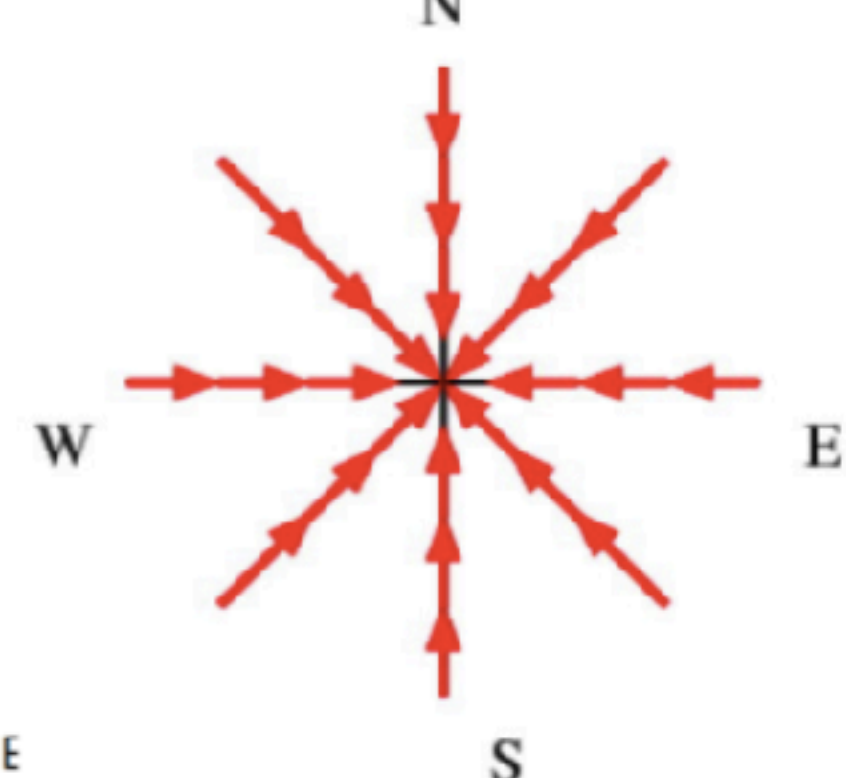
Askaryan
geomagnetic

polarization of radio signal

geomagnetic

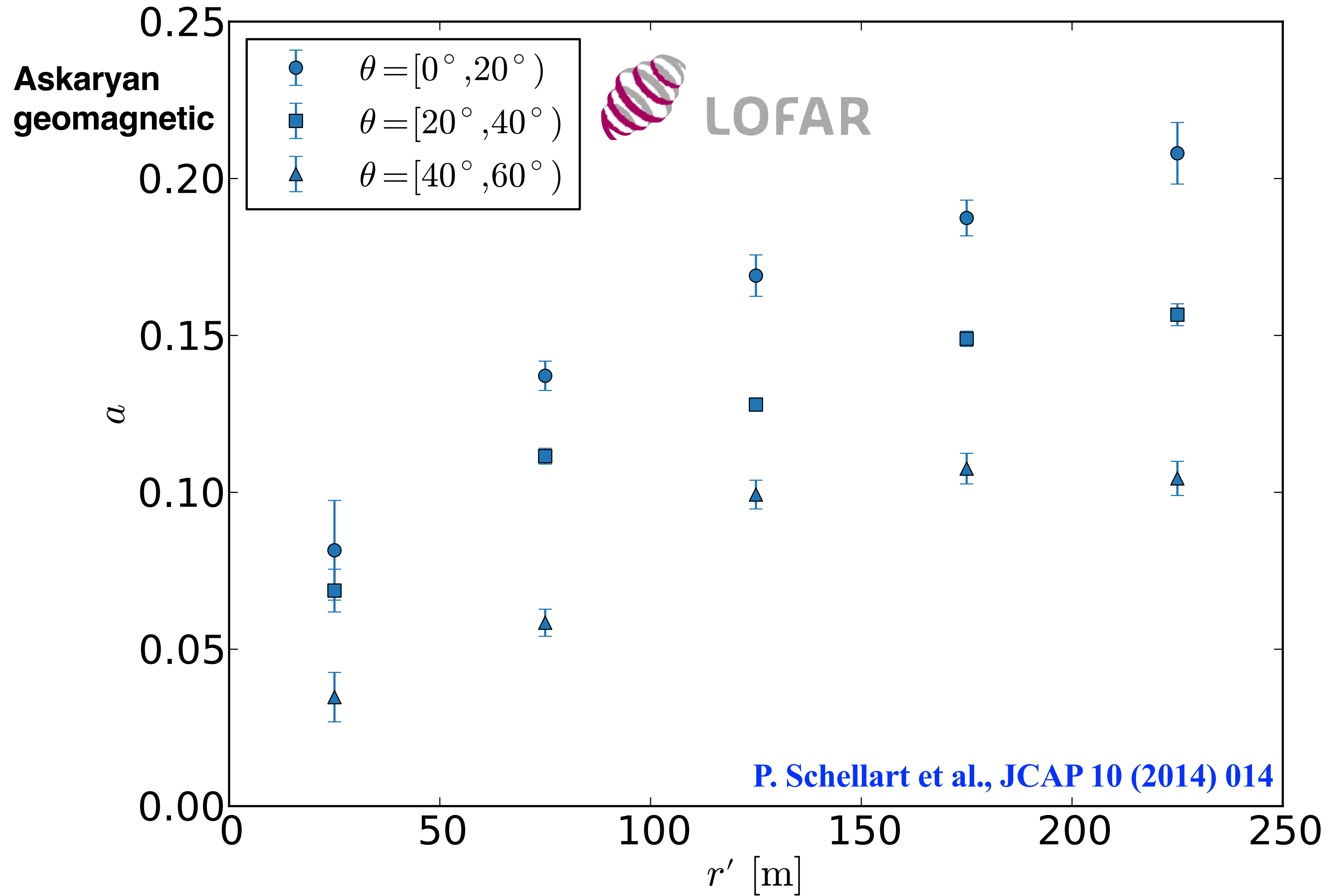
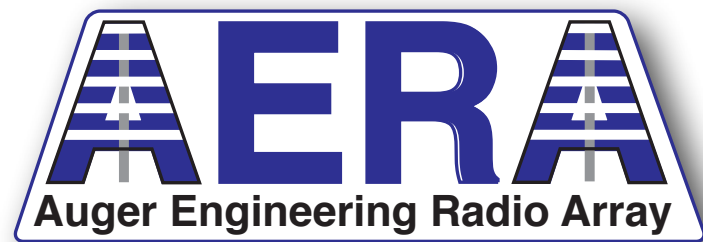
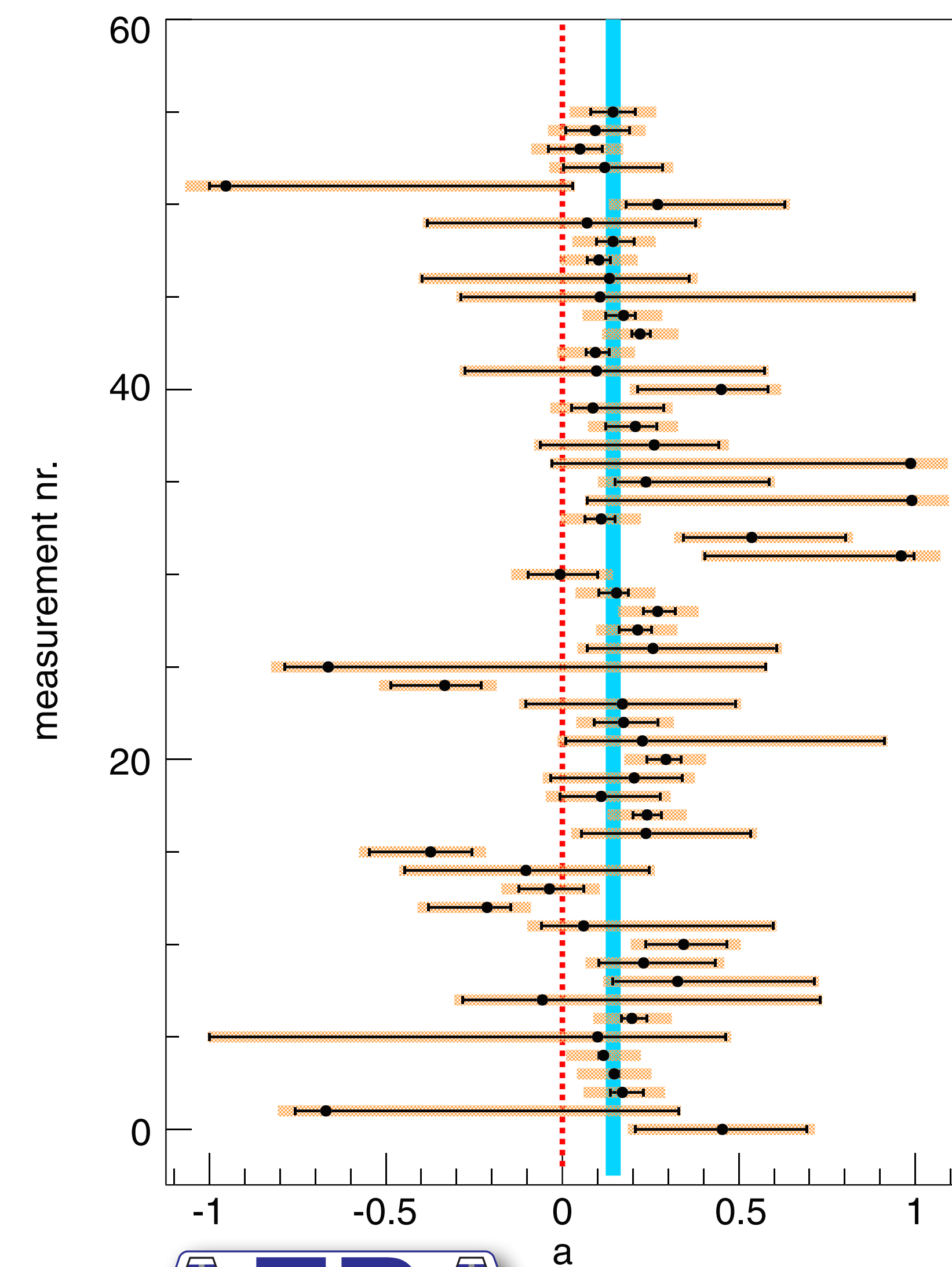


Askaryan



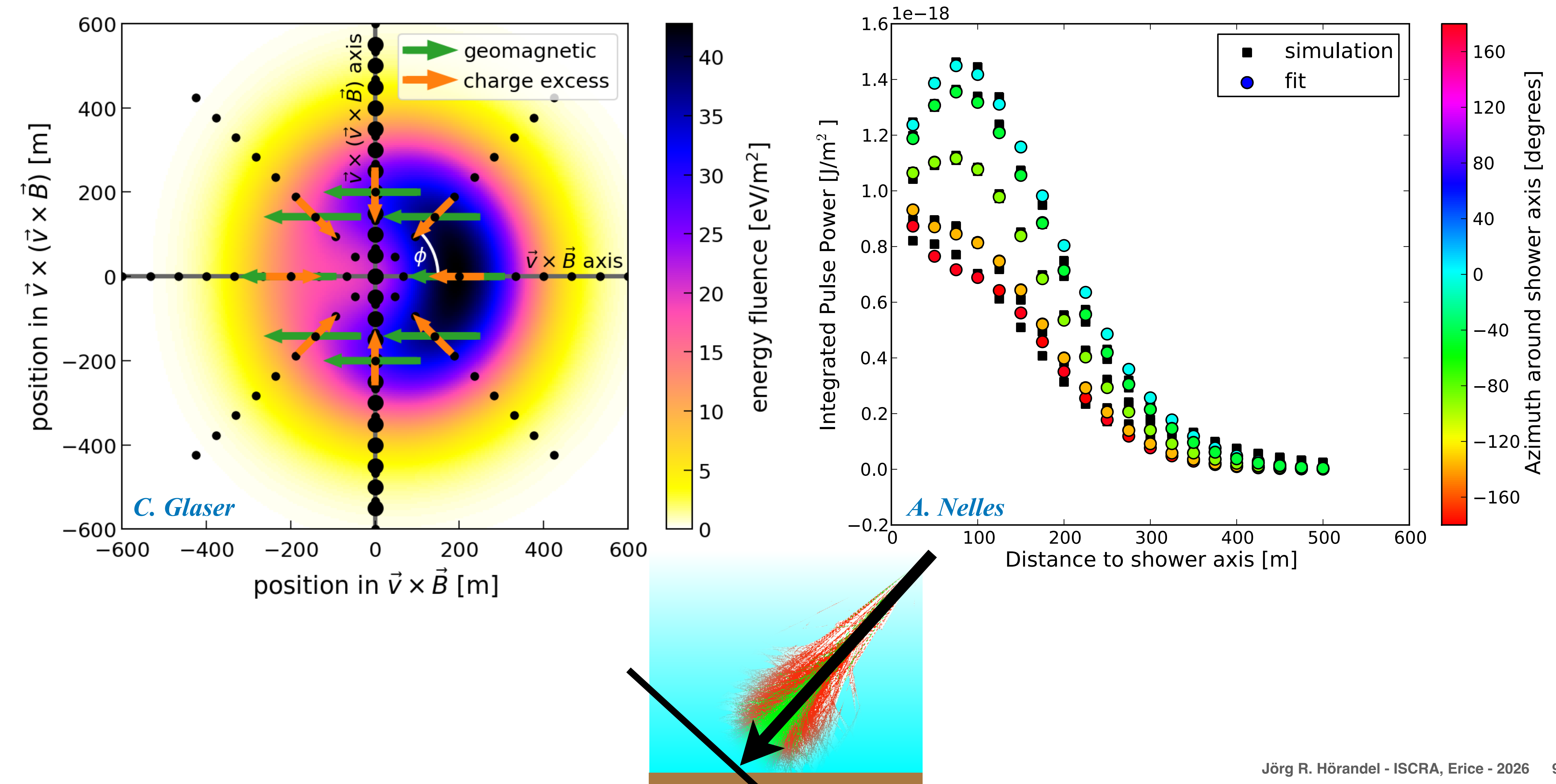
P. Schellart et al., JCAP 10 (2014) 014

Charge excess fraction

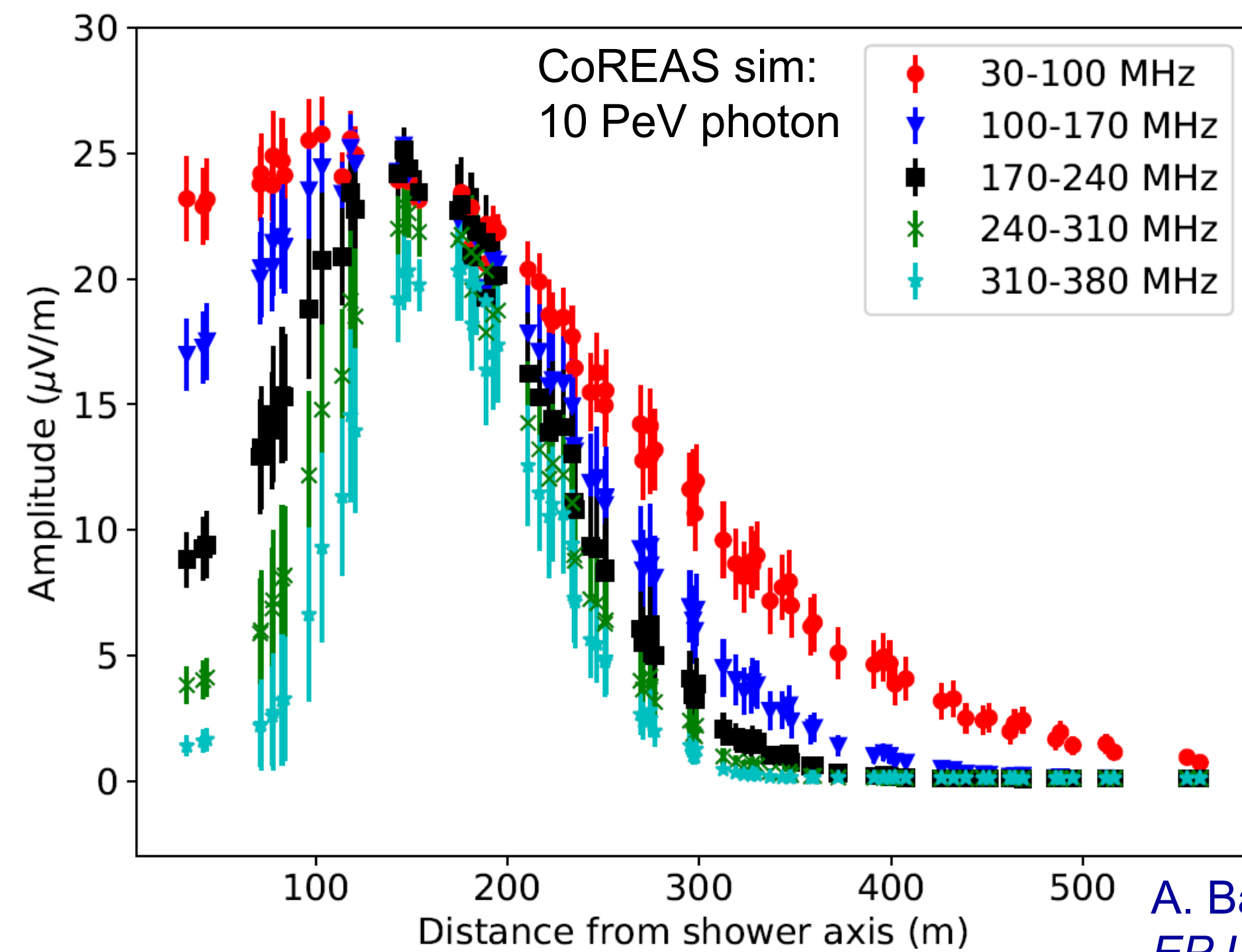
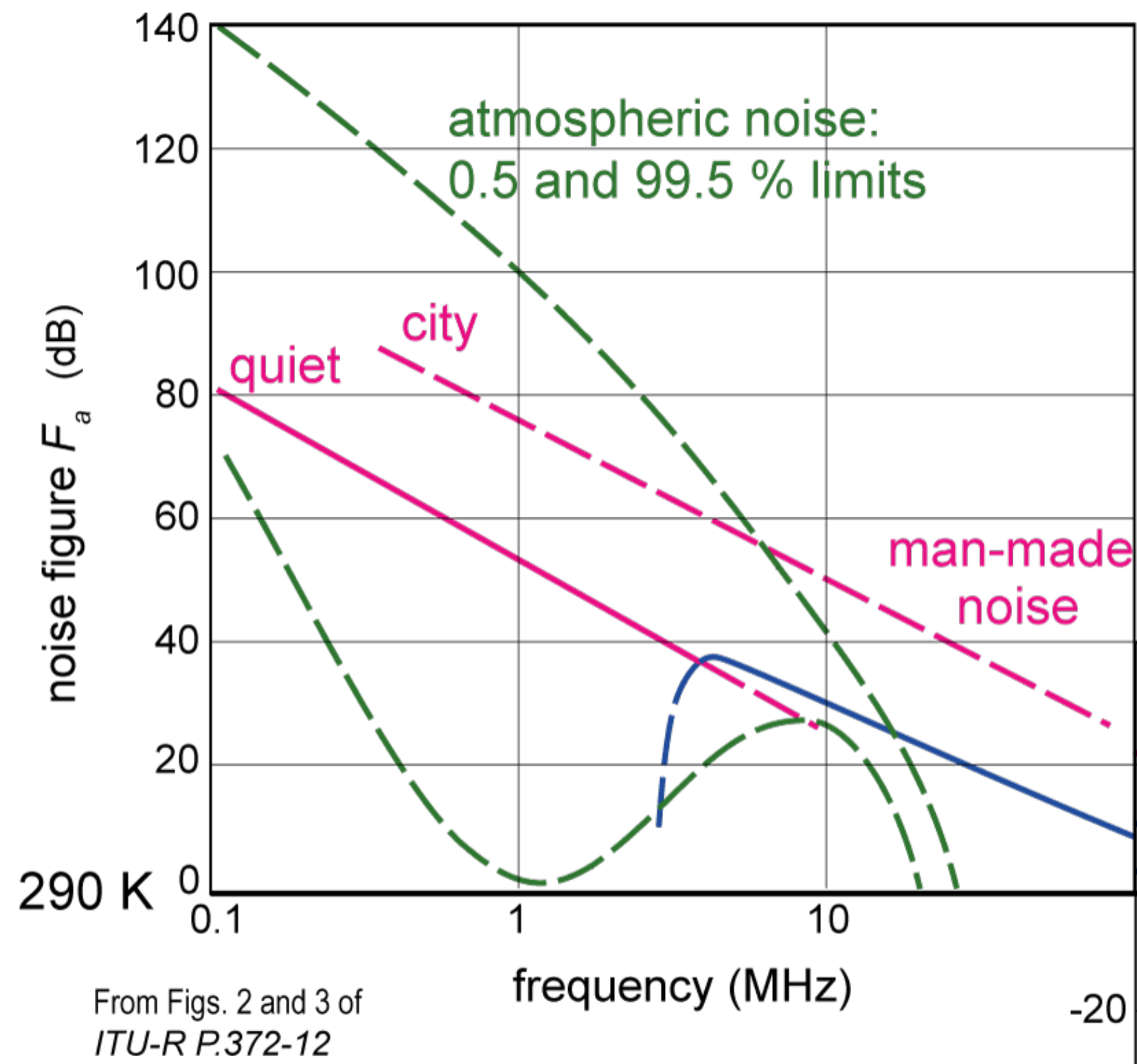


P. Schellart et al., JCAP 10 (2014) 014

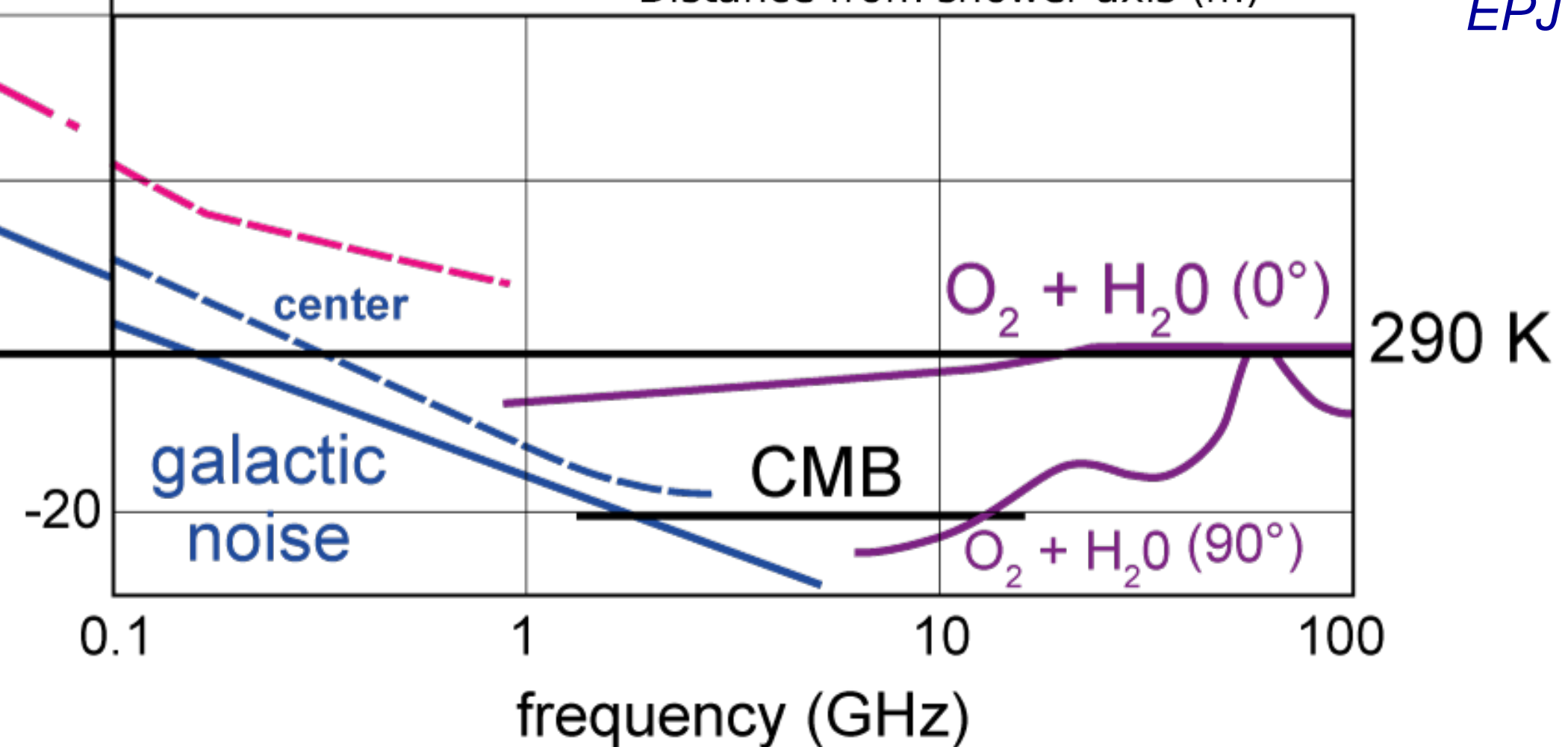
Footprint of radio emission on the ground



Radio background and signal

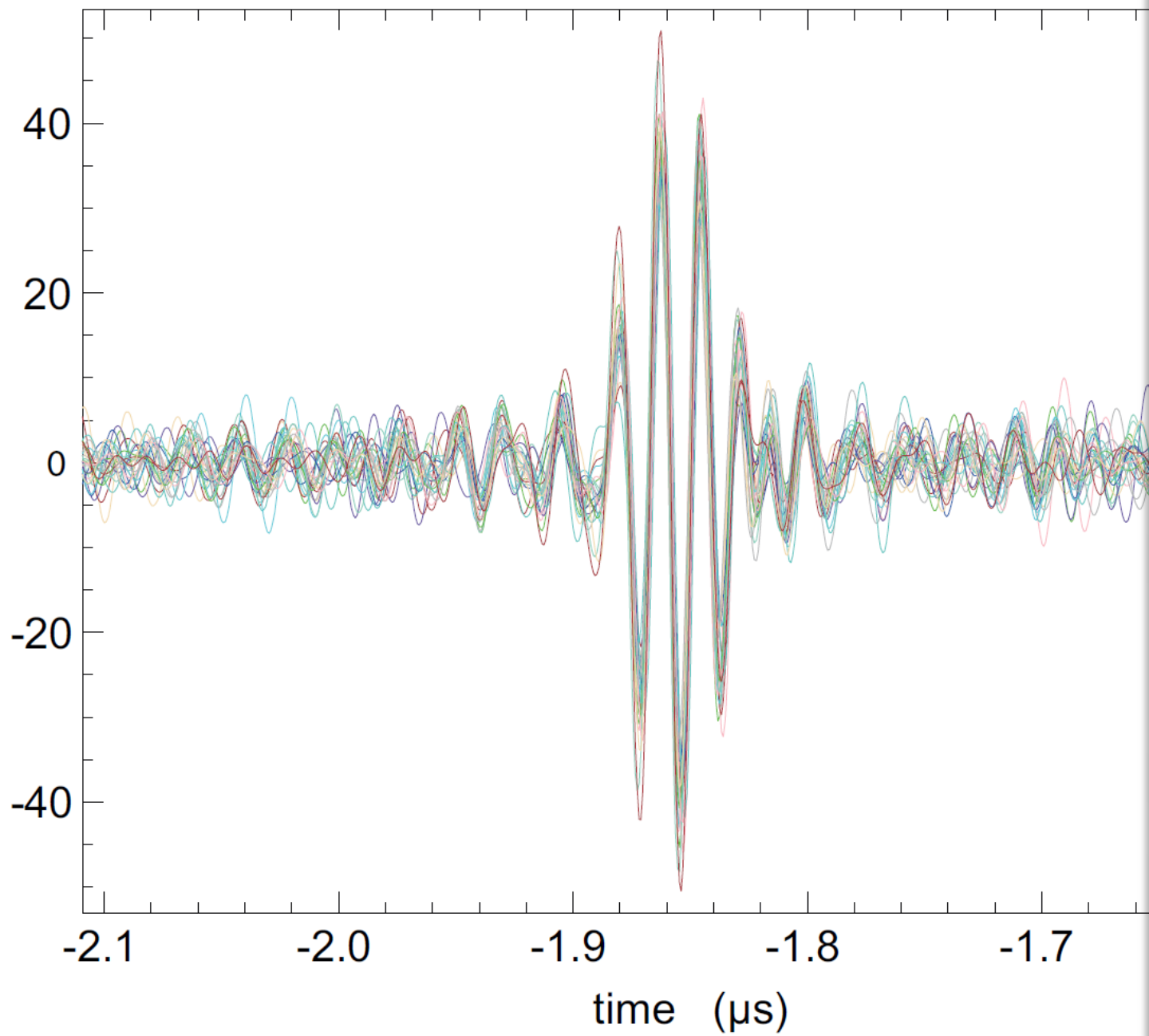


A. Balagopal V., et al.
EPJ C 78 (2018) 11





east-west field strengths per BW ($\mu\text{V}/\text{m}/\text{MHz}$)



LETTERS

Detection and imaging of atmospheric radio flashes from cosmic ray air showers

H. Falcke^{1,4,9}, W. D. Apel⁶, A. F. Badea⁶, L. Bähren⁴, K. Bekk⁶, A. Bercuci³, M. Bertaina¹¹, P. L. Biermann¹, J. Blümer^{5,6}, H. Bozdog⁶, I. M. Brancus³, S. Buitink⁹, M. Brüggemann¹⁰, P. Buchholz¹⁰, H. Butcher⁴, A. Chiavassa¹¹, K. Daumiller⁶, A. G. de Bruyn⁴, C. M. de Vos⁴, F. Di Piero¹¹, P. Doll⁶, R. Engel⁶, H. Gemmeke⁷, P. L. Ghia¹², R. Glasstetter¹³, C. Grupen¹⁰, A. Haungs⁶, D. Heck⁶, J. R. Hörandel⁵, A. Horneffer¹, T. Huege¹, K.-H. Kampert¹³, G. W. Kant⁴, U. Klein², Y. Kolotaev¹⁰, Y. Koopman³, O. Krömer⁷, J. Kuijpers⁹, S. Lafebvre⁹, G. Maier^{6,†}, H. J. Mathes⁶, H. J. Mayer⁶, J. Milke⁶, B. Mitrica³, C. Morello¹², G. Navarra¹¹, S. Nehls⁶, A. Nigl⁹, R. Obenland⁶, J. Oehlschläger⁶, S. Ostapchenko⁶, S. Over¹⁰, H. J. Pepping⁴, M. Petcu³, J. Petrovic⁹, S. Plewnia⁶, H. Rebel⁶, A. Risse⁸, M. Roth⁵, H. Schieler⁶, G. Schoonderbeek⁴, O. Sima³, M. Stümpert⁵, G. Toma³, G. C. Trinchero¹², H. Ulrich⁶, S. Valchierotti¹¹, J. van Buren⁶, W. van Cappellen⁴, W. Walkowiak¹⁰, A. Weindl⁶, S. Wijnholds⁴, J. Wochele⁶, J. Zabierowski⁸, J. A. Zensus¹ & D. Zimmermann¹⁰

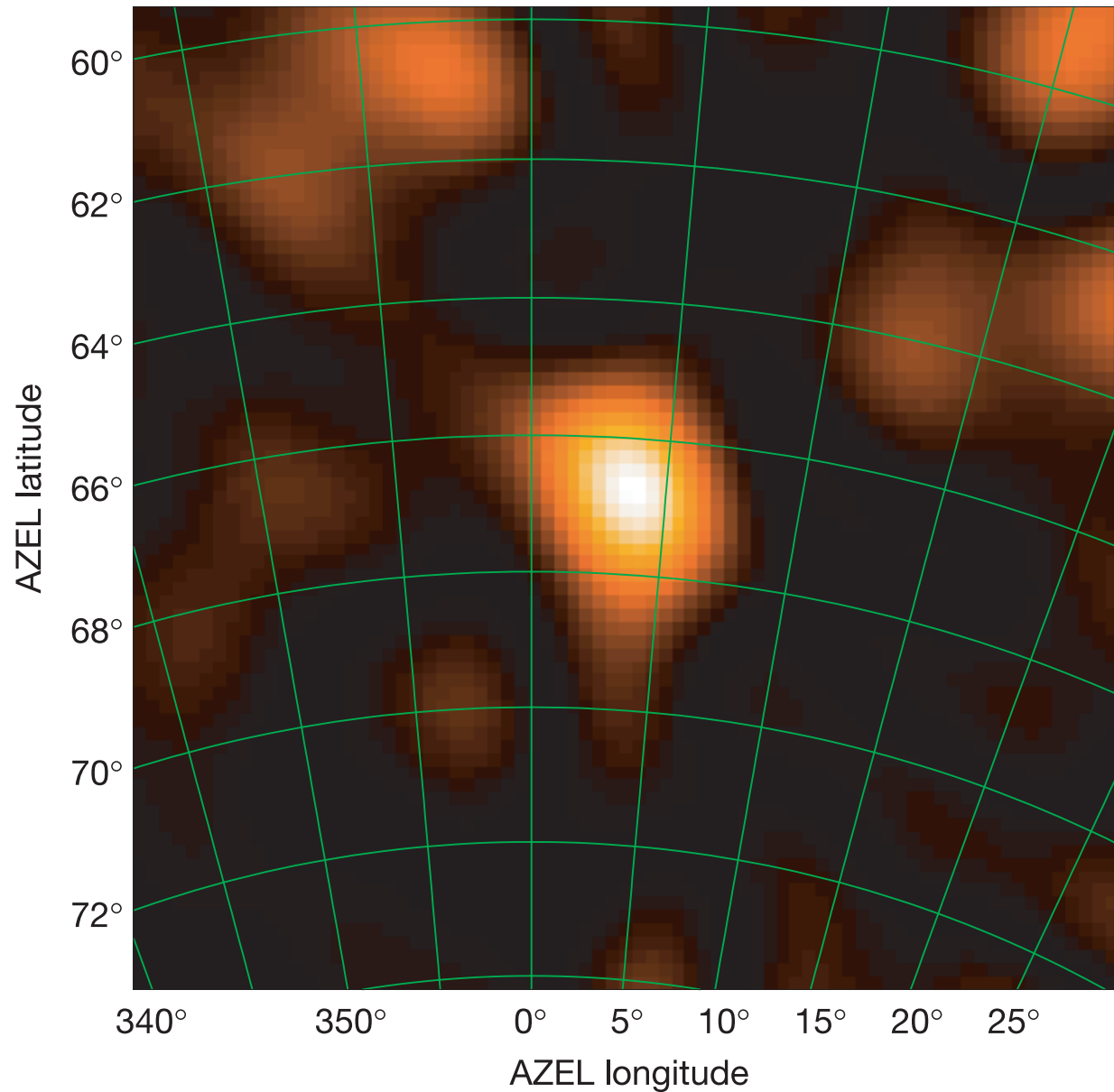
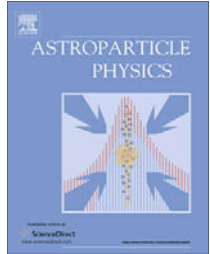


Figure 1 | Radio map of an air shower. For each pixel in the map, we formed a beam in this direction integrated over 12.5 ns and show the resulting electric field intensity. Longitude and latitude give the azimuth and elevation (AZEL) direction (north is to the top, east to the right). The map is focused towards a distance of 2,000 m (fixed curvature radius for each pixel). The cosmic ray event is seen as a bright blob of $2.4^\circ \times 1.8^\circ$ size. Most of the noise in this map is due to interferometer sidelobes caused by the sparse radio array. No image deconvolution has been performed.



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. Charrier^a, J. Chauvin^c, M. Chendeb^e, A. Cordier^d, S. Dagoret-Campagne^d, R. Dallier^a, L. Denis^b, C. Dumez-Viou^b, C. Fabrice^b, T. Garçon^a, X. Garrido^d, N. Gautherot^f, T. Gousset^a, F. Haddad^a, D.H. Koang^c, J. Lamblin^a, P. Lautridou^a, D. Lebrun^c, A. Lecacheux^b, F. Lefeuvre^g, L. Martin^{a,*}, E. Meyer^f, F. Meyer^f, N. Meyer-Vernet^b, D. Monnier-Ragaigne^d, F. Montanet^c, K. Payet^c, G. Plantier^e, O. Ravel^a, B. Revenu^a, C. Riviere^c, T. Saugrin^a, A. Sourice^e, P. Stassi^c, A. Stutz^c, S. Valcares^a

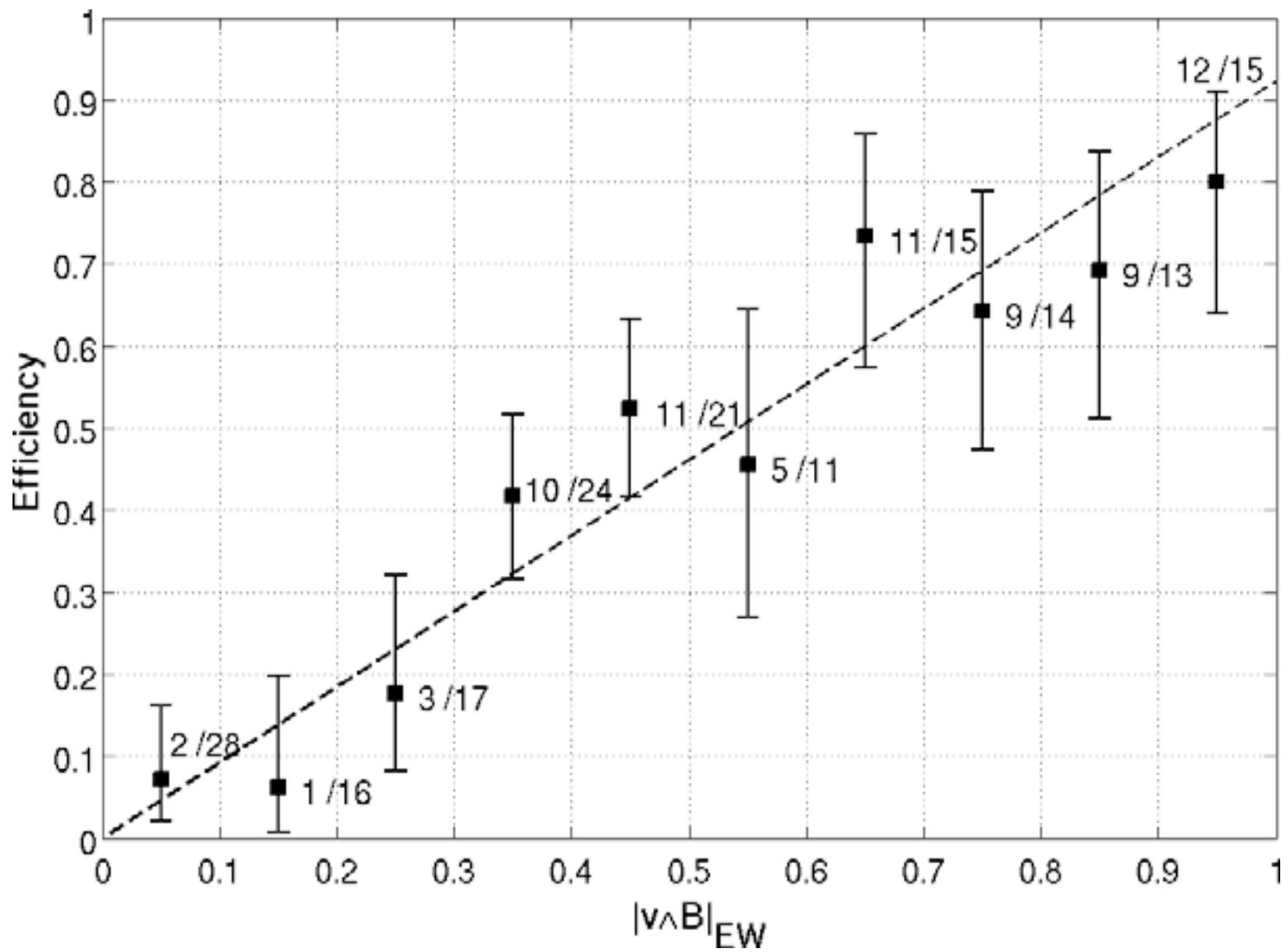


Fig. 11. Number of radio events relative to the number of scintillator events ($E > 10^{17}$ eV) with respect to $|(v \wedge B)_{EW}|/(vB)$.



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

VINCENT MARIN¹, FOR THE CODALEMA COLLABORATION^{1,2,3,4,5,6,7}

¹SUBATECH, Université de Nantes/Ecole des Mines de Nantes/IN2P3-CNRS, Nantes France. ²LESIA, USN de Nançay, Observatoire de Paris-Meudon/INSU-CNRS, Meudon France. ³LPSC, Université Joseph Fourier/INPG/IN2P3-CNRS, Grenoble France. ⁴LAL, Université Paris-Sud/IN2P3-CNRS, Orsay France. ⁵GSII, ESEO, Angers France. ⁶LAOB, Université de Besançon/INSU-CNRS, Besançon France. ⁷LPCE, Université d'Orléans/INSU-CNRS, Orléans France.

vincent.marin@subatech.in2p3.fr

DOI: 10.7529/ICRC2011/V01/0942

Abstract: The systematic shift between the shower core estimation using the particle array data and the shower core estimation using the radio array data of the CODALEMA experiment is discussed. Using the simulation code SELFAS2 we show that the consideration of the charge excess contribution in the total radio emission of air showers generates a shift of the apparent ground radio core along the east-west axis. This radio core shift is then characterized for the CODALEMA statistic and compared with the experimental data. The good agreement between data and simulation suggests that this behavior can be considered as an experimental signature of the charge excess contribution.

Keywords: CODALEMA, SELFAS, radio detection, charge excess

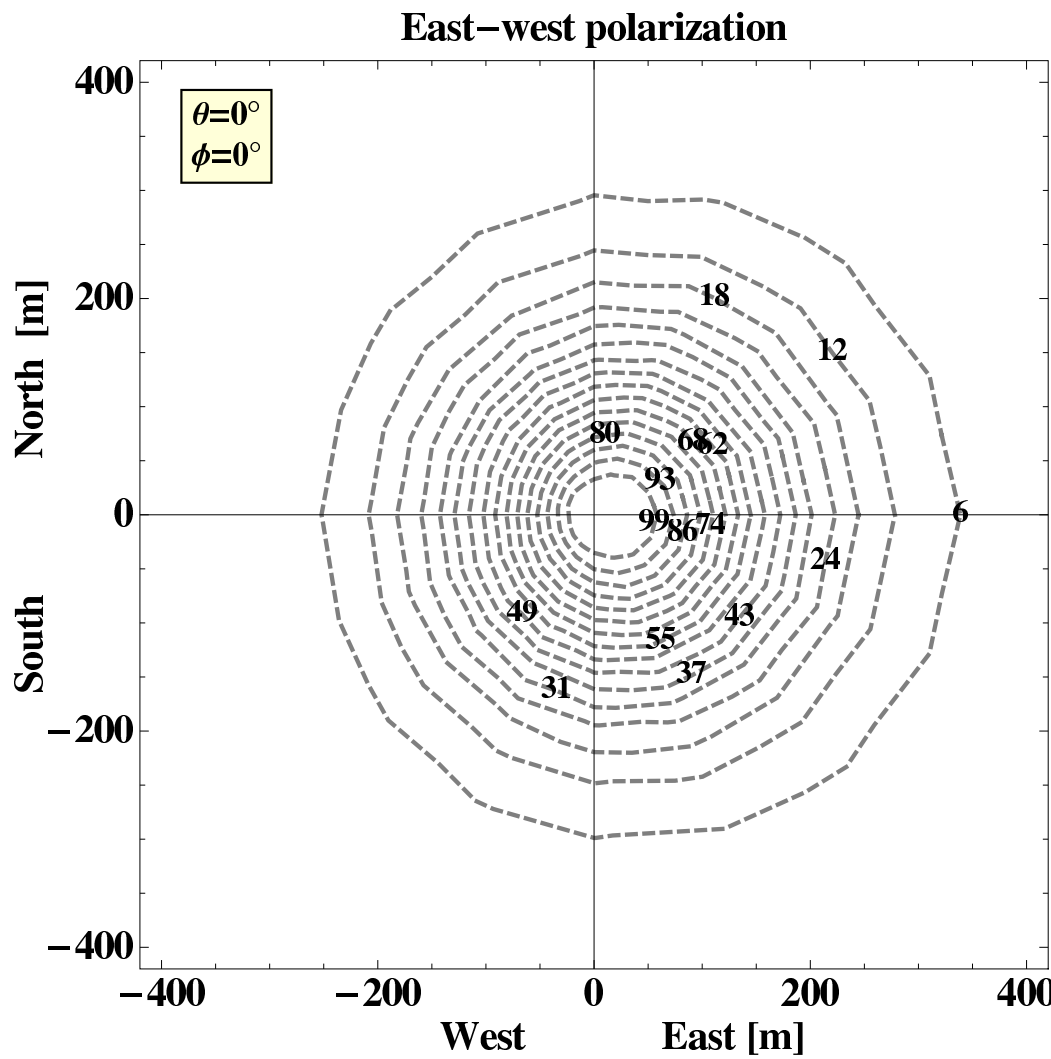
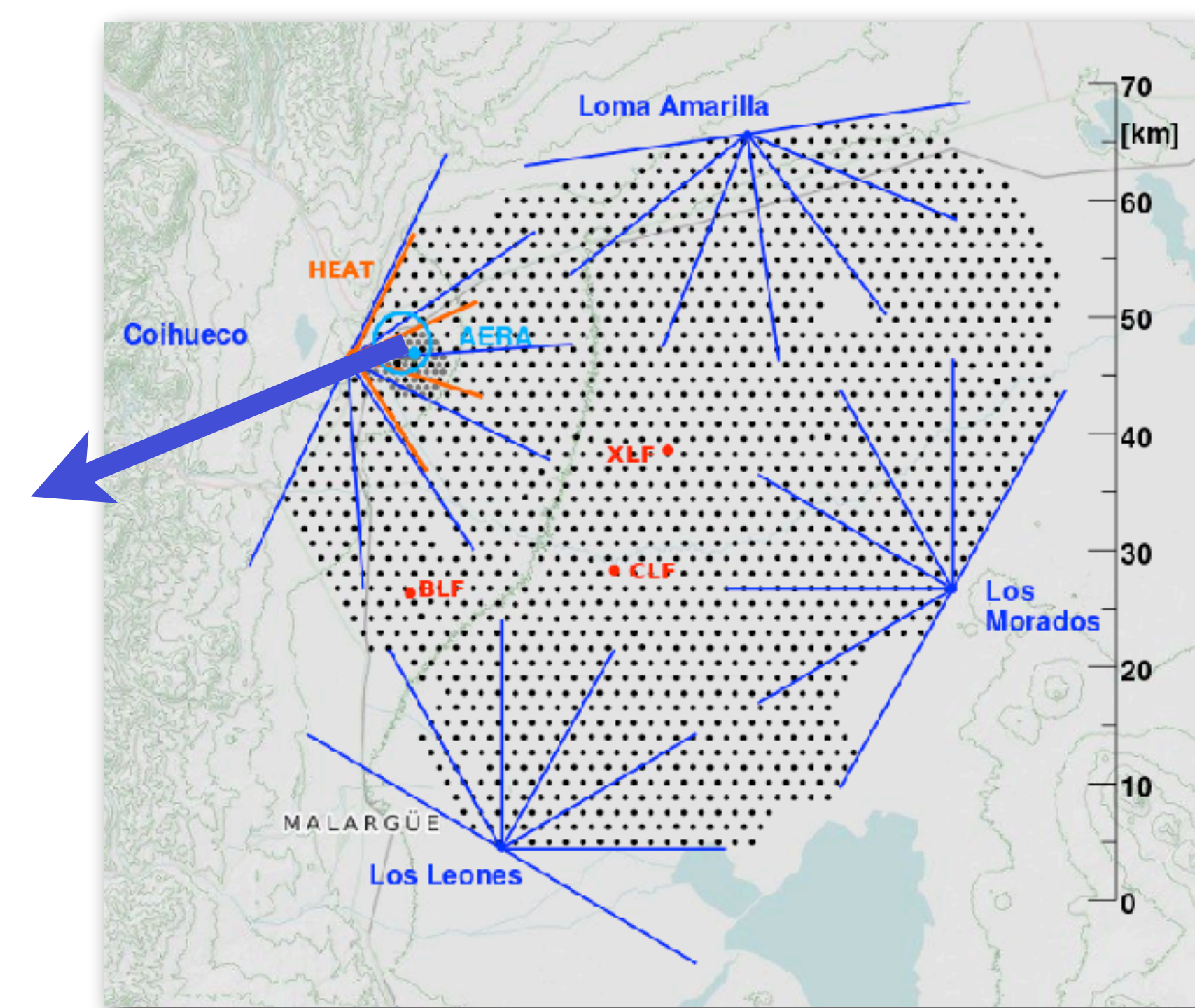
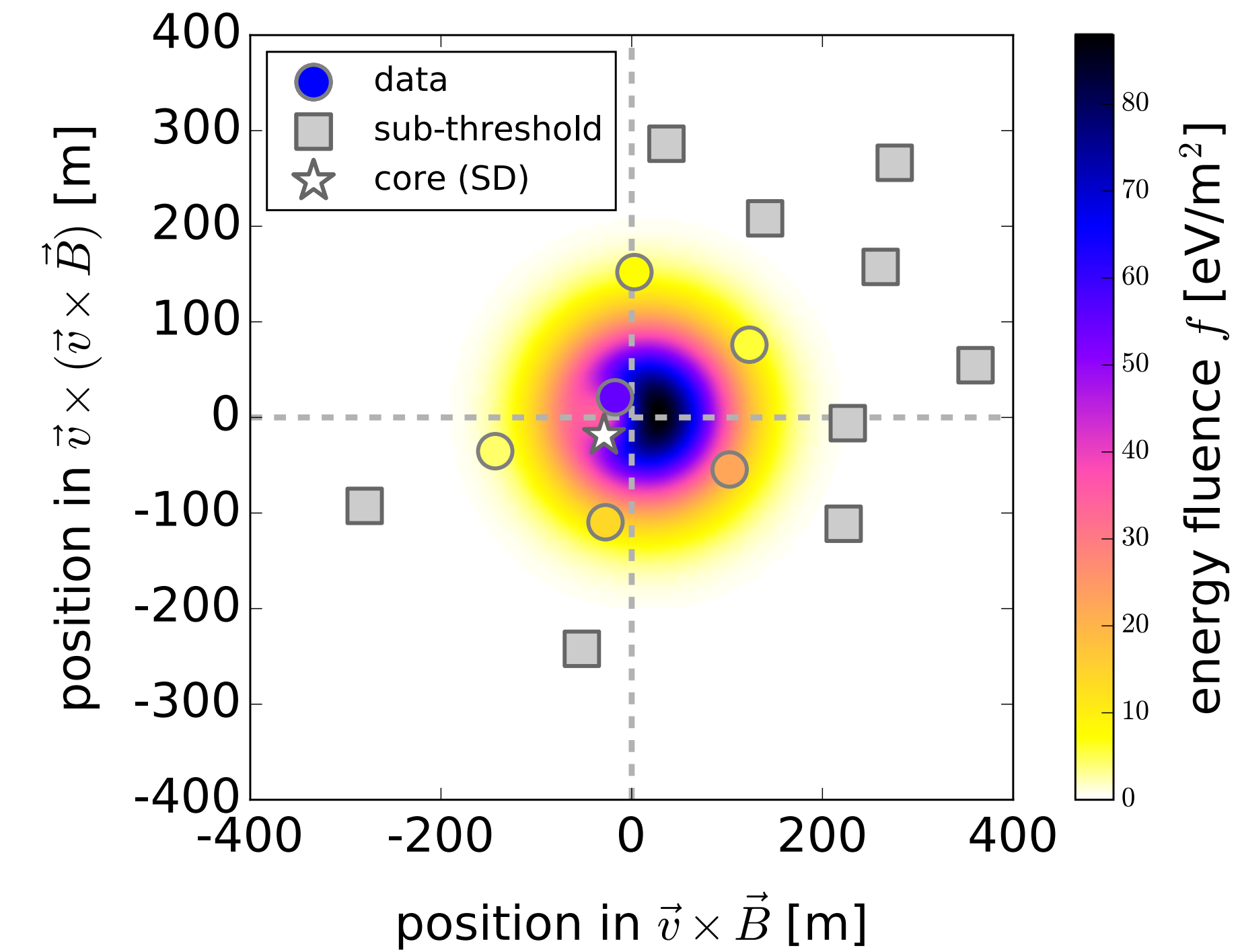


FIGURE 1 – Ground footprint of the signal deposited (absolute value) by a 10^{17} eV vertical EAS in the east-west polarization simulated with SELFAS2. The origin of the frame corresponds to the simulated ground particles shower core. The contour lines are in $\mu V.m^{-1}$, a 23-83 MHz numerical passband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

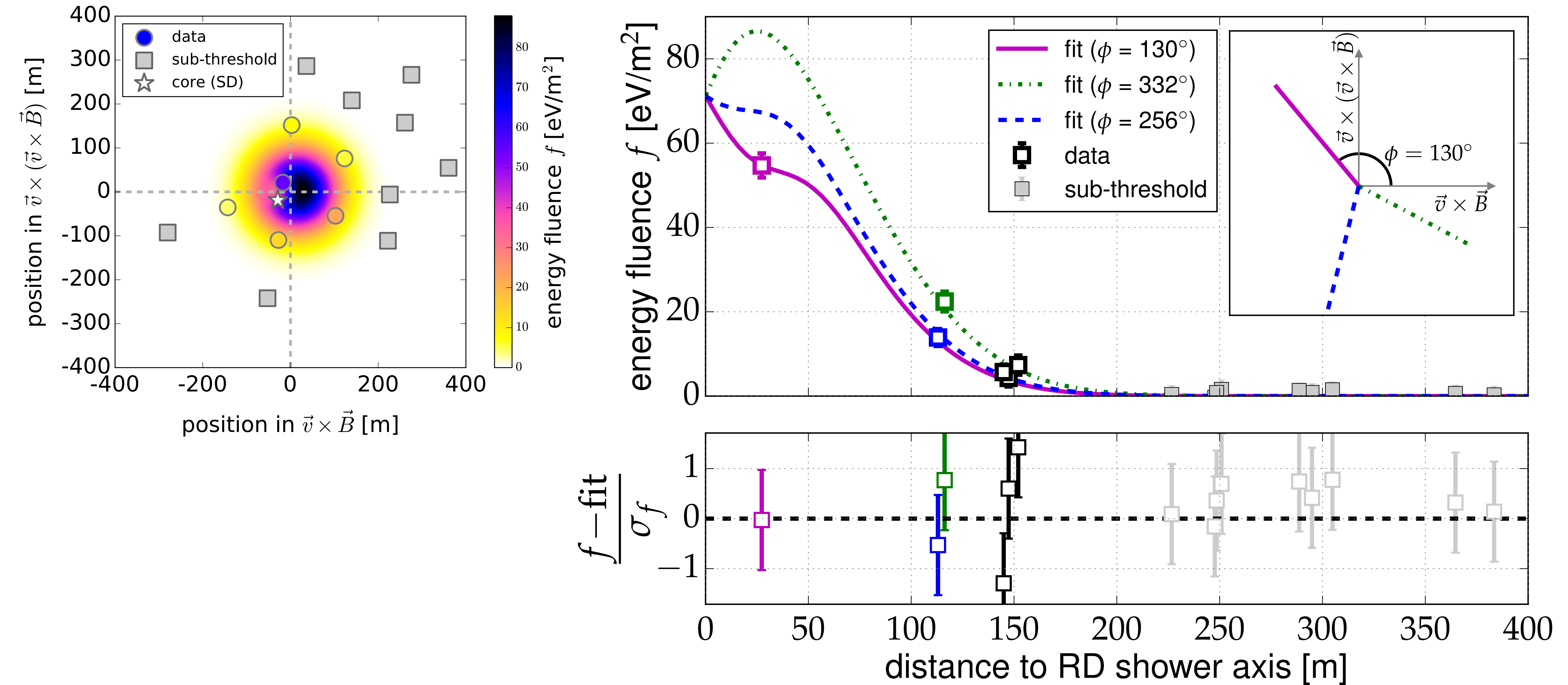
~150 antennas
~17 km²
30-80 MHz



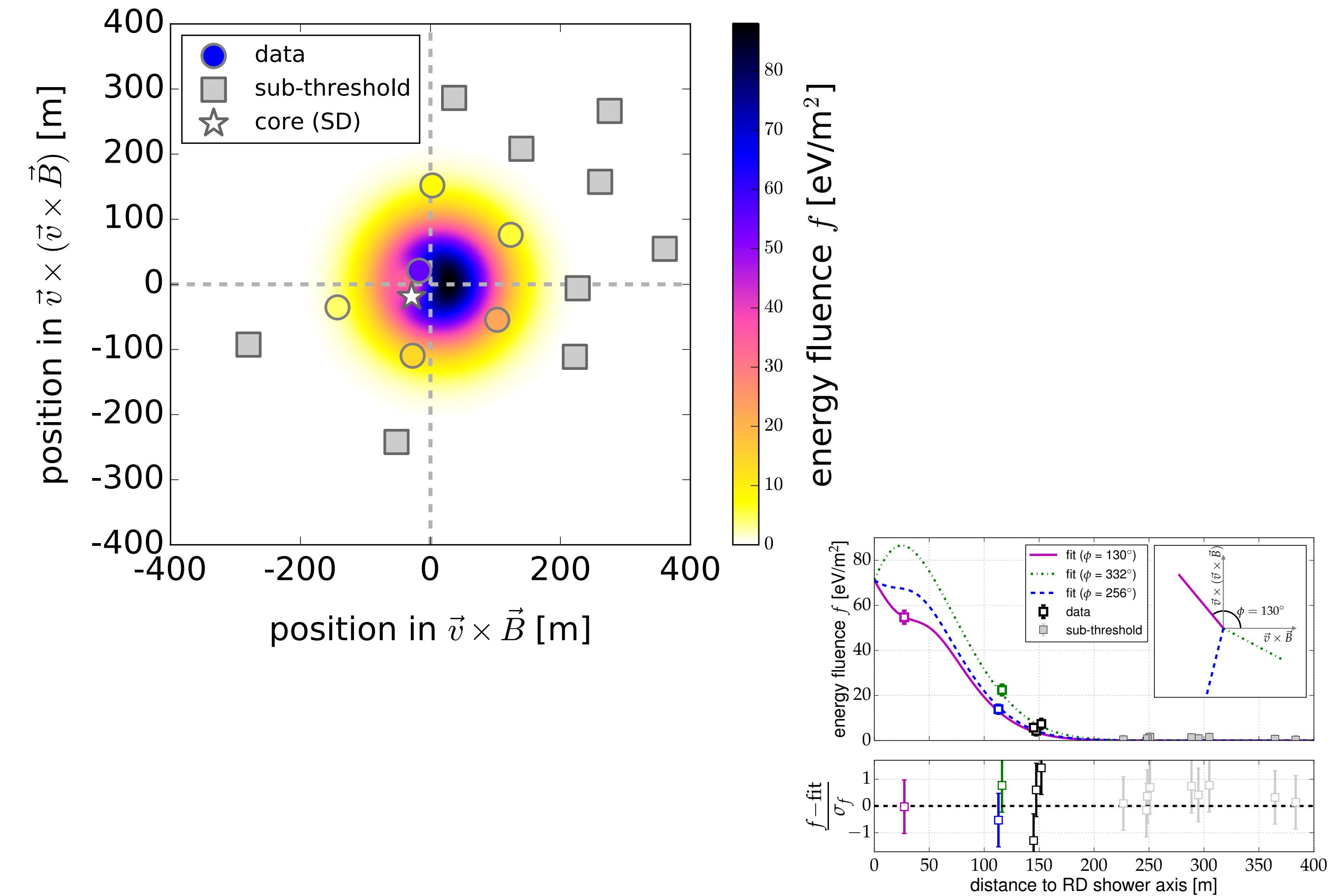
Measurement of the Radiation Energy in the Radio Signal of Extensive Air Showers as a Universal Estimator of Cosmic-Ray Energy



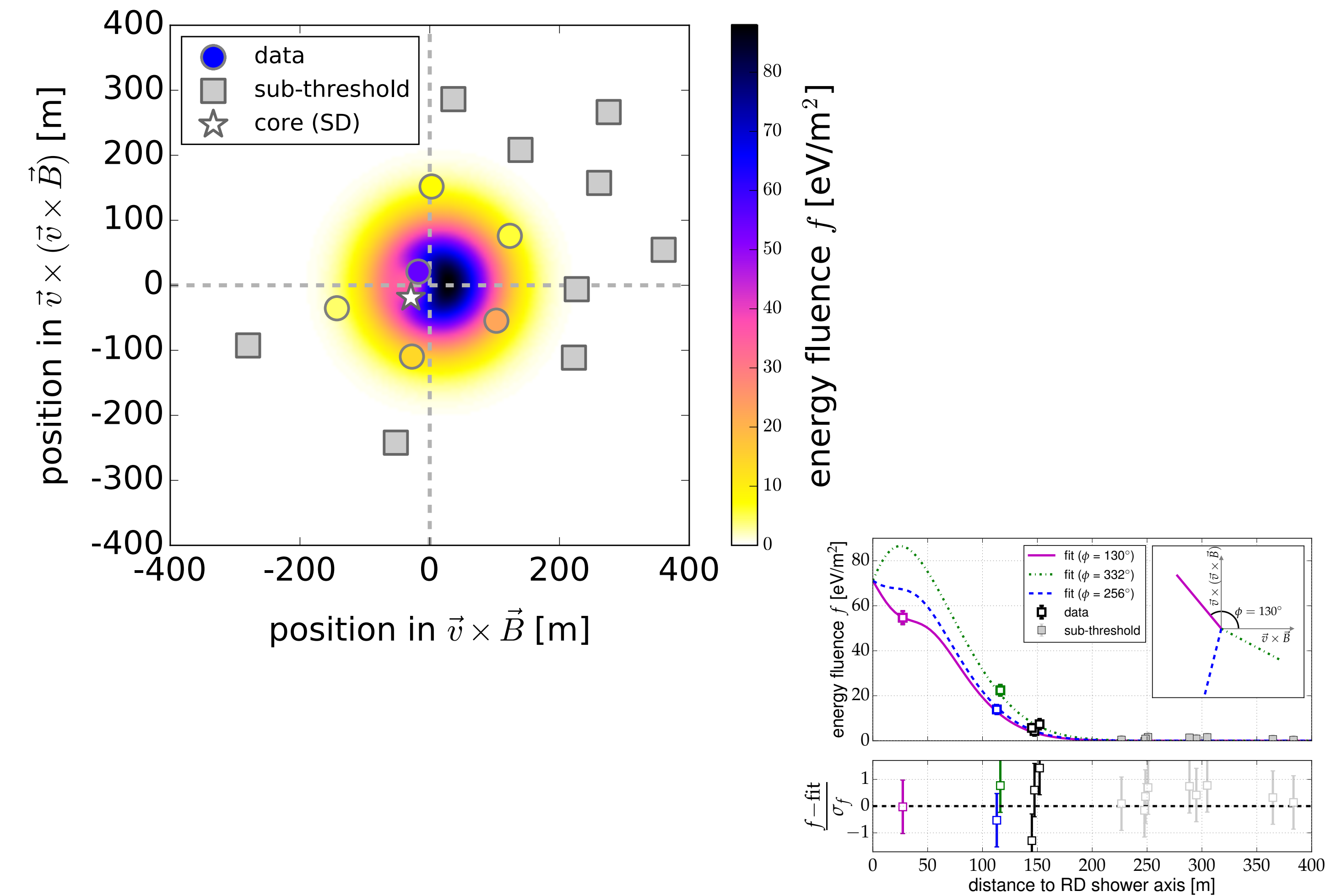
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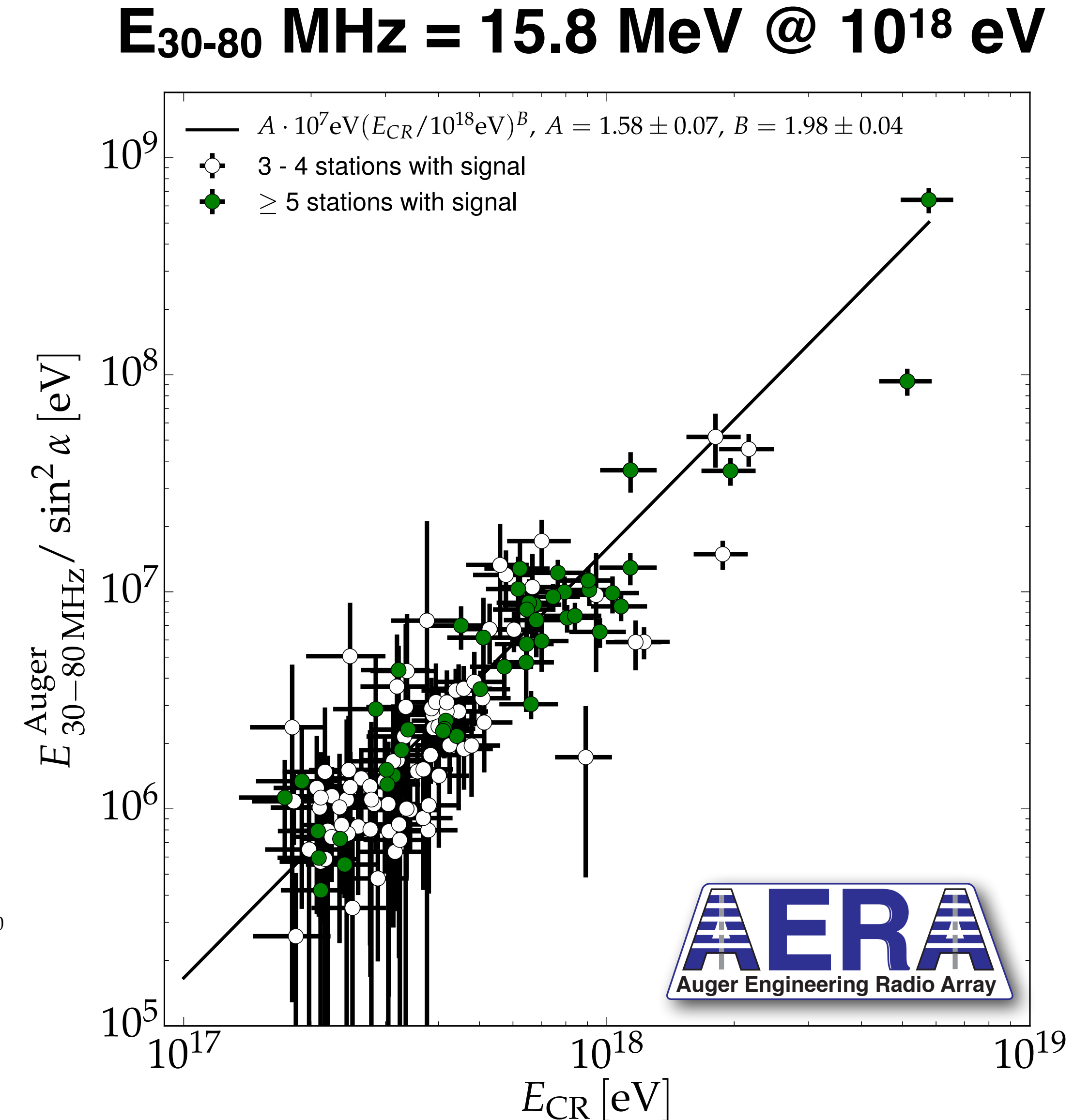
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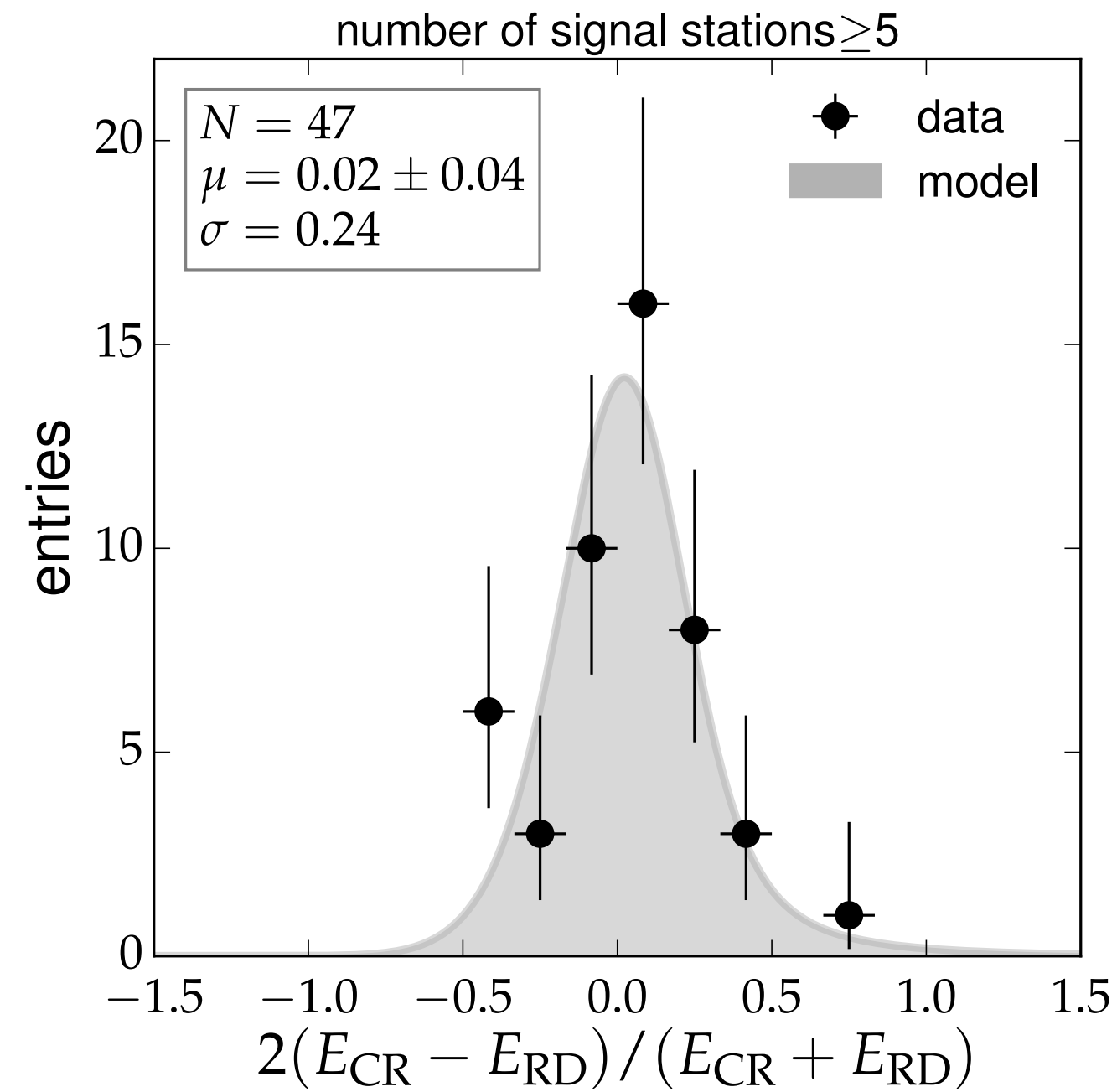
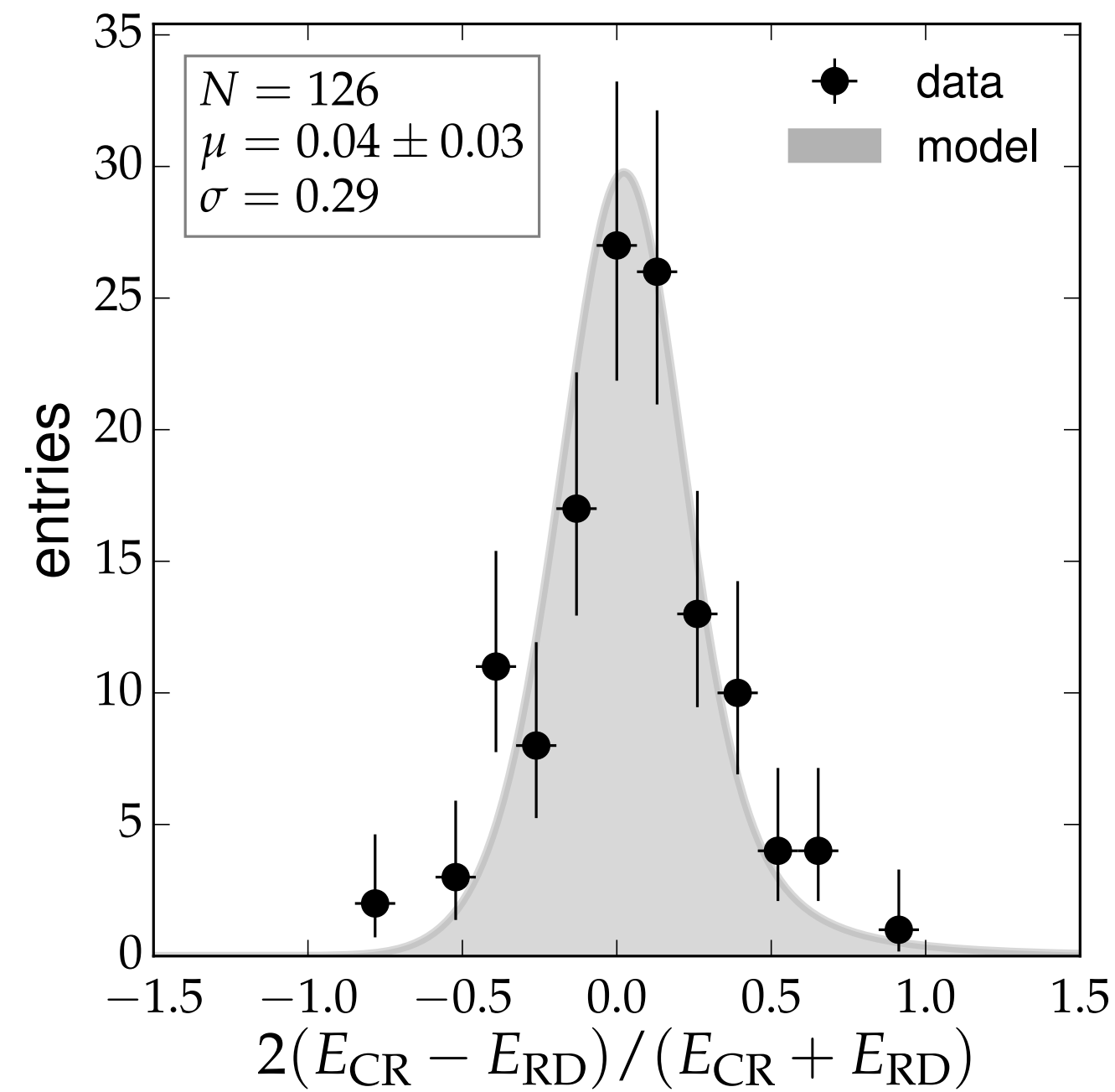
Measurement of the Radiation Energy in the Radio Signal of Extensive Air Showers as a Universal Estimator of Cosmic-Ray Energy



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

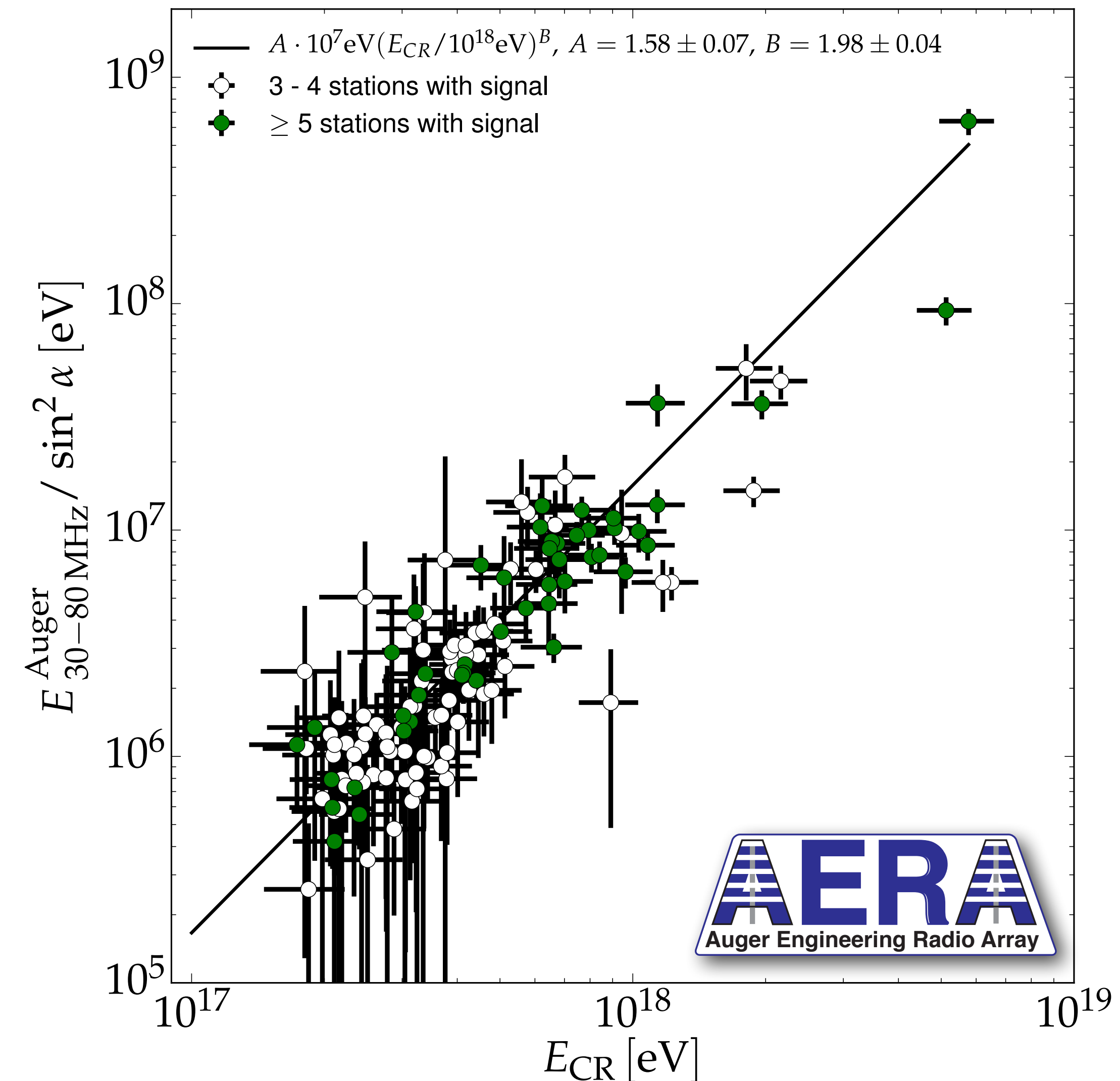


Energy Estimation of Cosmic Rays with the Engineering Radio Array of the Pierre Auger Observatory



$$\sigma \approx 24\%$$

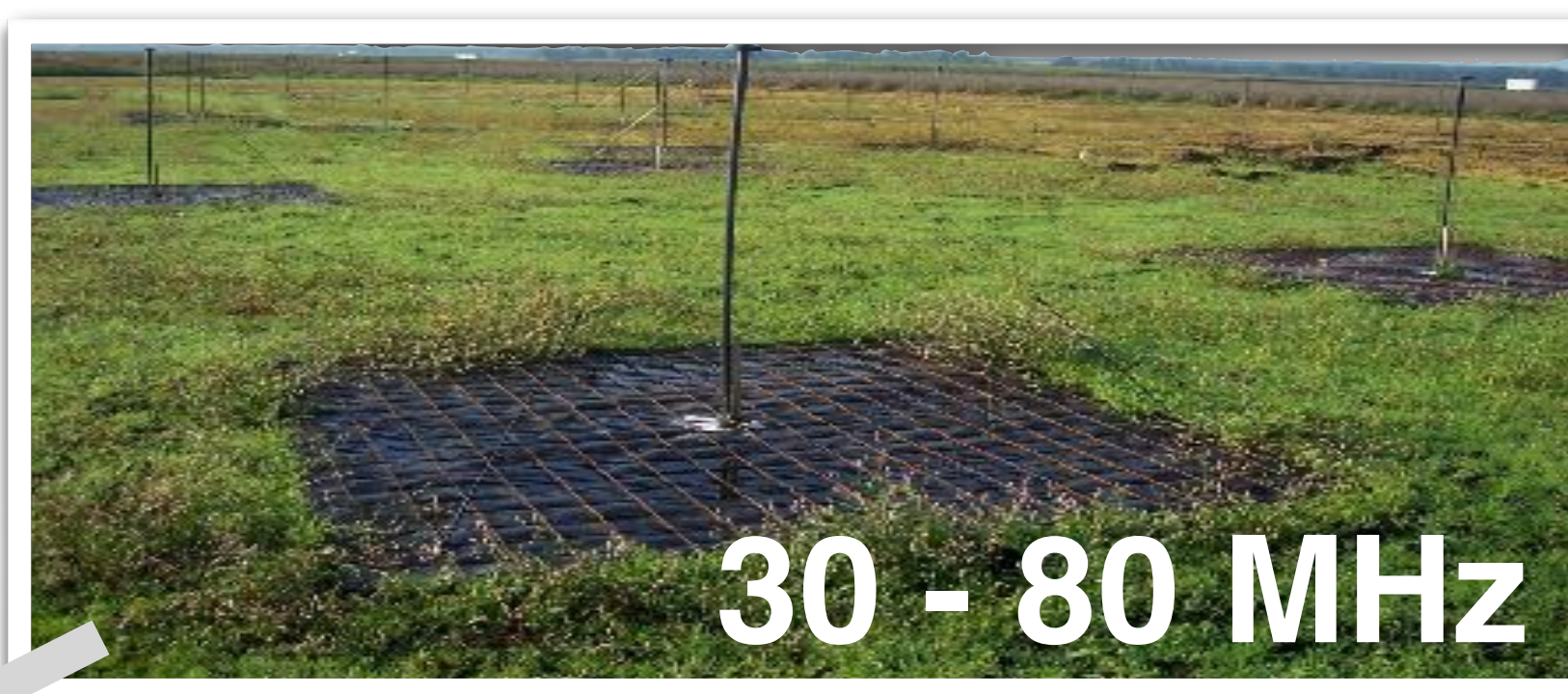
$$E_{30-80 \text{ MHz}} = 15.8 \text{ MeV} @ 10^{18} \text{ eV}$$



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

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

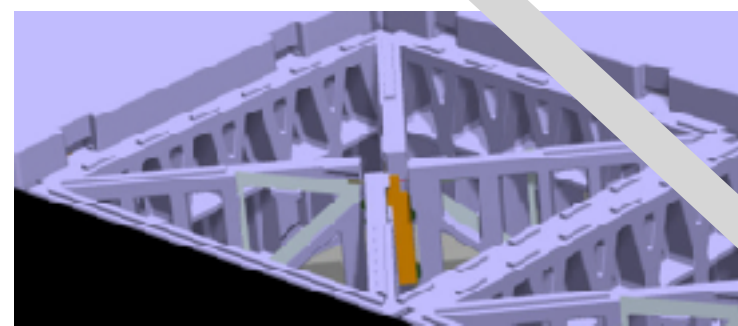
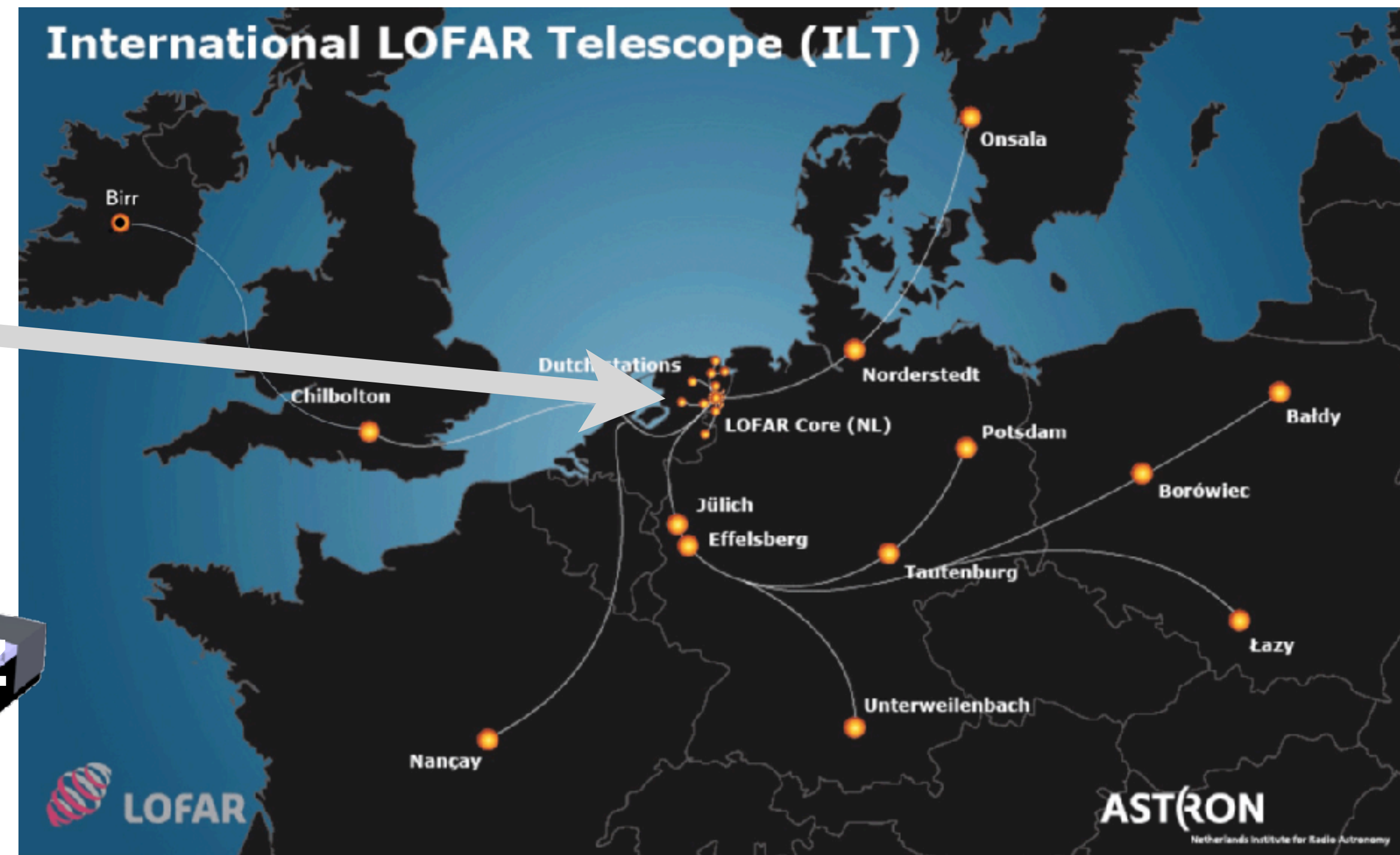
scintillators



30 - 80 MHz



core
23 stations ~5 km²



120 - 240 MHz

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

LORA
LOFAR Radboud Array
scintillator detectors

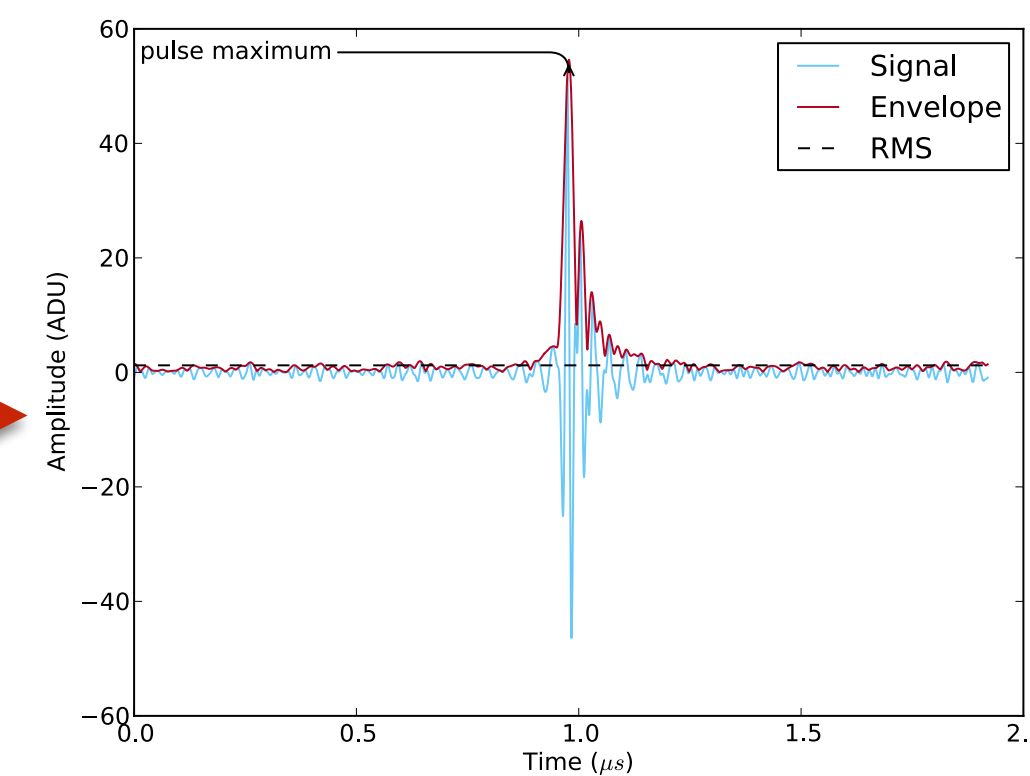
Superterp:

- * 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)



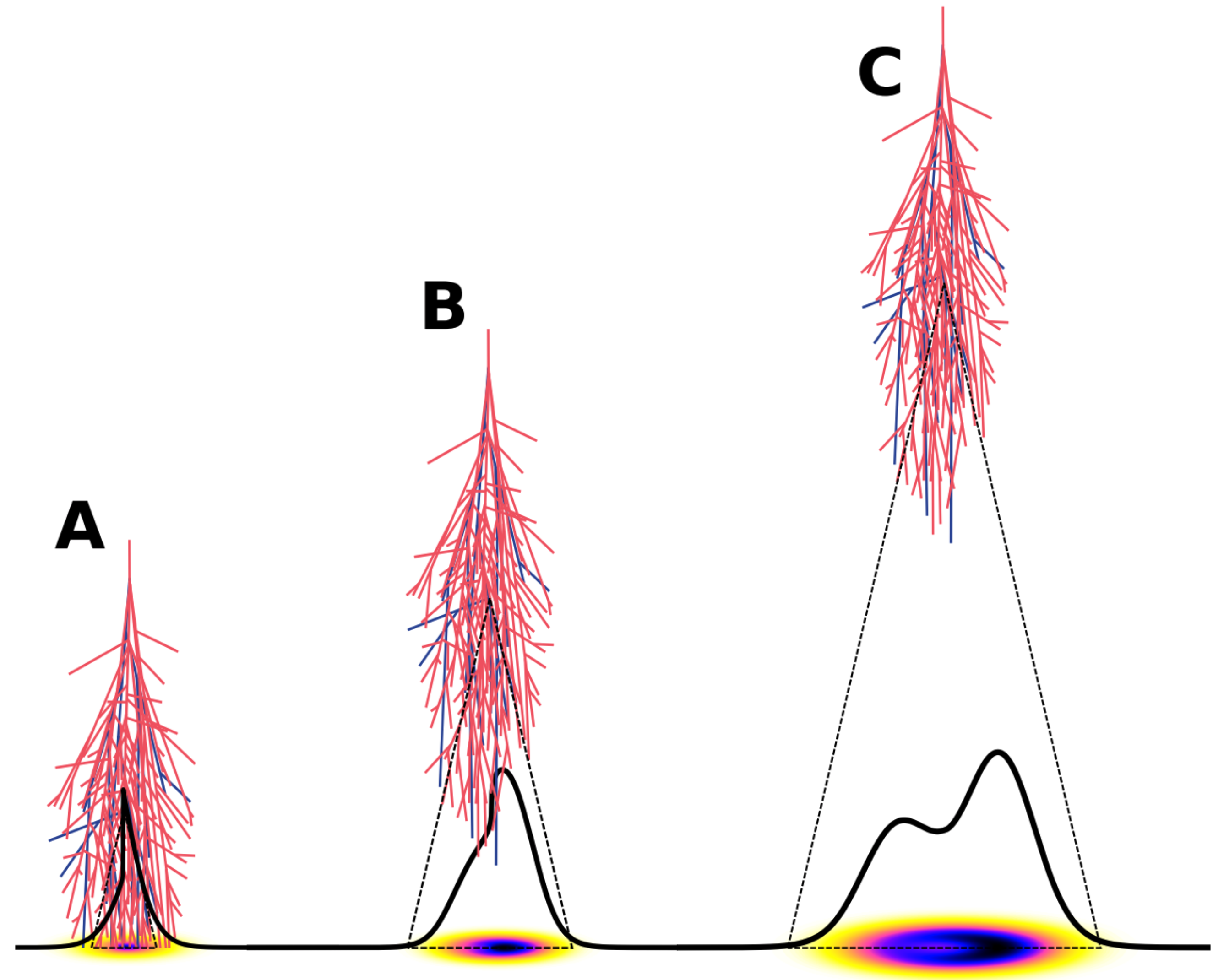
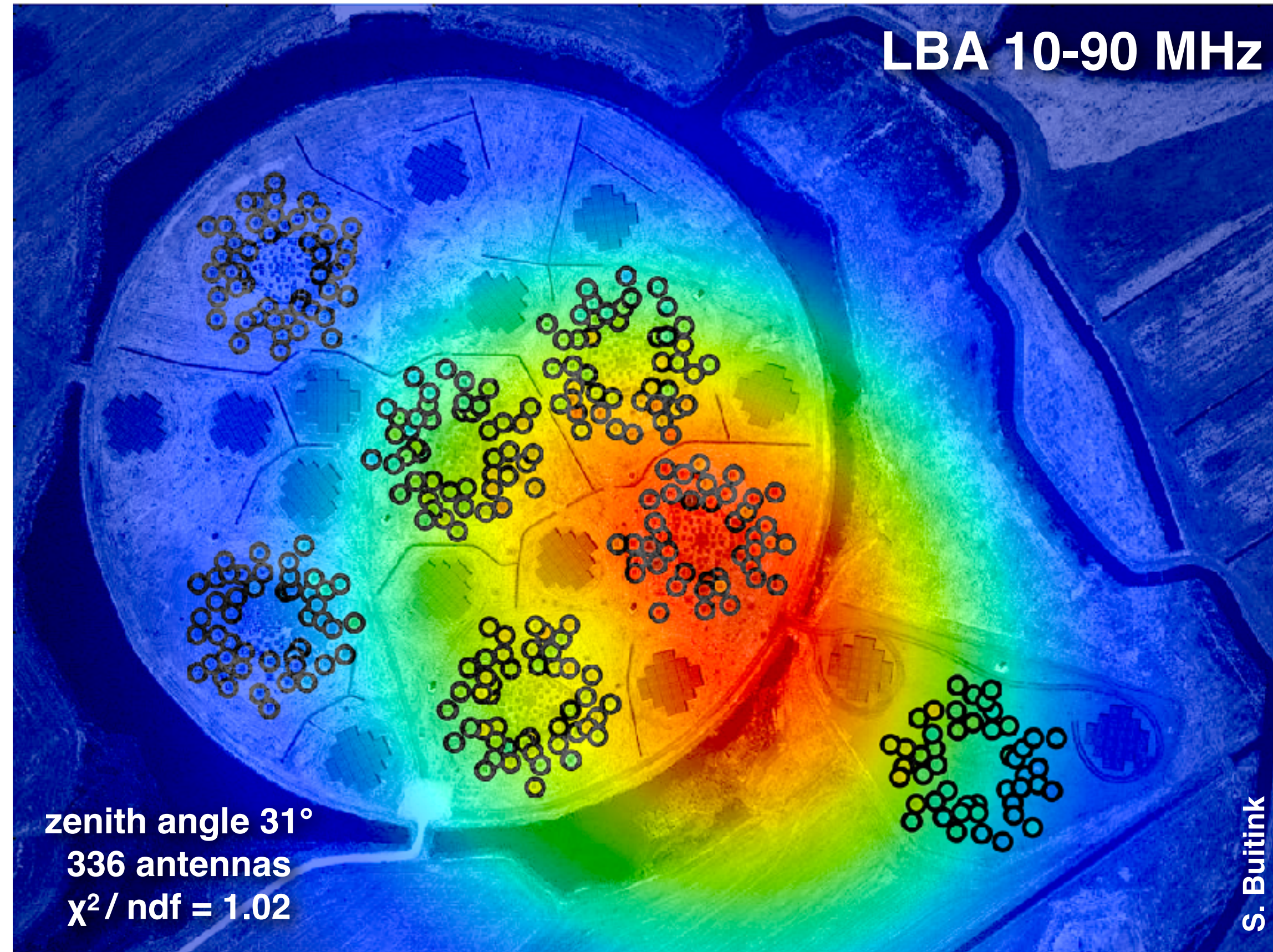
buffer

2 ms read-out

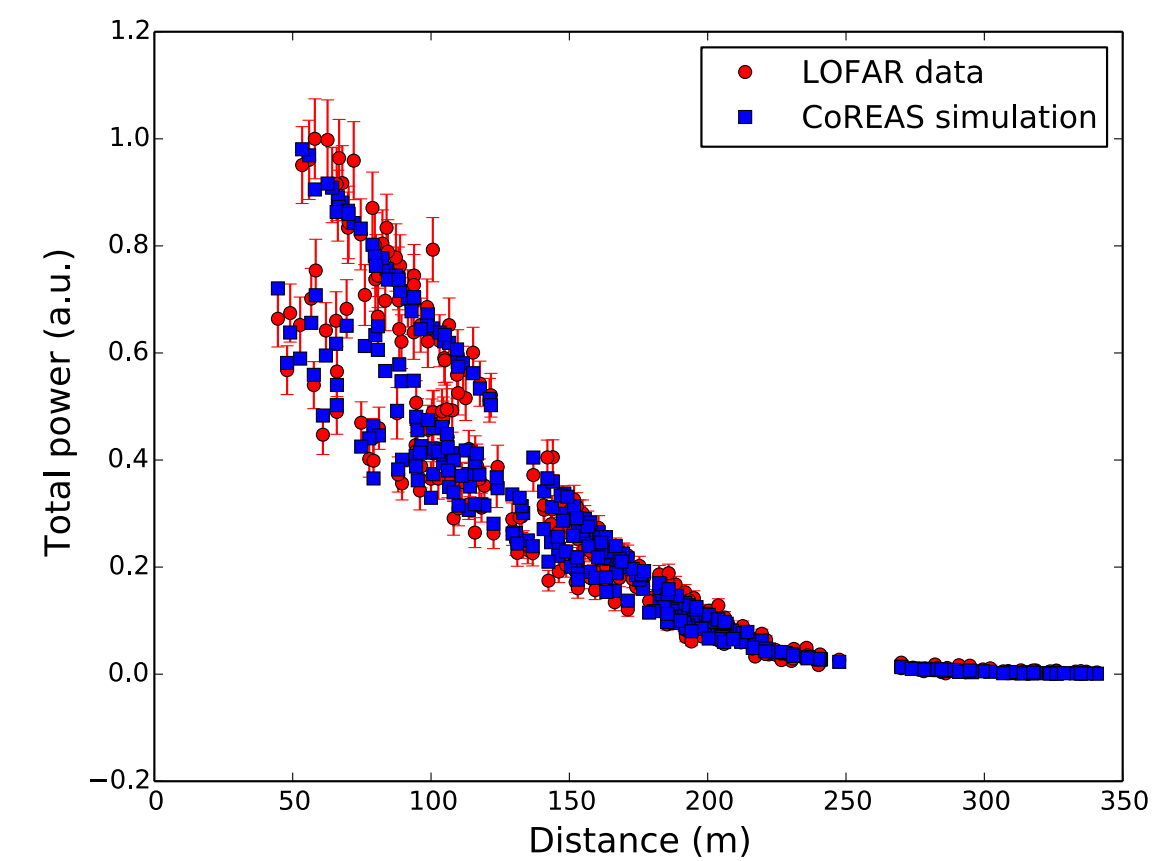
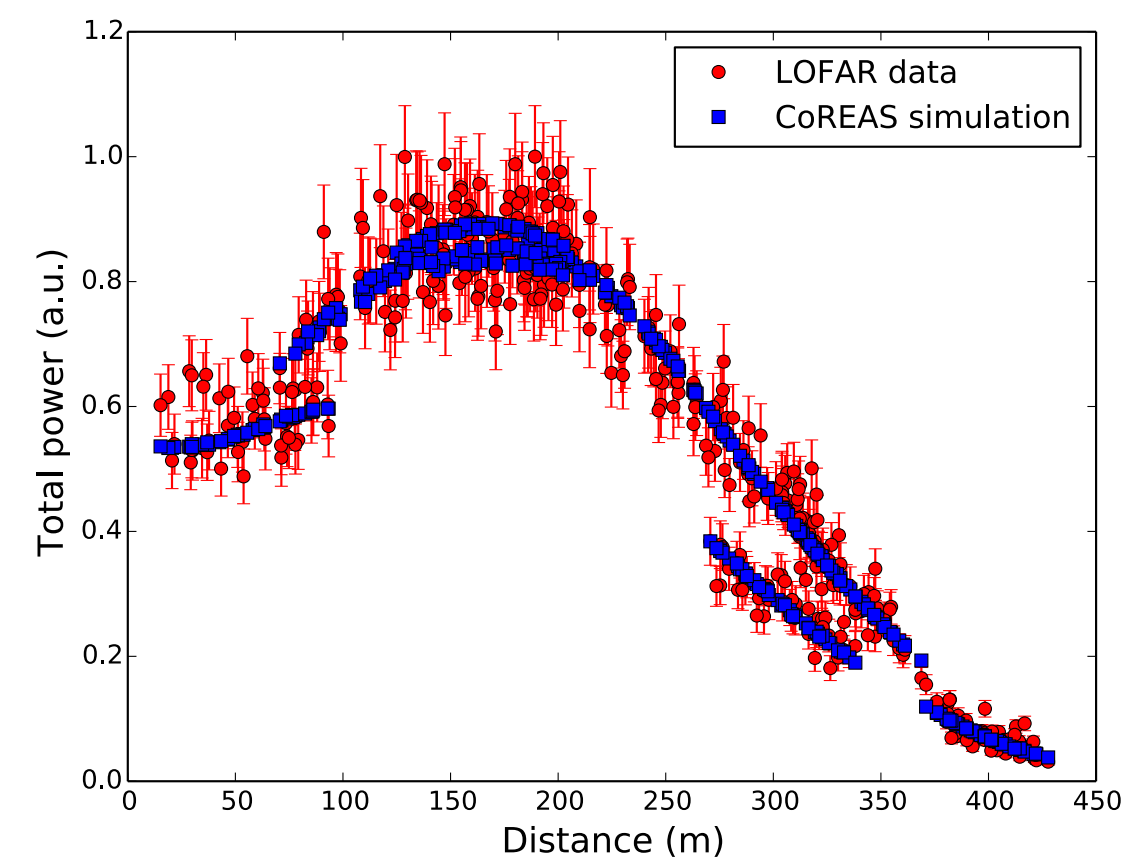
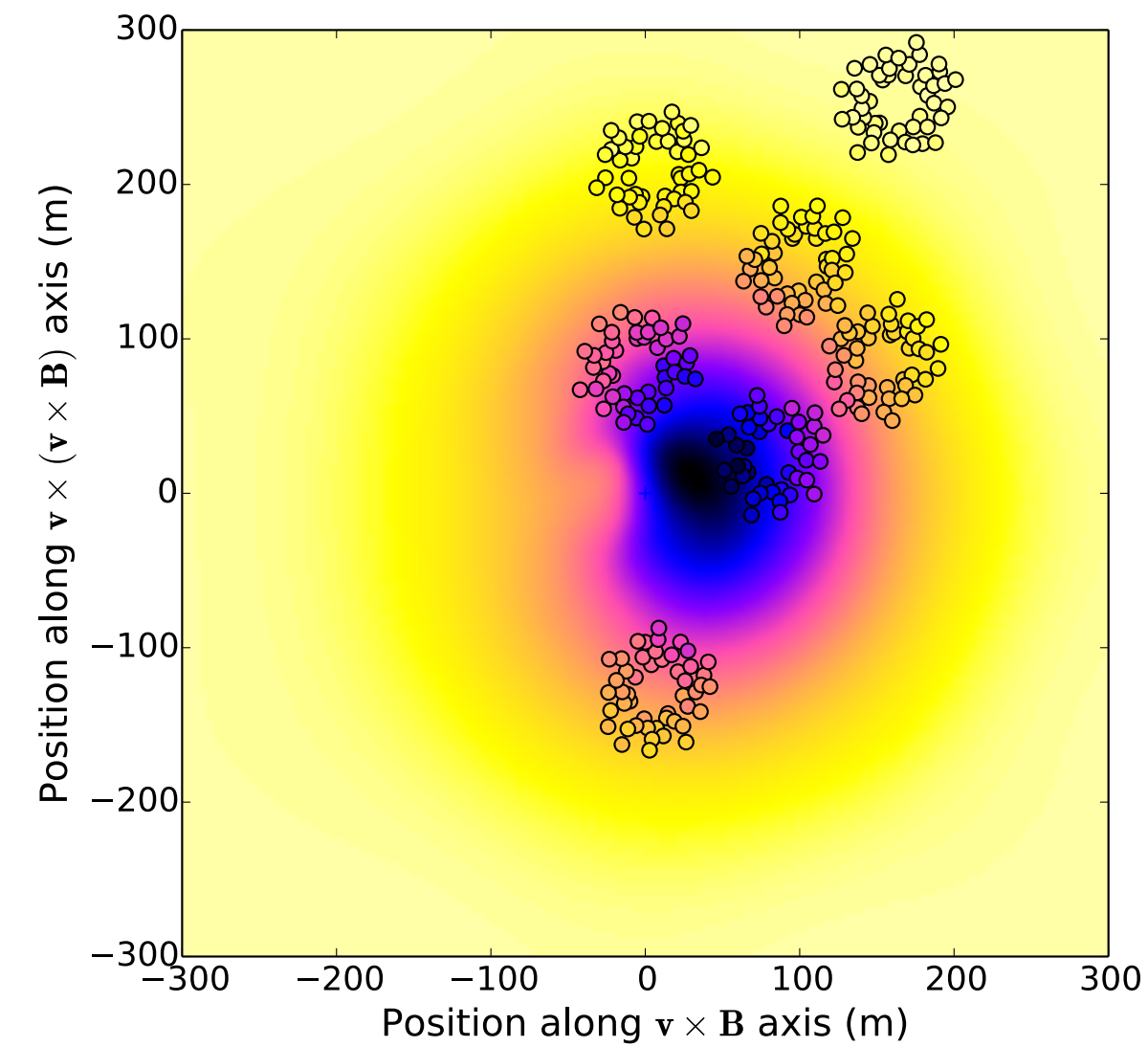
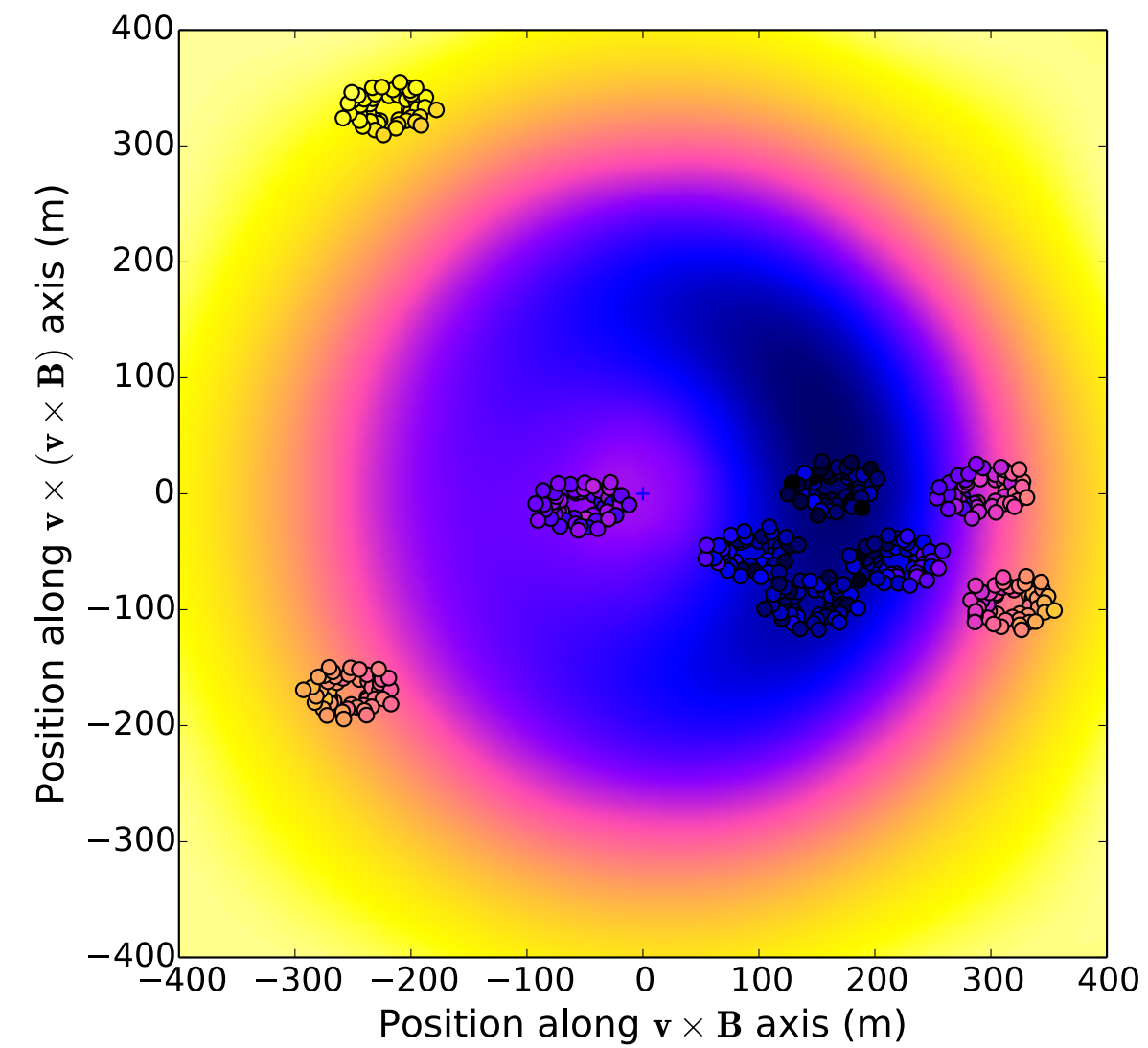
Selection this analysis:
4+ LBA stations

Low Band Antennas (LBA)
30 - 80 MHz

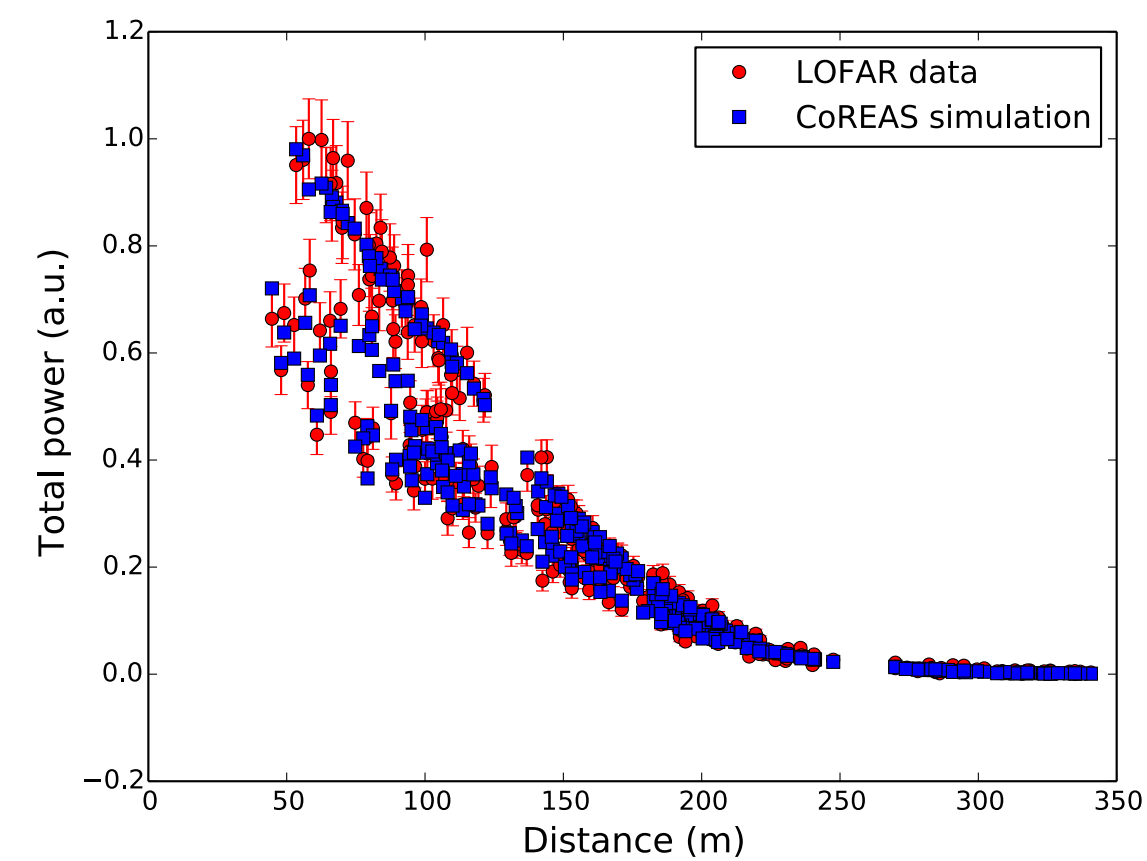
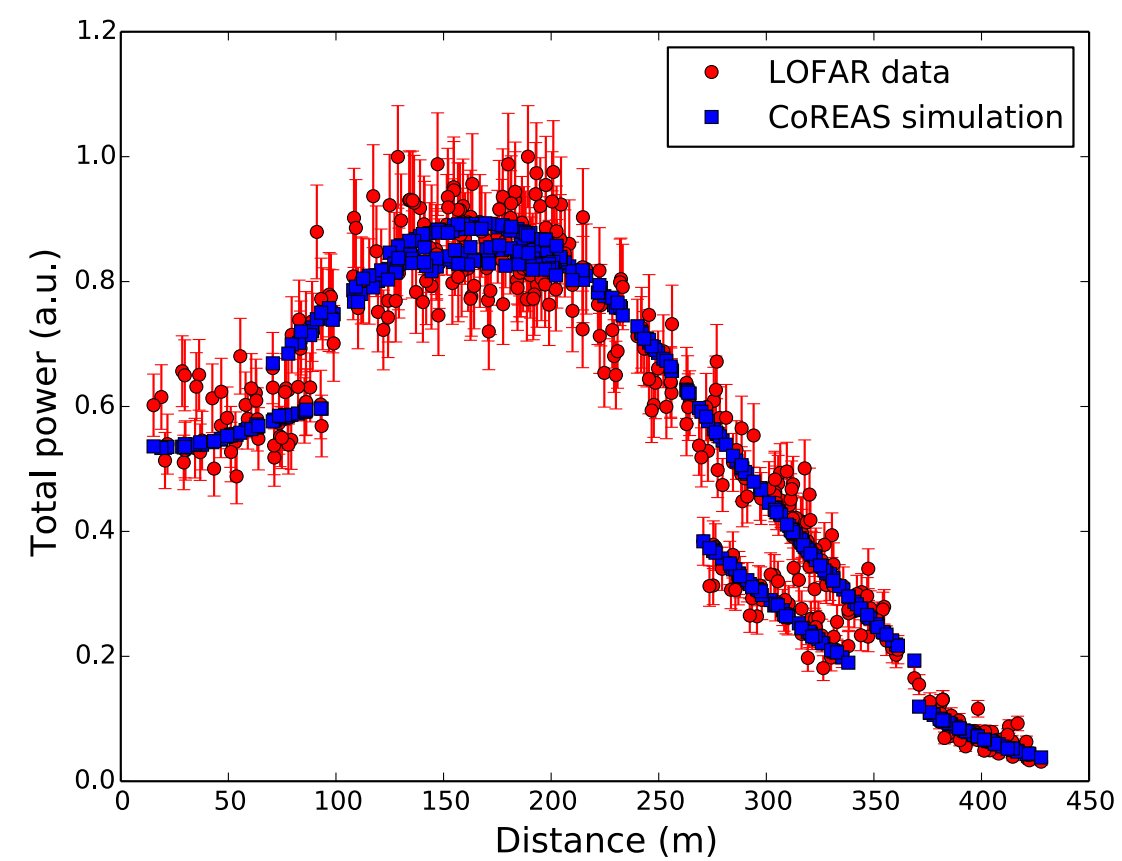
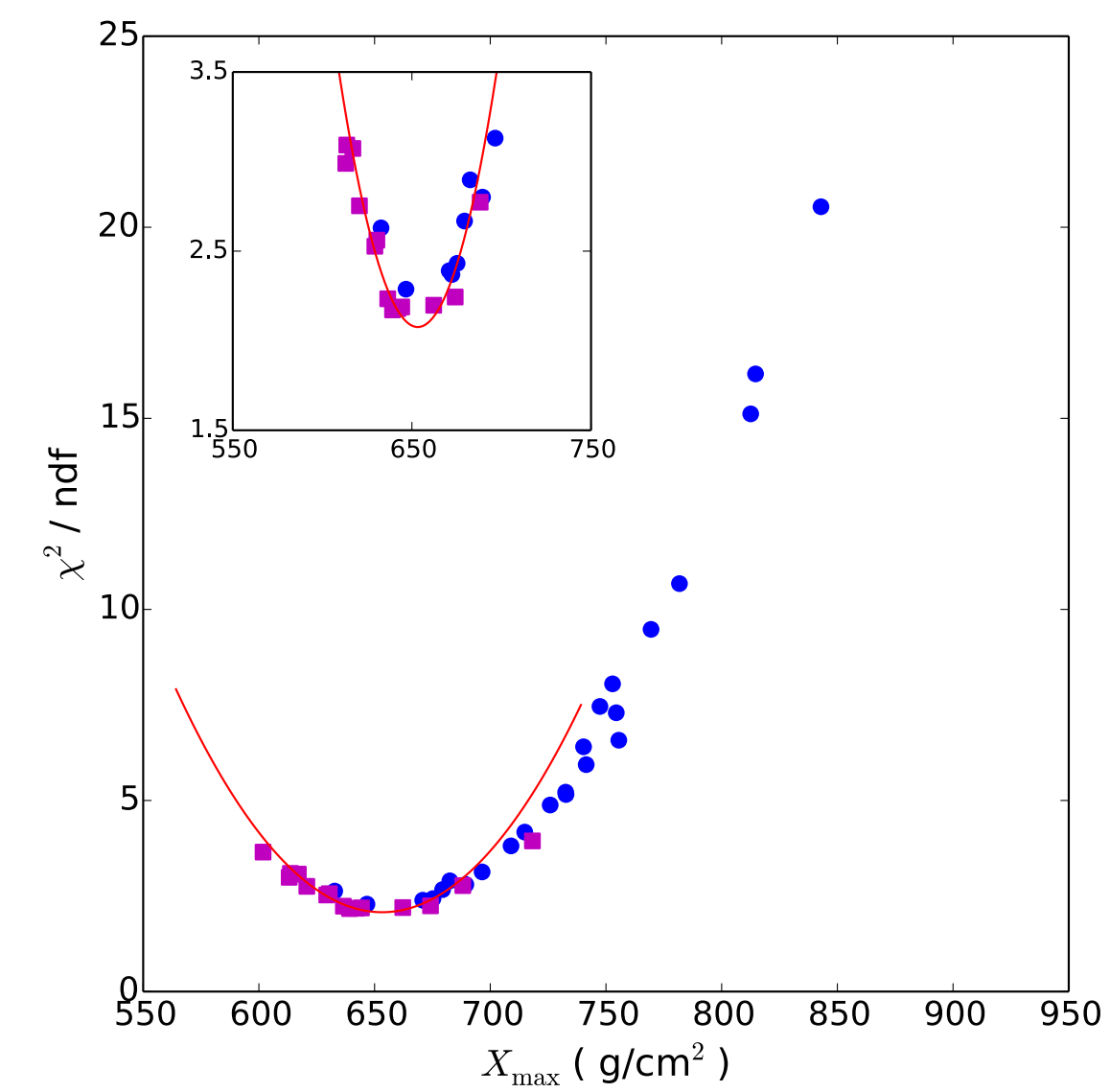
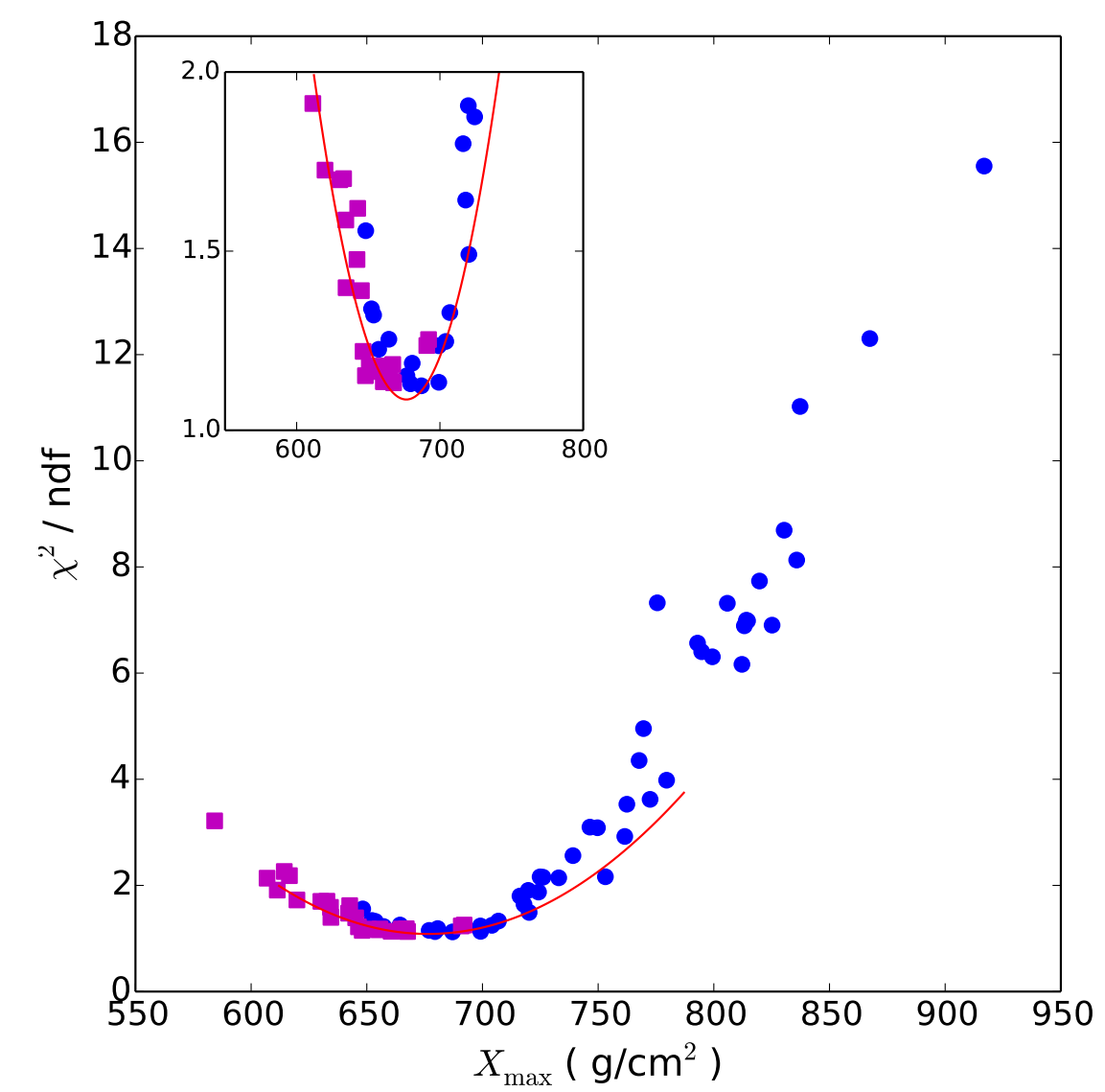
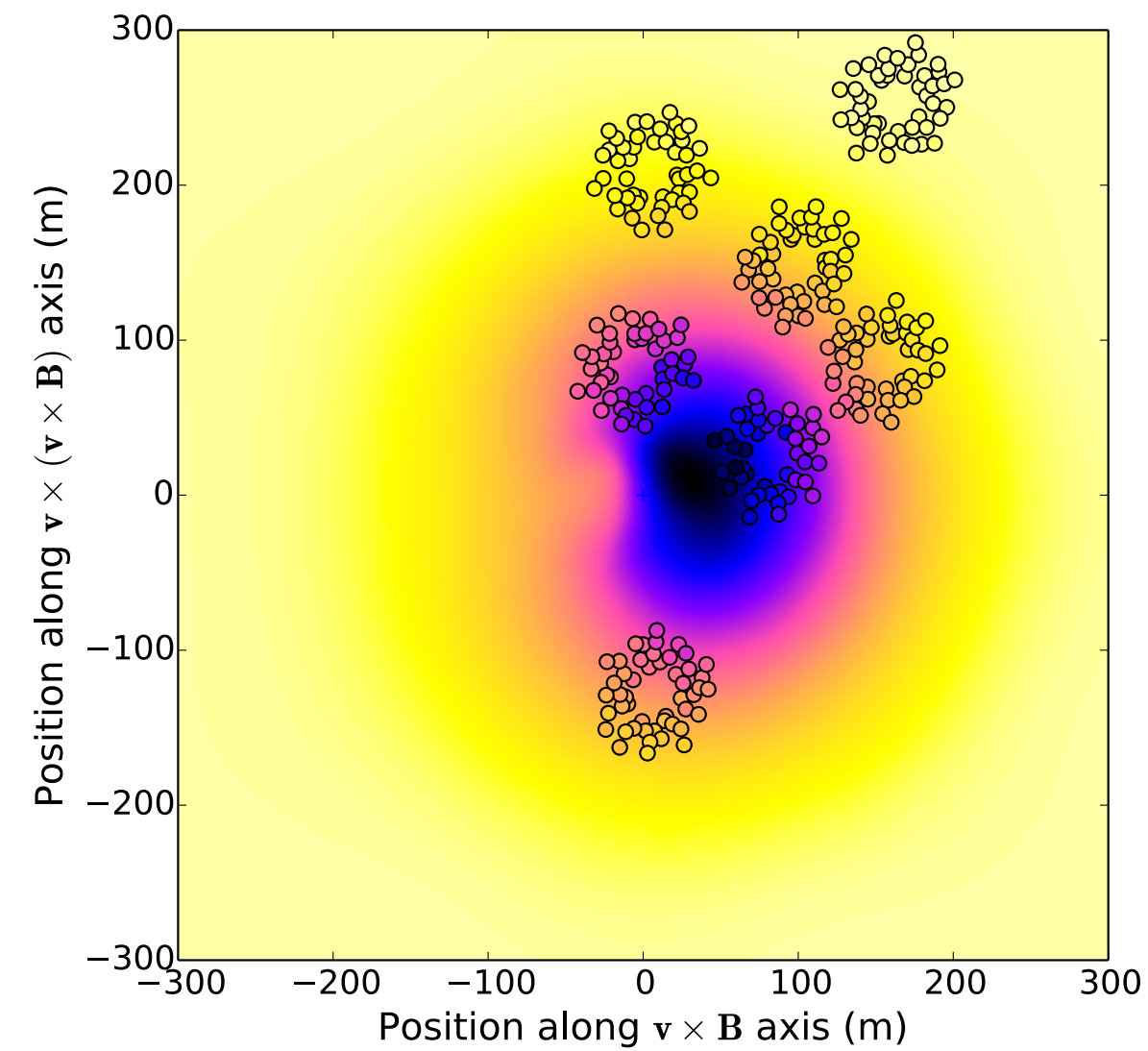
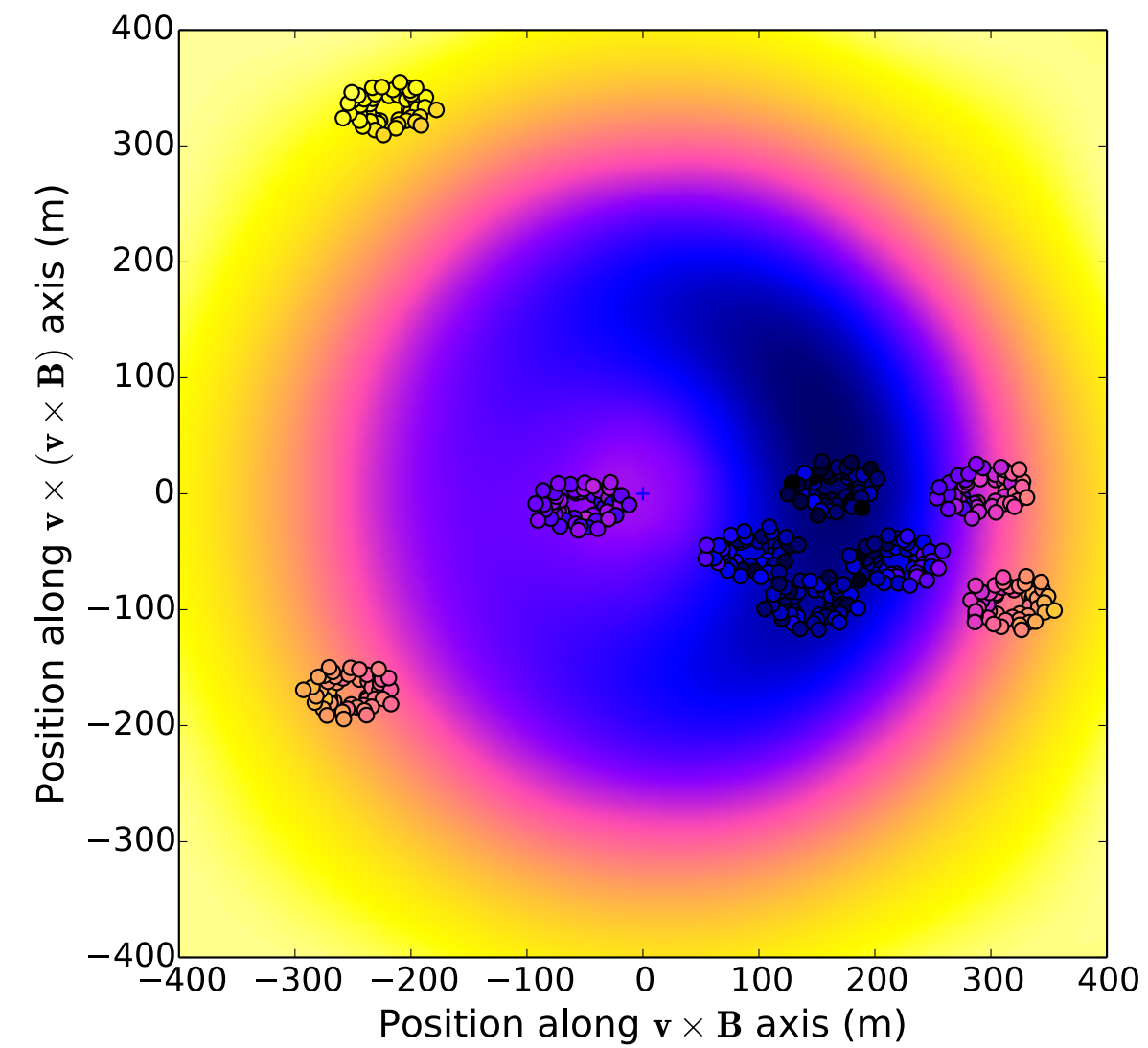
$X_{\max}$ measurement with radio



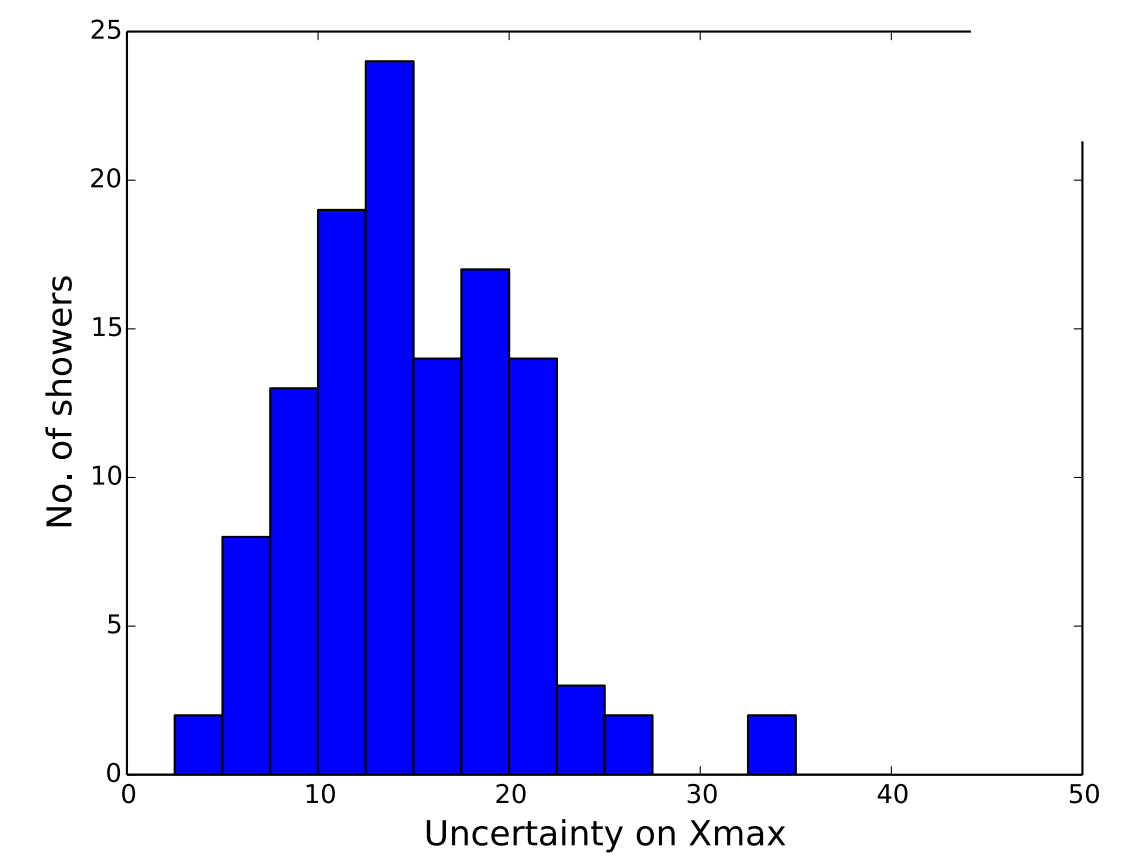
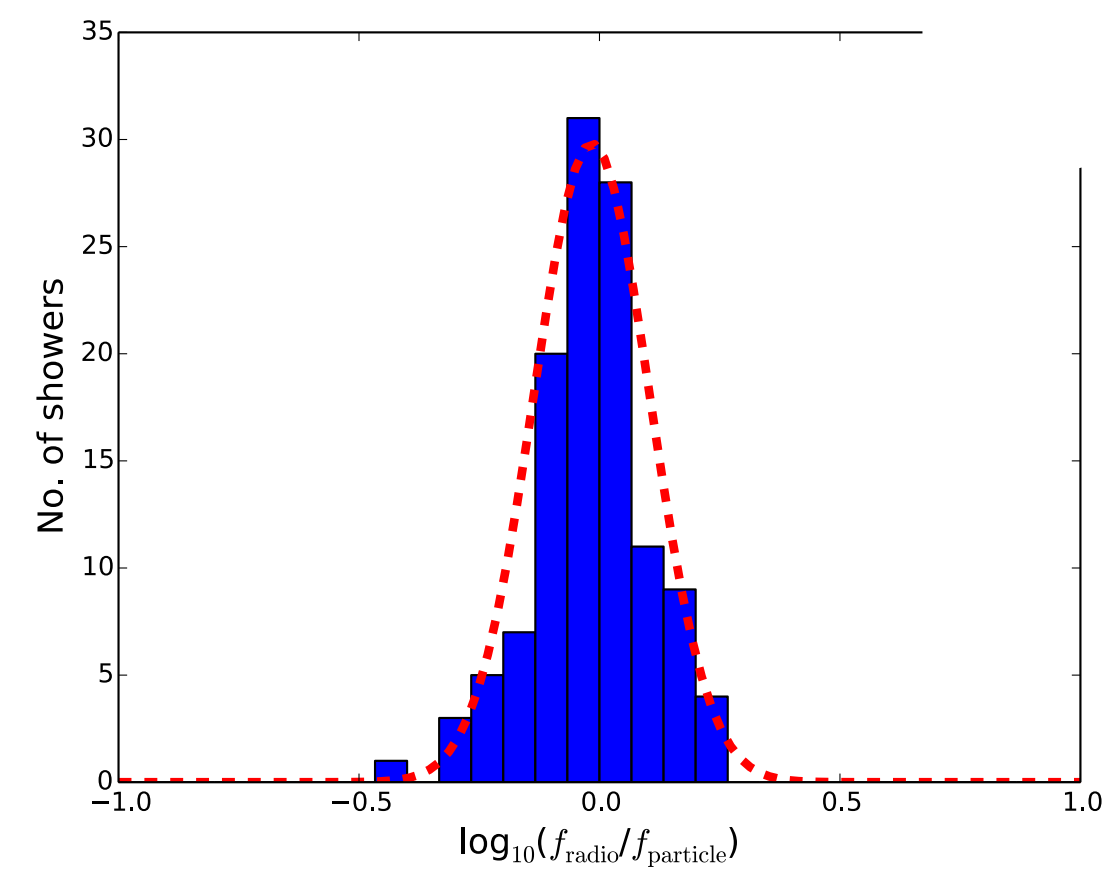
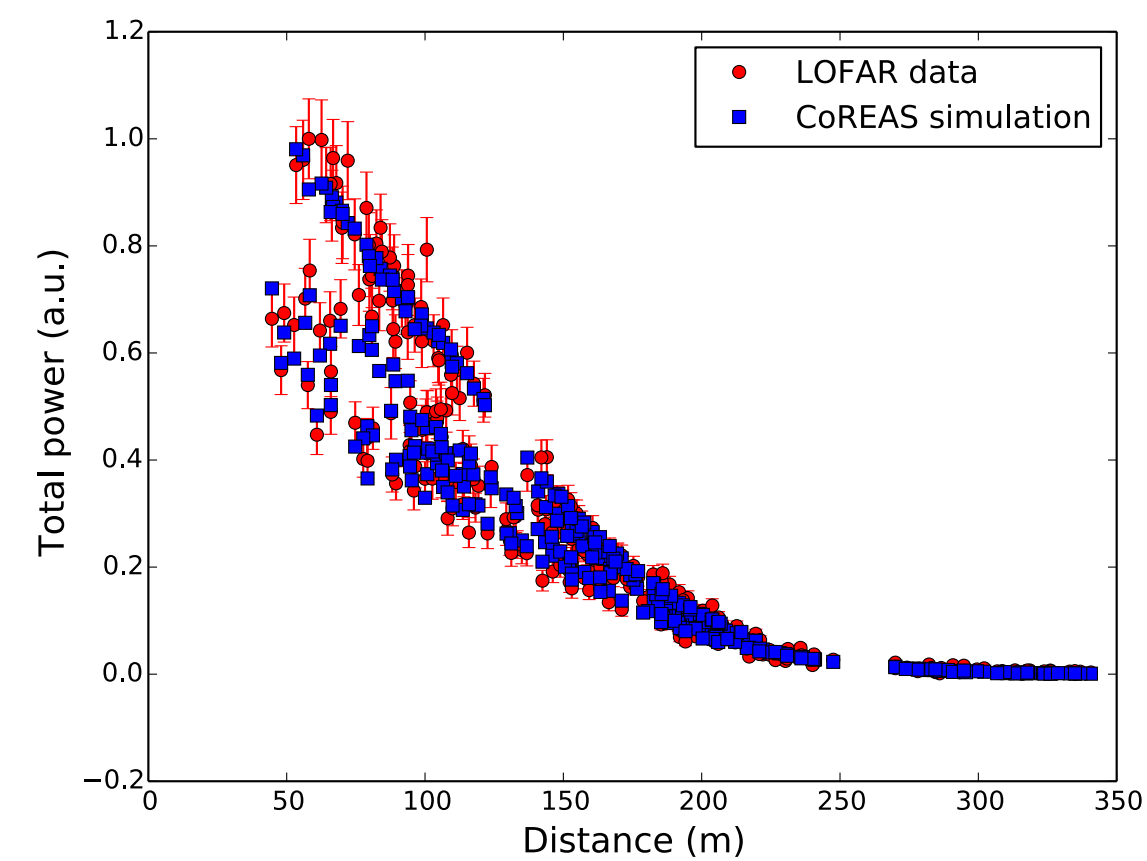
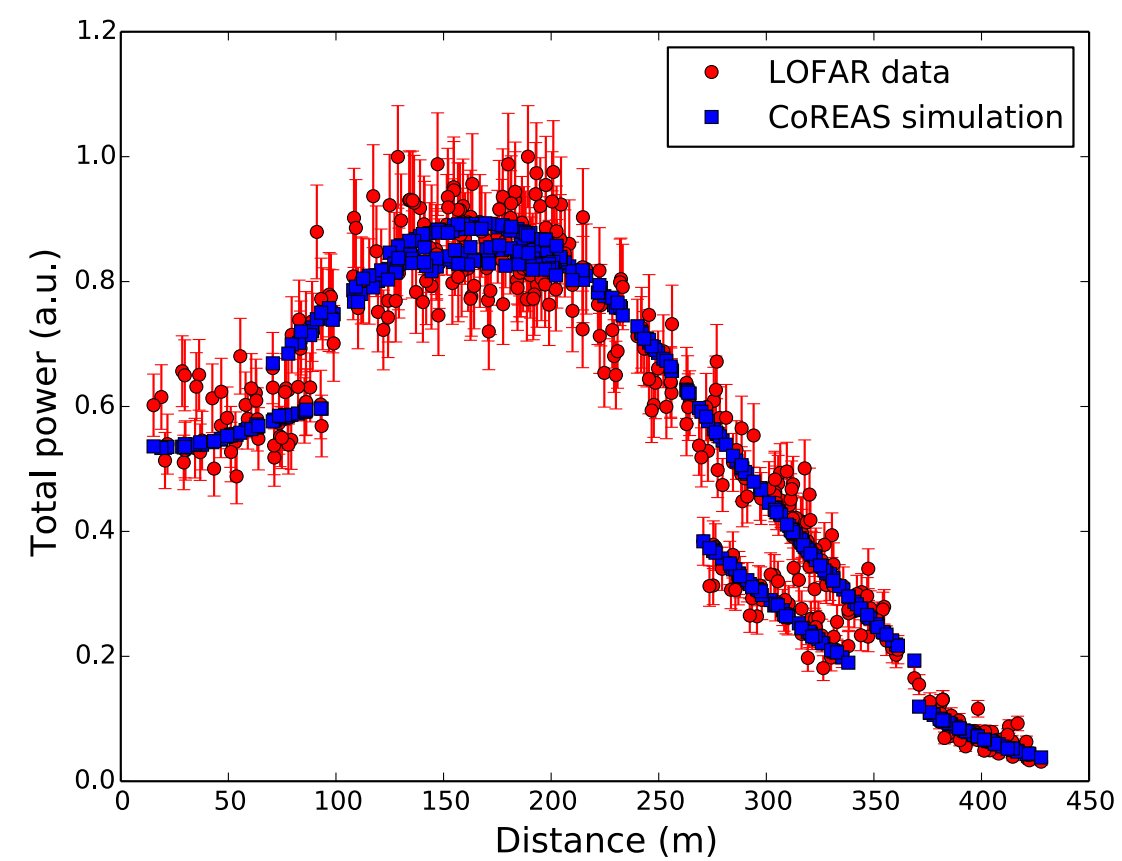
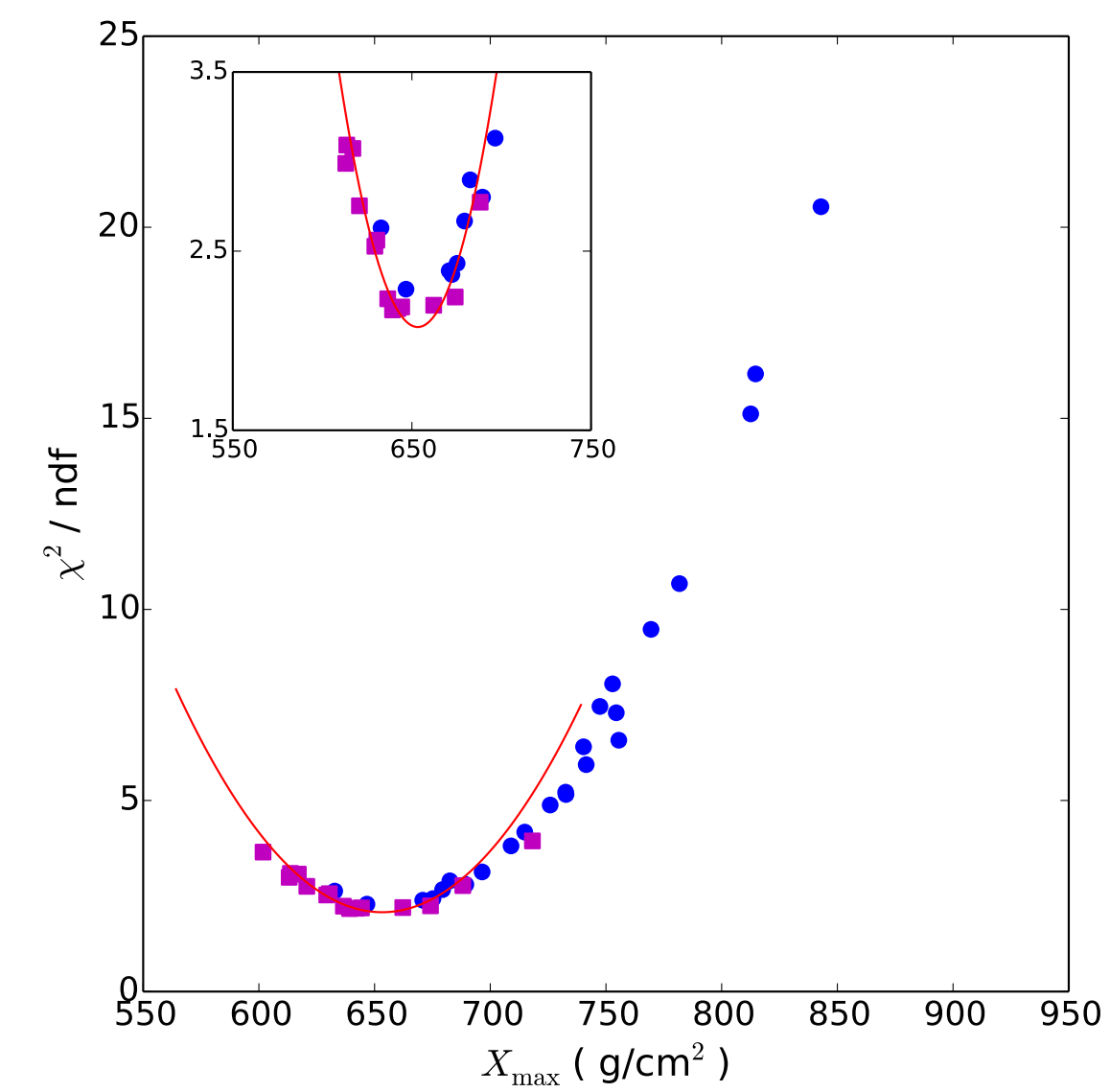
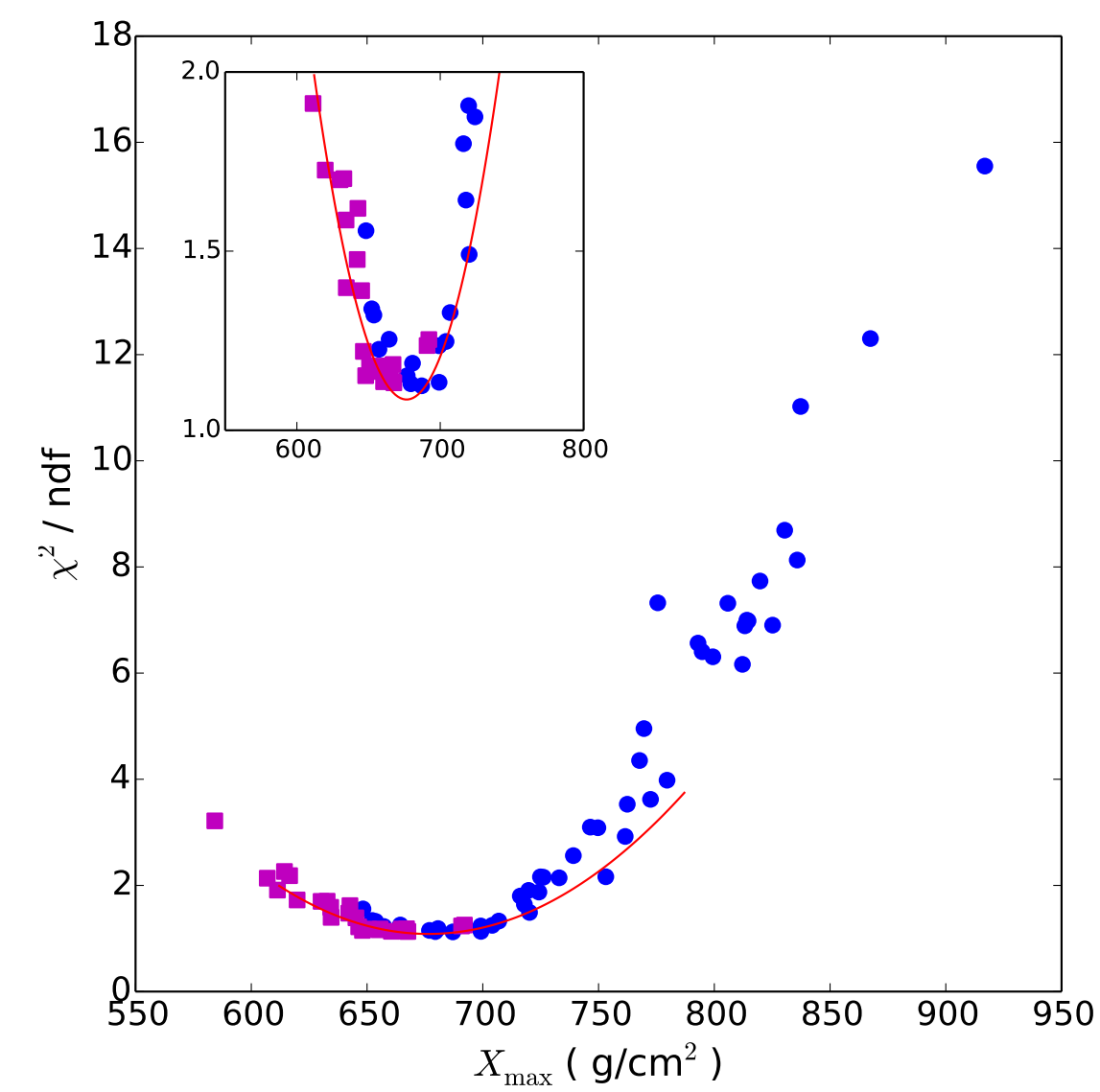
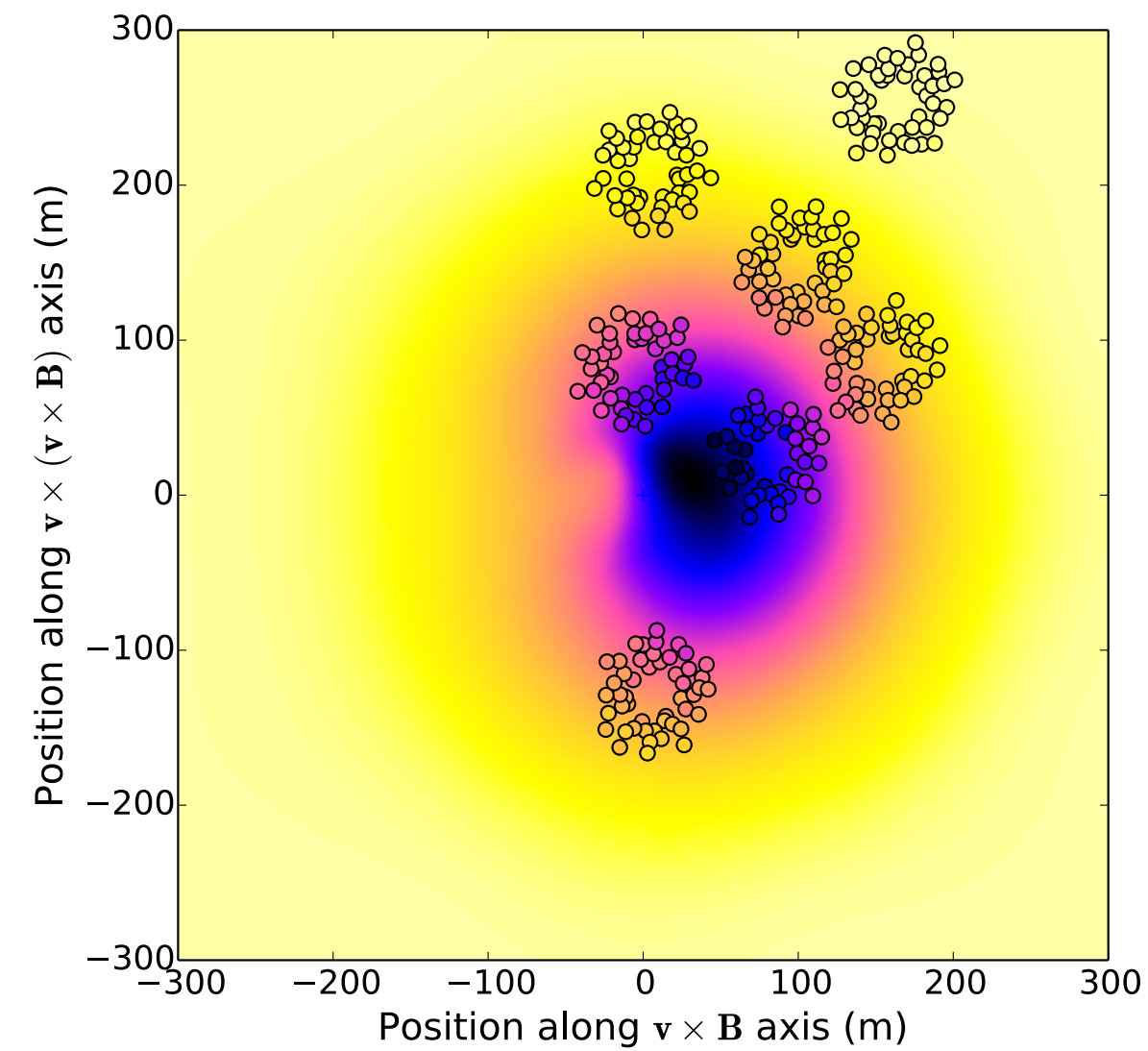
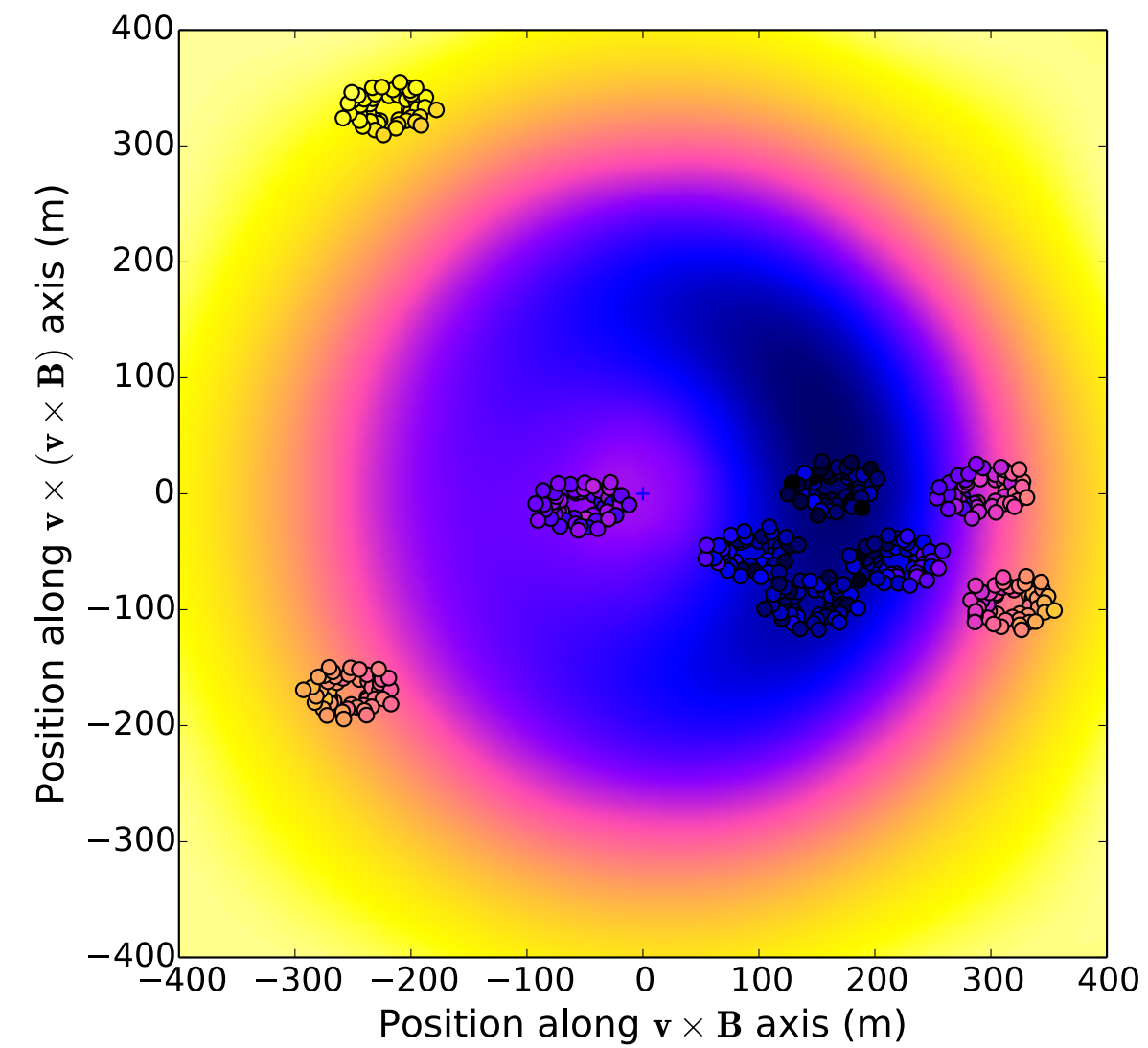
Measurement of particle mass



Measurement of particle mass



Measurement of particle mass



$$\sigma_E \approx 32\%$$

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

Depth of the shower maximum



LETTER *nature*

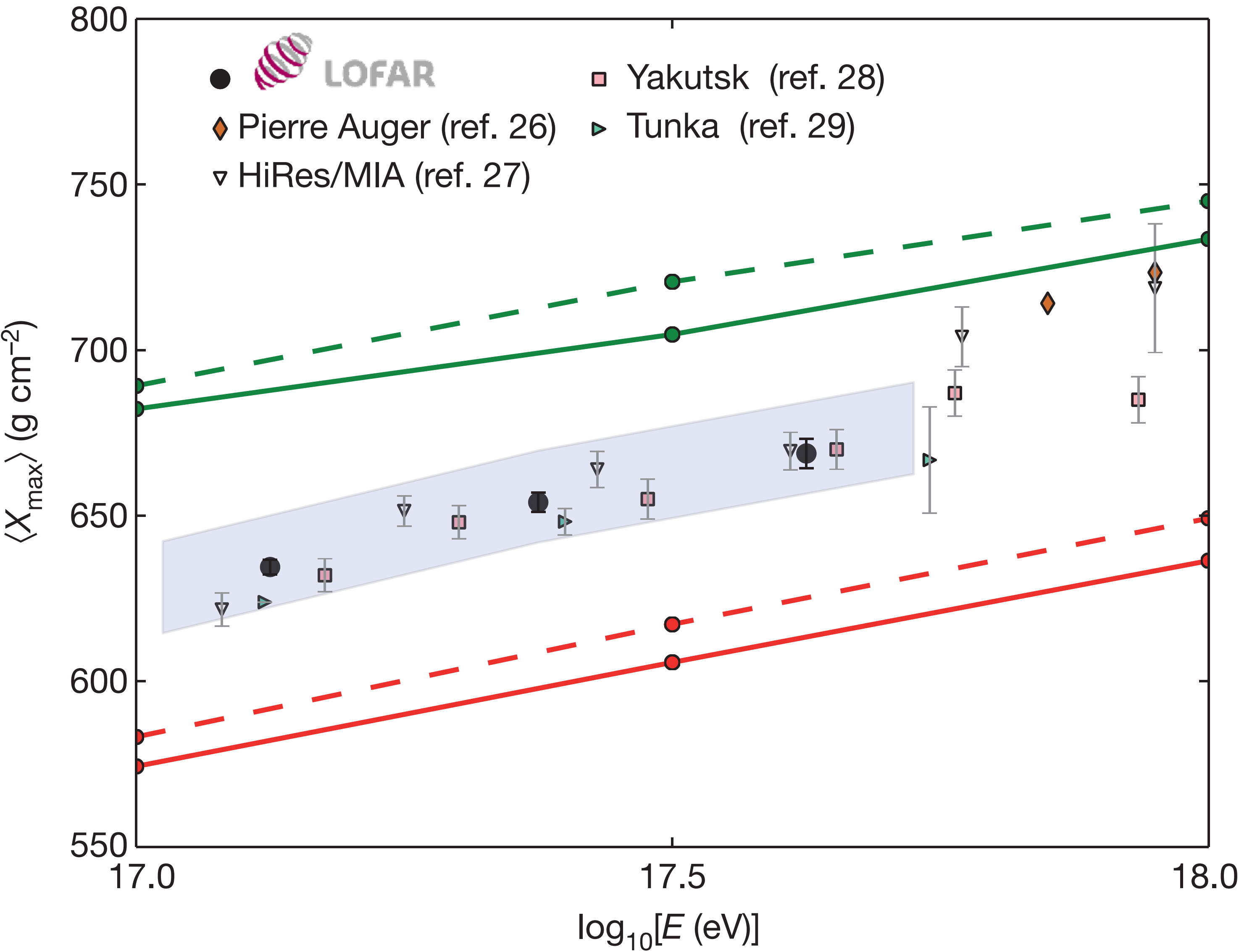
doi:10.1038/nature16976

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

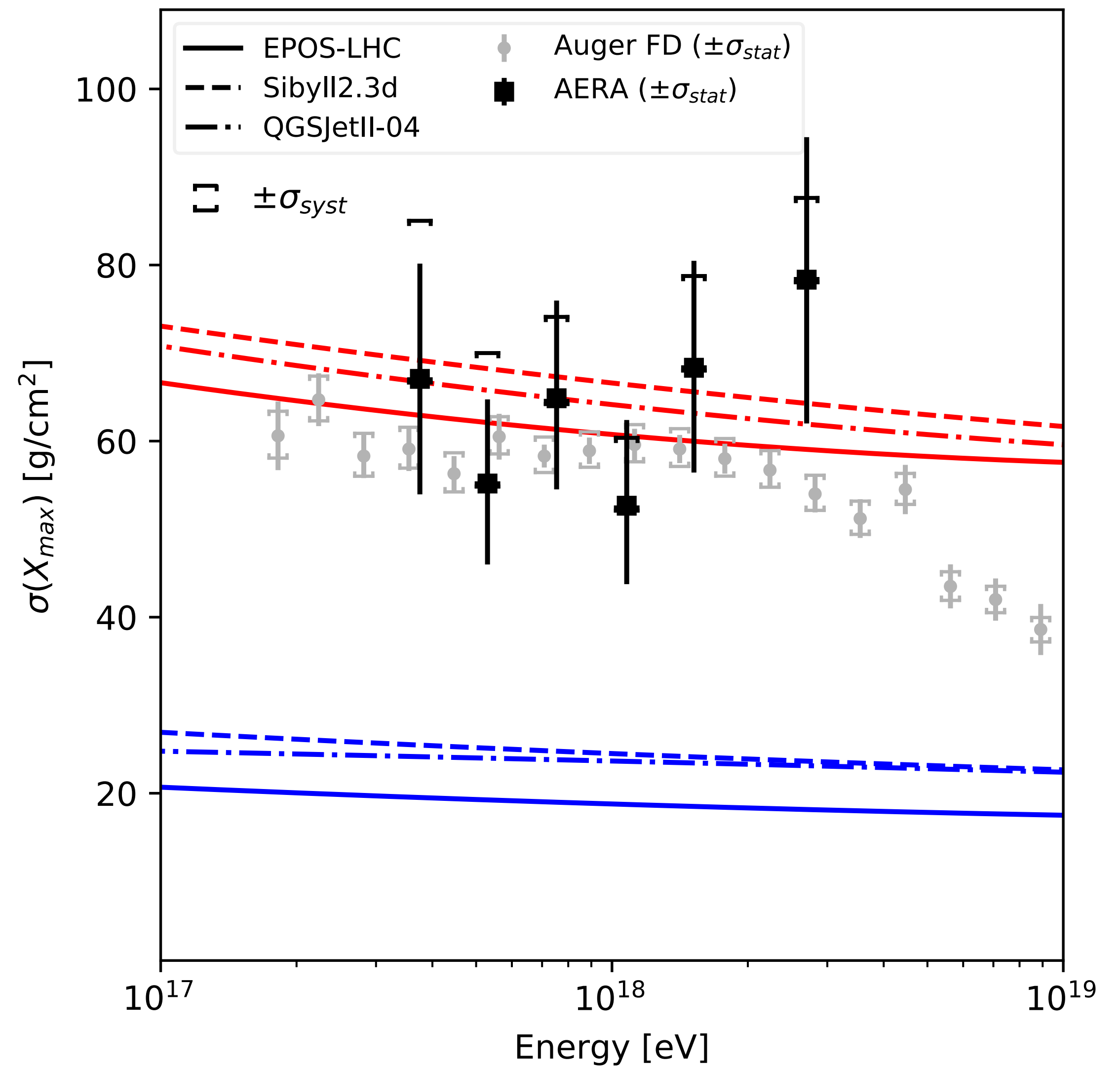
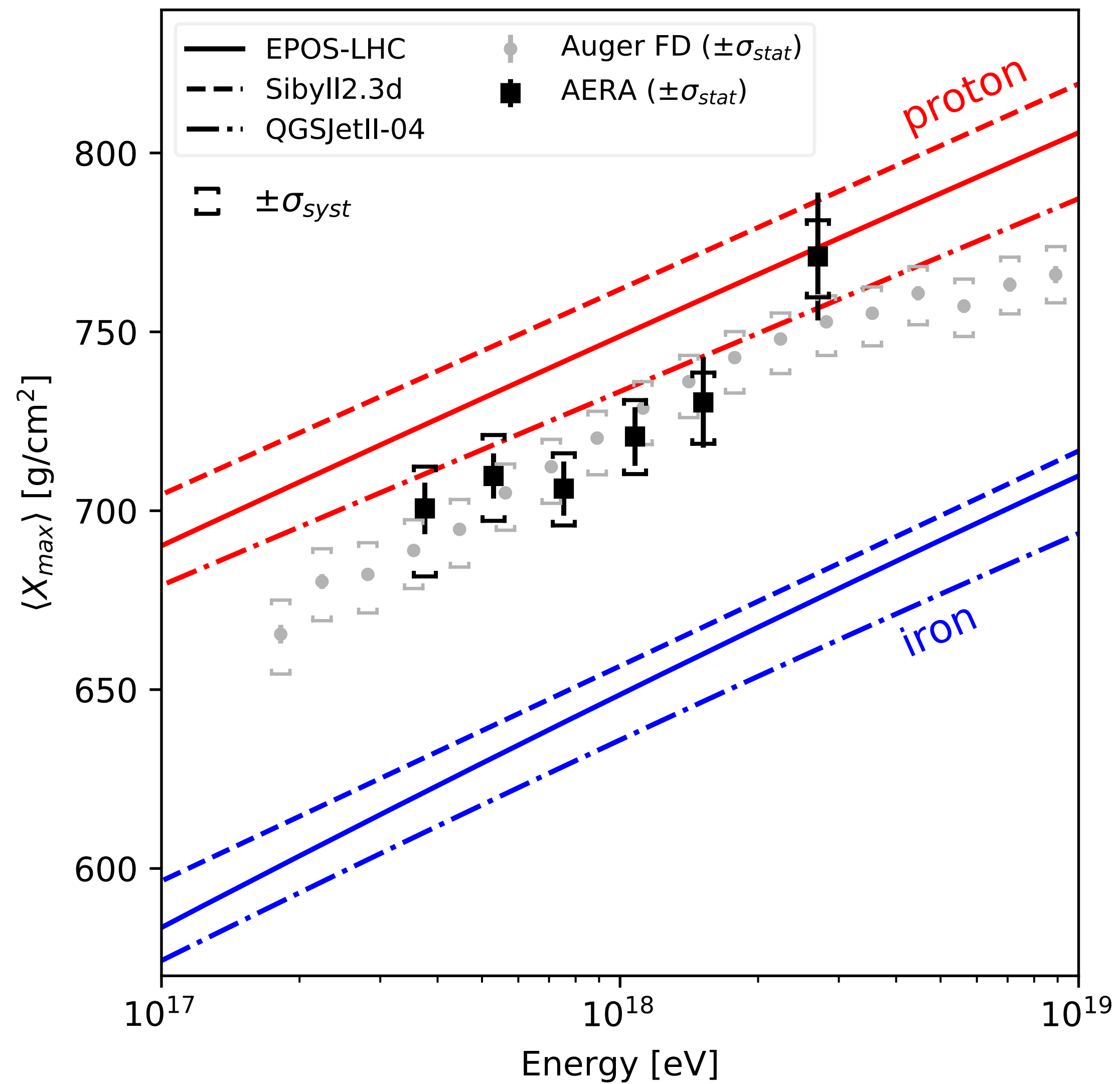
S. Buitink^{1,2}, A. Corstanje², H. Falcke^{2,3,4,5}, J. R. Hörandel^{2,4}, T. Huege⁶, A. Nelles^{2,7}, J. P. Rachen², L. Rossetto², P. Schellart², O. Scholten^{8,9}, S. ter Veen³, S. Thoudam², T. N. G. Trinh⁸, J. Anderson¹⁰, A. Asgekar^{3,11}, I. M. Avruch^{12,13}, M. E. Bell¹⁴, M. J. Bentum^{3,15}, G. Bernardi^{16,17}, P. Best¹⁸, A. Bonafede¹⁹, F. Breitling²⁰, J. W. Broderick²¹, W. N. Brouw^{3,13}, M. Brüggen¹⁹, H. R. Butcher²², D. Carbone²³, B. Ciardi²⁴, J. E. Conway²⁵, F. de Gasperin¹⁹, E. de Geus^{3,26}, A. Deller³, R. –J. Dettmar²⁷, G. van Diepen³, S. Duscha³, J. Eislöffel²⁸, D. Engels²⁹, J. E. Enriquez³, R. A. Fallows³, R. Fender³⁰, C. Ferrari³¹, W. Frieswijk³, M. A. Garrett^{3,32}, J. M. Grießmeier^{33,34}, A. W. Gunst³, M. P. van Haarlem³, T. E. Hassall²¹, G. Heald^{3,13}, J. W. T. Hessels^{3,23}, M. Hoeft²⁸, A. Horneffer⁵, M. Iacobelli³, H. Intema^{32,35}, E. Juette²⁷, A. Karastergiou³⁰, V. I. Kondratiev^{3,36}, M. Kramer^{5,37}, M. Kuniyoshi³⁸, G. Kuper³, J. van Leeuwen^{3,23}, G. M. Loose³, P. Maat³, G. Mann²⁰, S. Markoff²³, R. McFadden³, D. McKay–Bukowski^{39,40}, J. P. McKean^{3,13}, M. Mevius^{3,13}, D. D. Mulcahy²¹, H. Munk³, M. J. Norden³, E. Orru³, H. Paas⁴¹, M. Pandey–Pommier⁴², V. N. Pandey³, M. Pietka³⁰, R. Pizzo³, A. G. Polatidis³, W. Reich⁵, H. J. A. Röttgering³², A. M. M. Scaife²¹, D. J. Schwarz⁴³, M. Serylak³⁰, J. Sluman³, O. Smirnov^{17,44}, B. W. Stappers³⁷, M. Steinmetz²⁰, A. Stewart³⁰, J. Swinbank^{23,45}, M. Tagger³³, Y. Tang³, C. Tasse^{44,46}, M. C. Toribio^{3,32}, R. Vermeulen³, C. Vocks²⁰, C. Vogt³, R. J. van Weeren¹⁶, R. A. M. J. Wijers²³, S. J. Wijnholds³, M. W. Wise^{3,23}, O. Wucknitz⁵, S. Yatawatta³, P. Zarka⁴⁷ & J. A. Zensus⁵

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 signal¹ comes from accelerators capable of producing cosmic rays of these energies². 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 maximum³ (X_{max} ; the depth of the air shower when it contains the most particles) or of the composition of shower particles reaching the ground⁴. Current measurements⁵ 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 technique⁹ 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

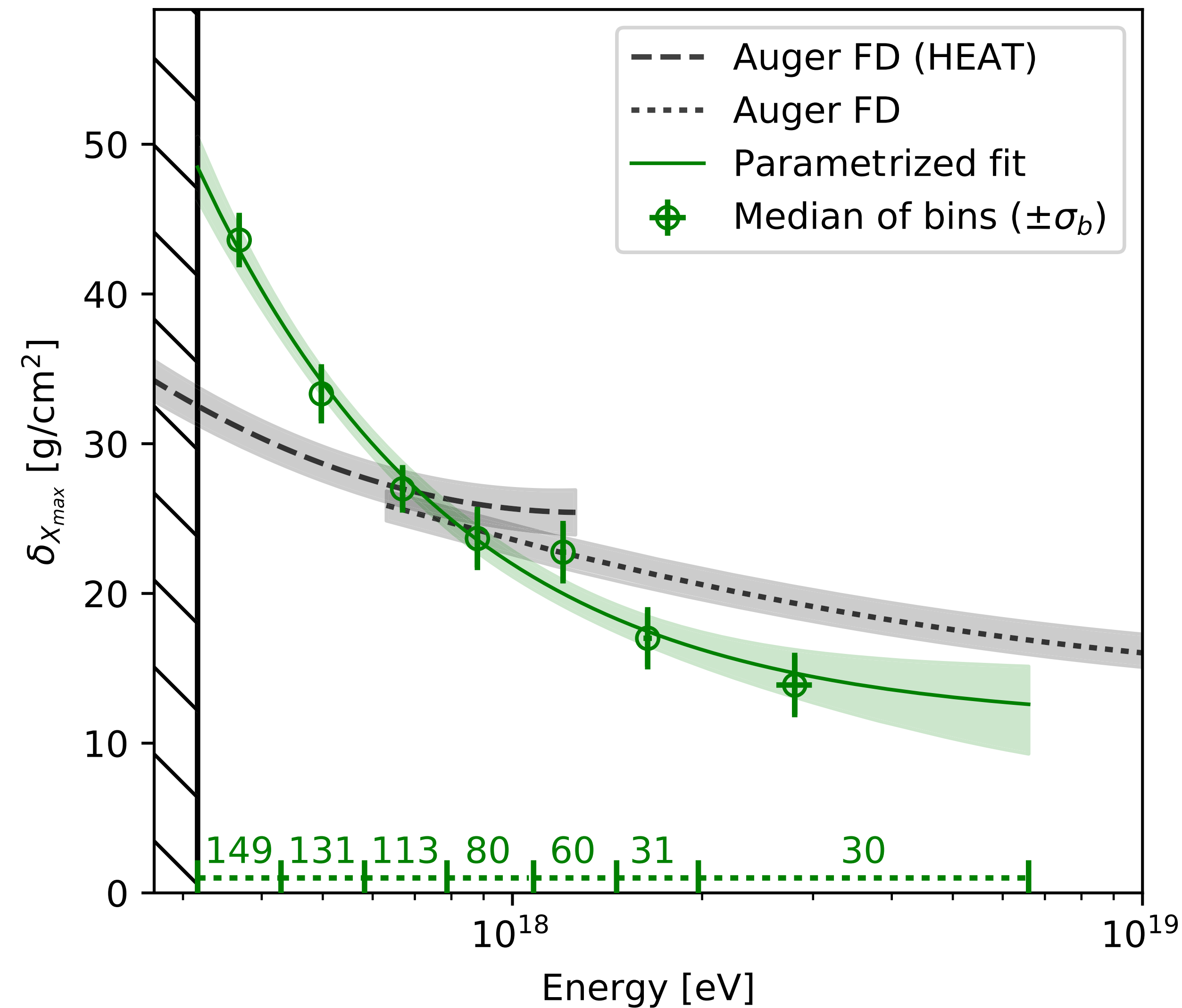
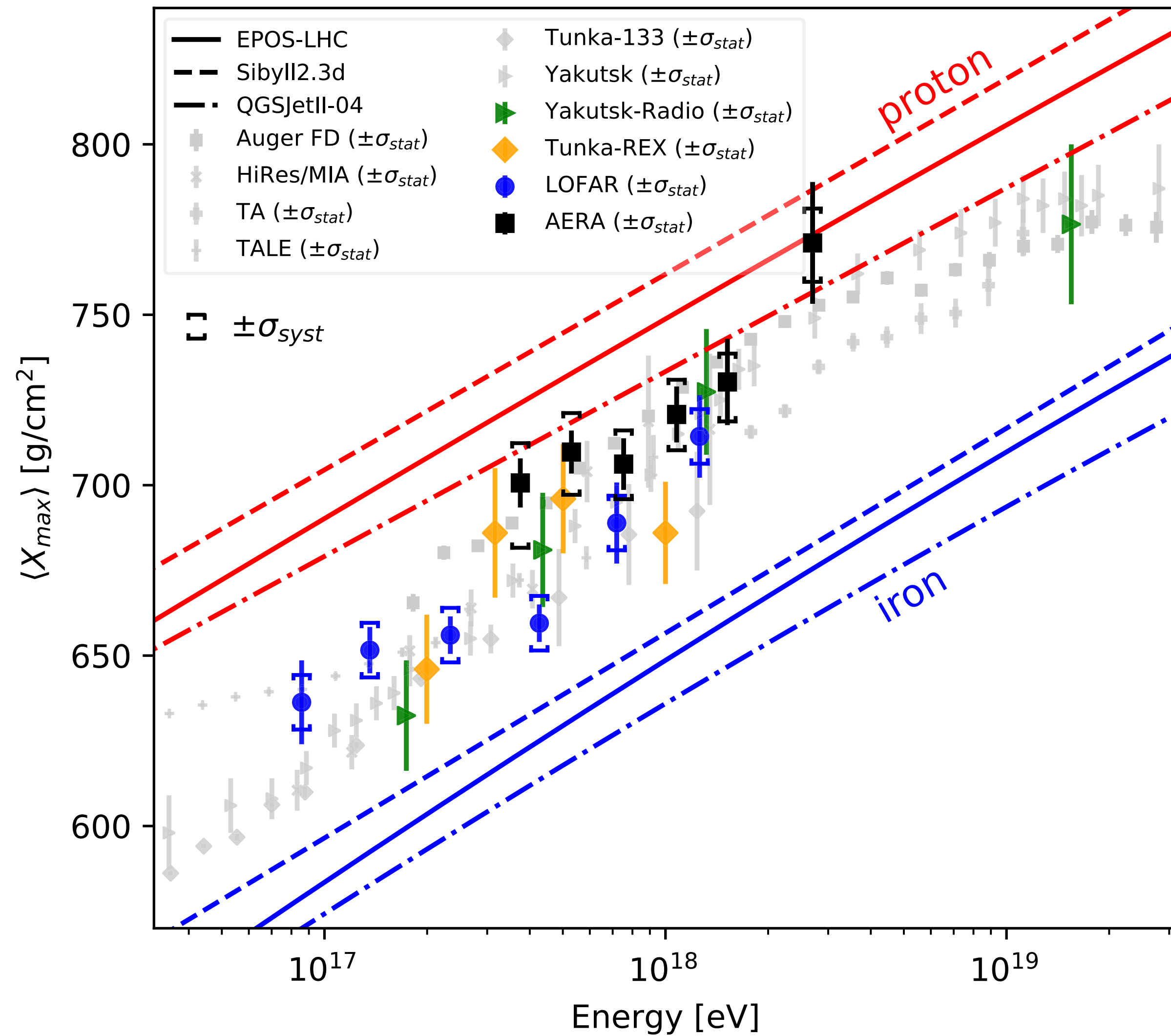
initiated by cosmic rays with energies of 10^{17} – $10^{17.5}$ electronvolts. This high resolution in X_{max} enables us to determine the mass spectrum of the cosmic rays: we find a mixed composition, with a light-mass fraction (protons and helium nuclei) of about 80 per cent. Unless, contrary to current 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 (LOFAR¹³), a radio telescope consisting of thousands of crossed dipoles with built-in air-shower-detection capability¹⁴. 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



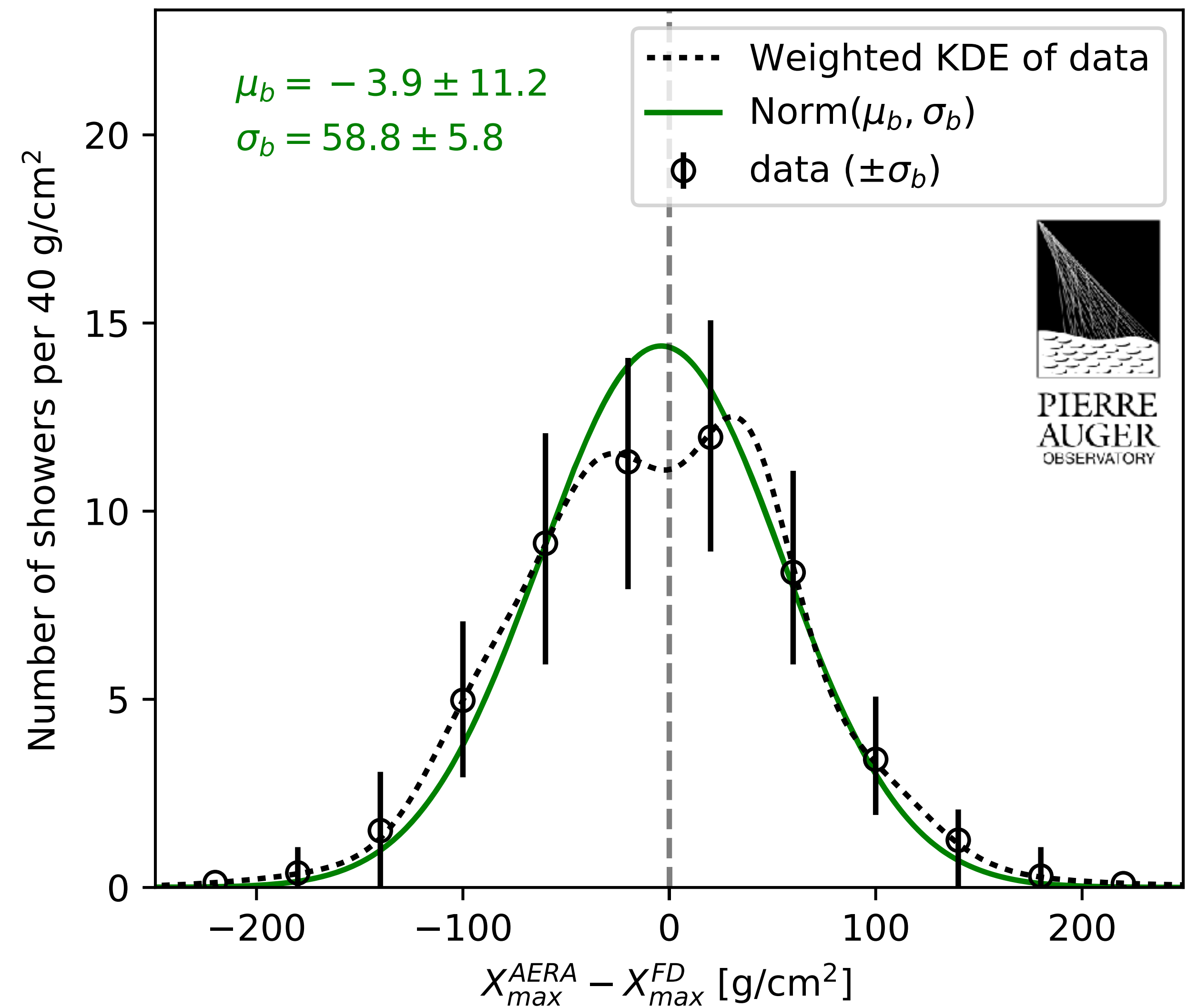
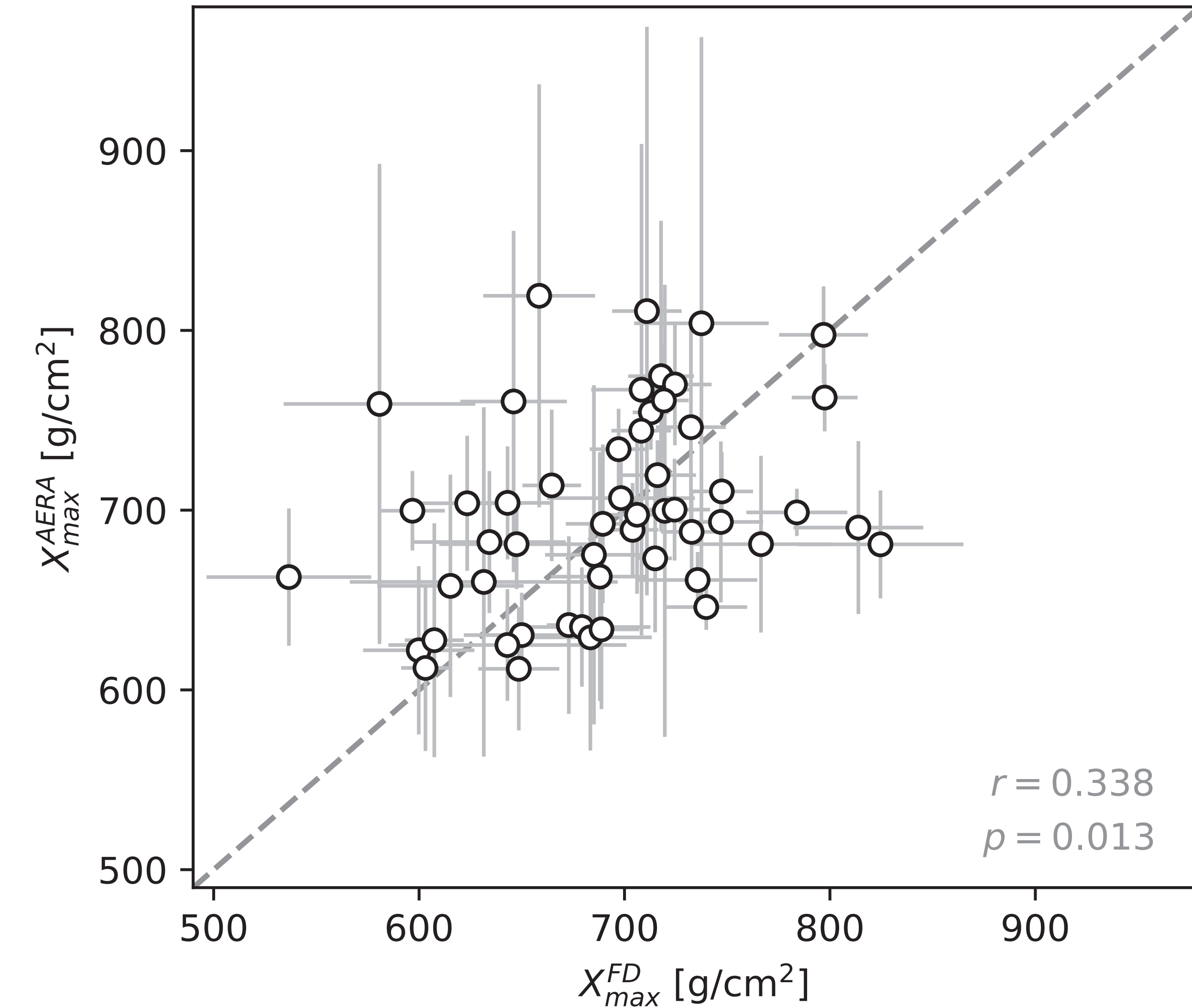
Depth of the shower maximum



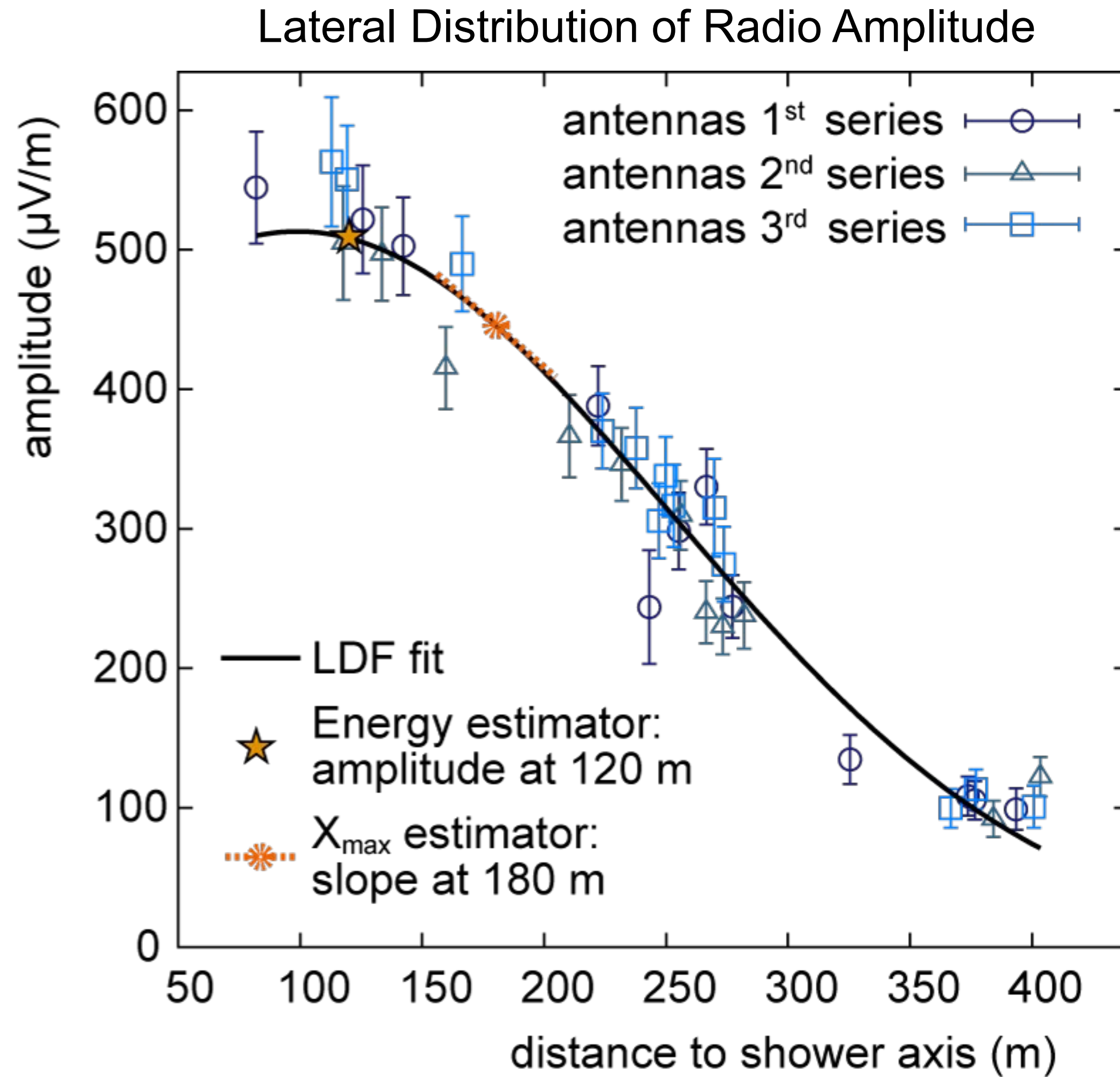
Depth of the shower maximum



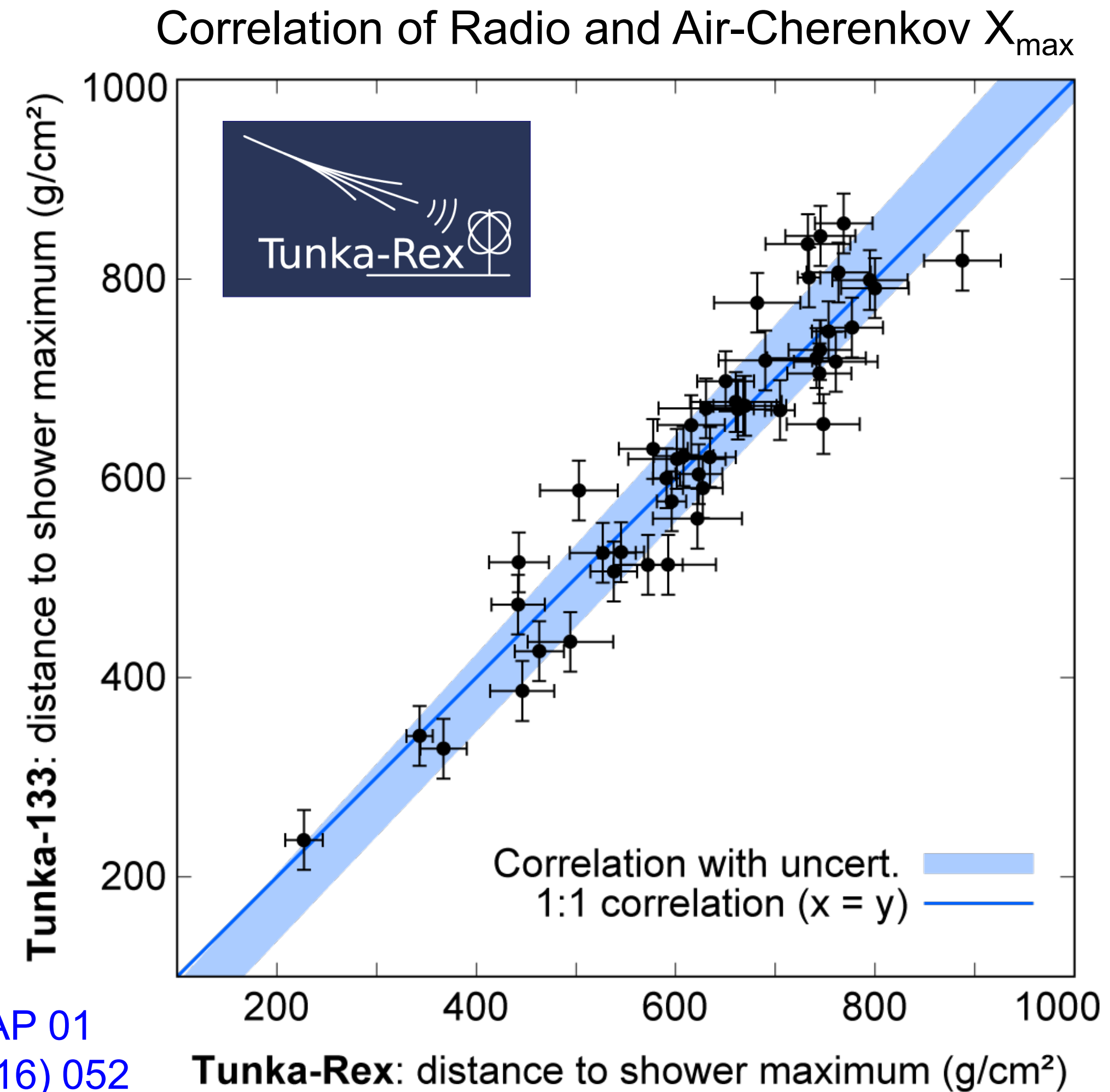
Agreement radio - fluorescence measurements



Agreement radio - Cherenkov measurements

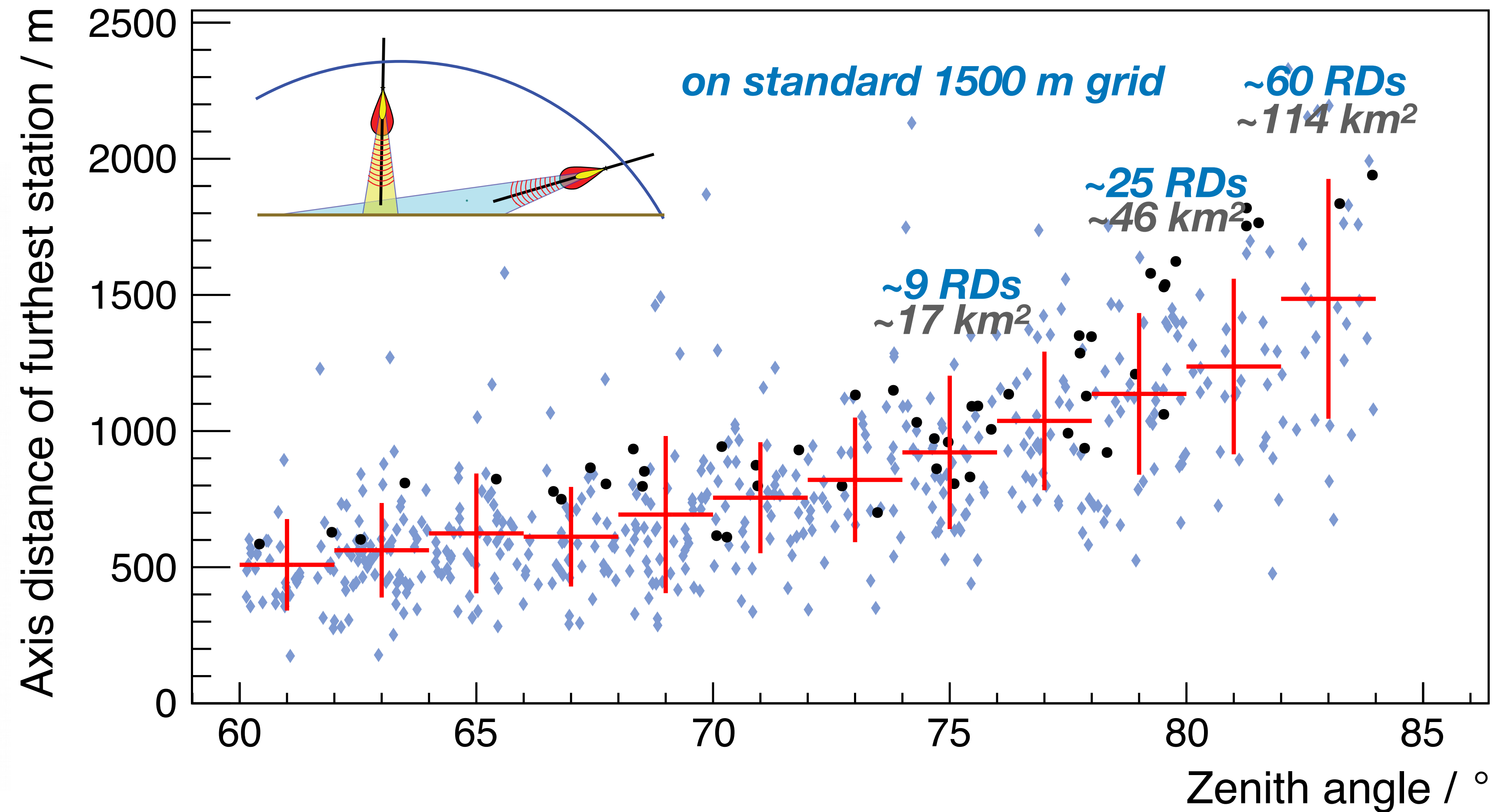
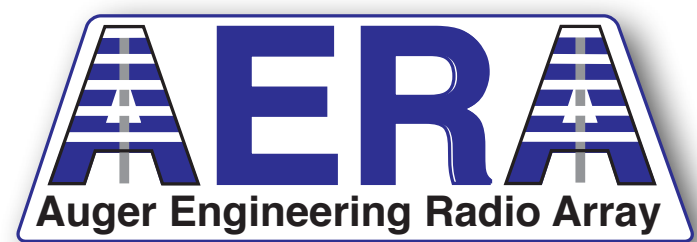
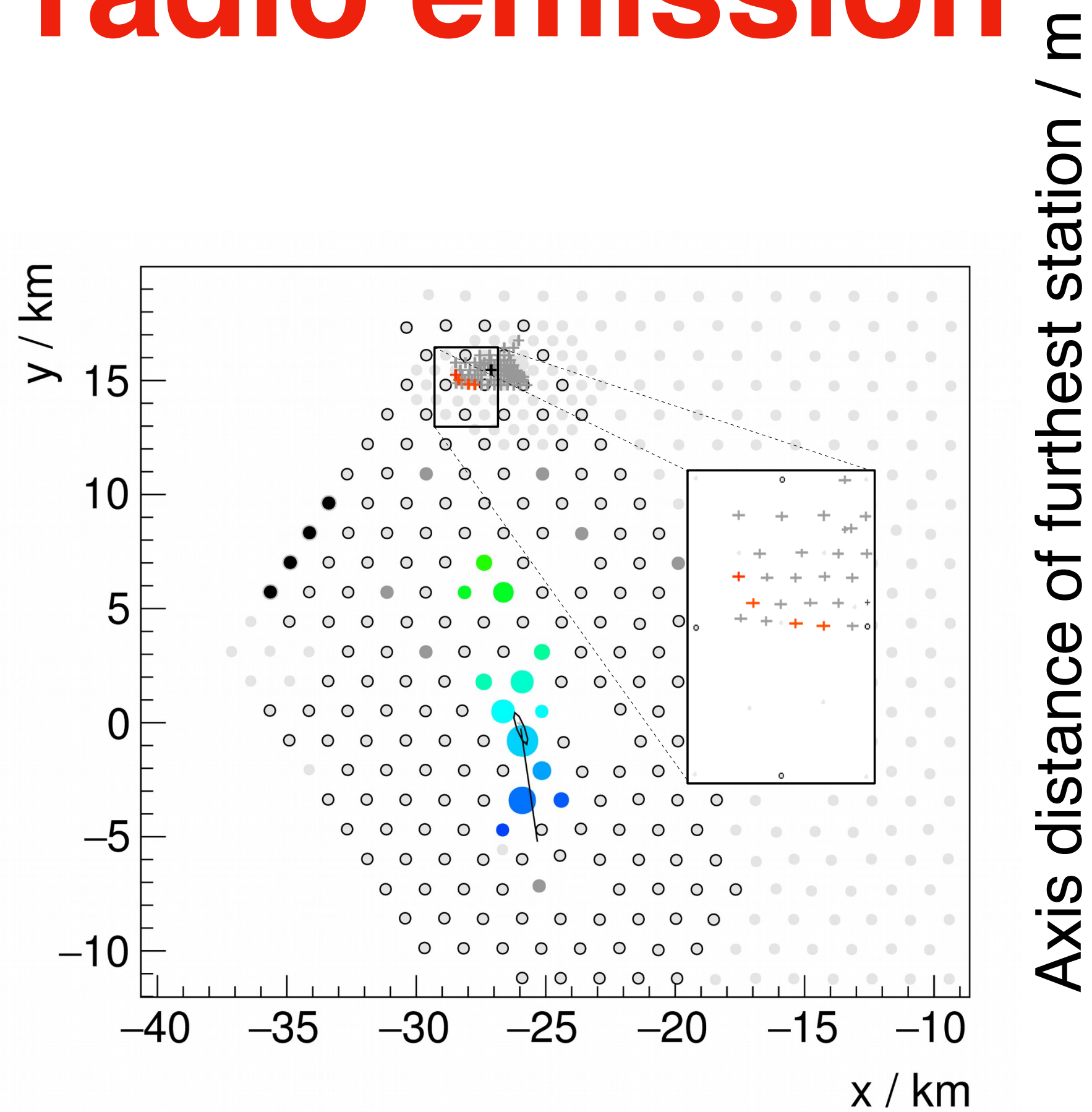


JCAP 01
(2016) 052



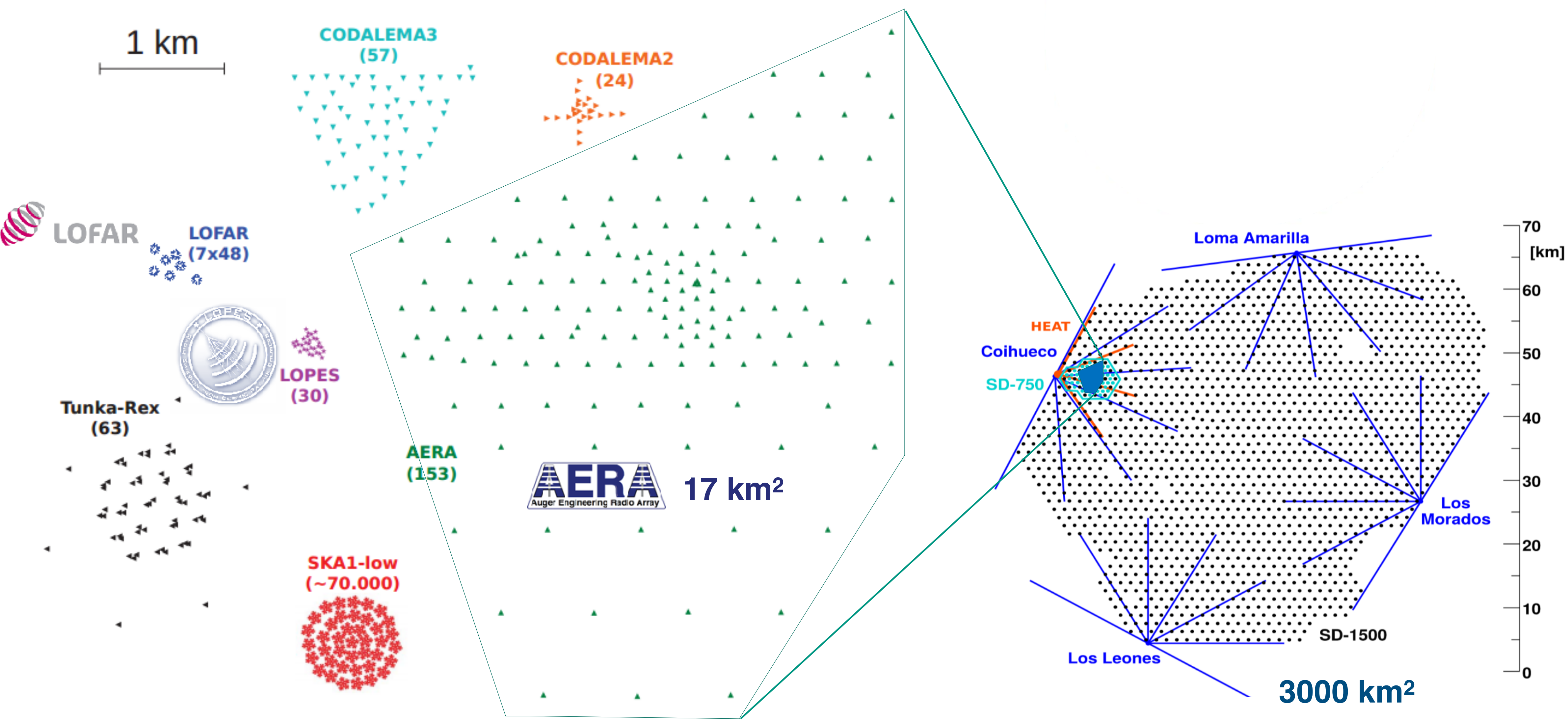
SALLA antenna
at Tunka-Rex

Horizontal air showers have large footprints in radio emission

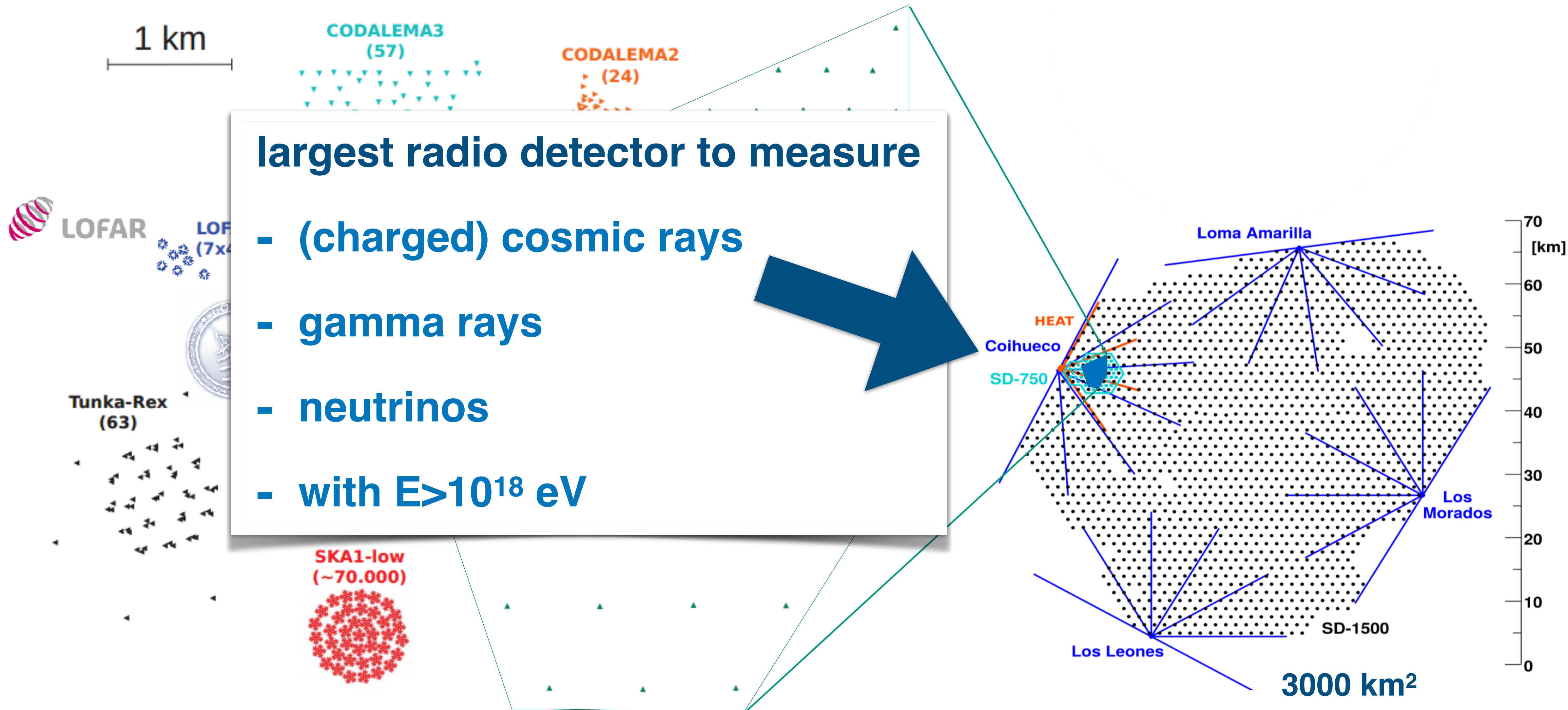


this is MEASURED with the *small* 17km² AERA

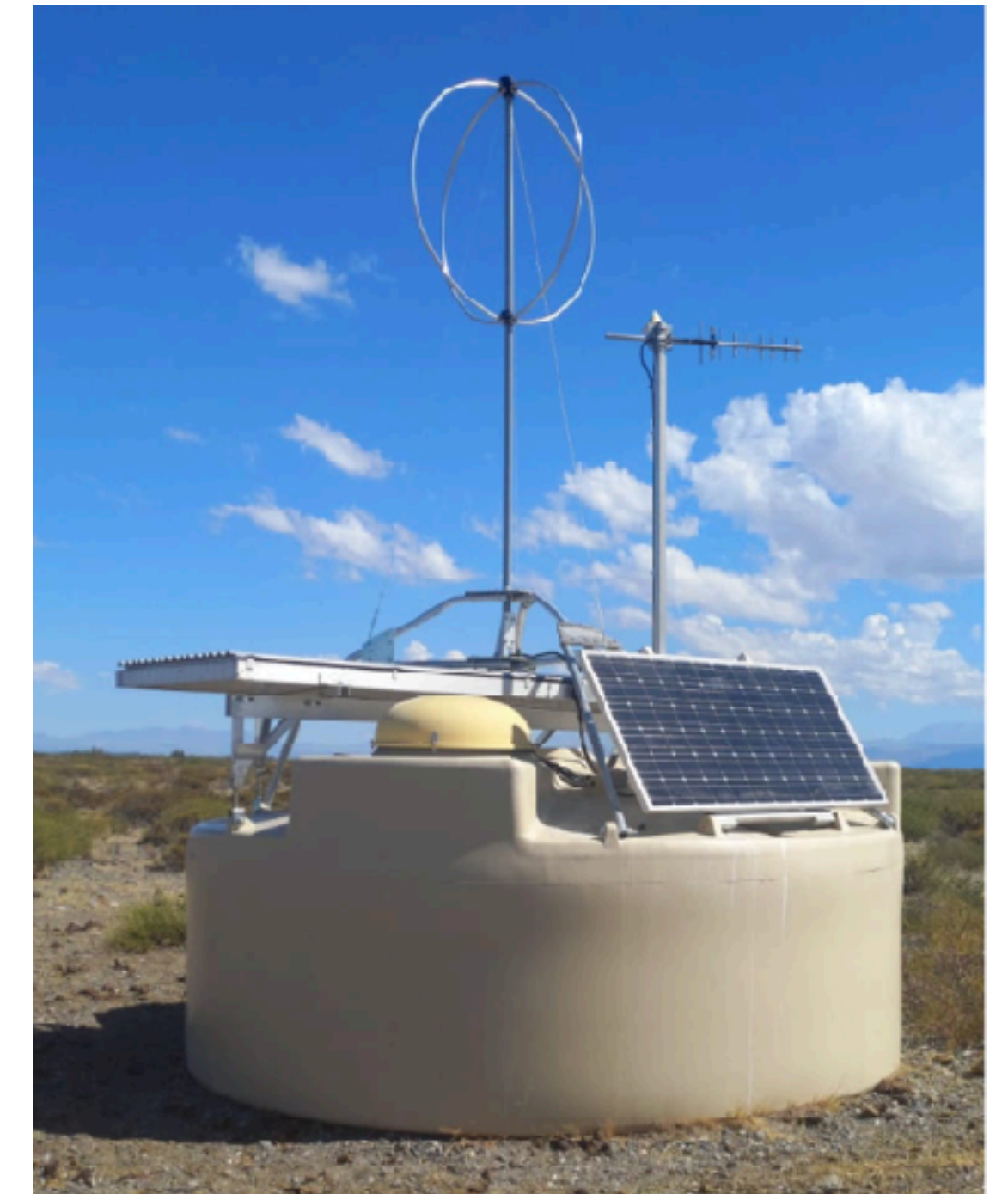
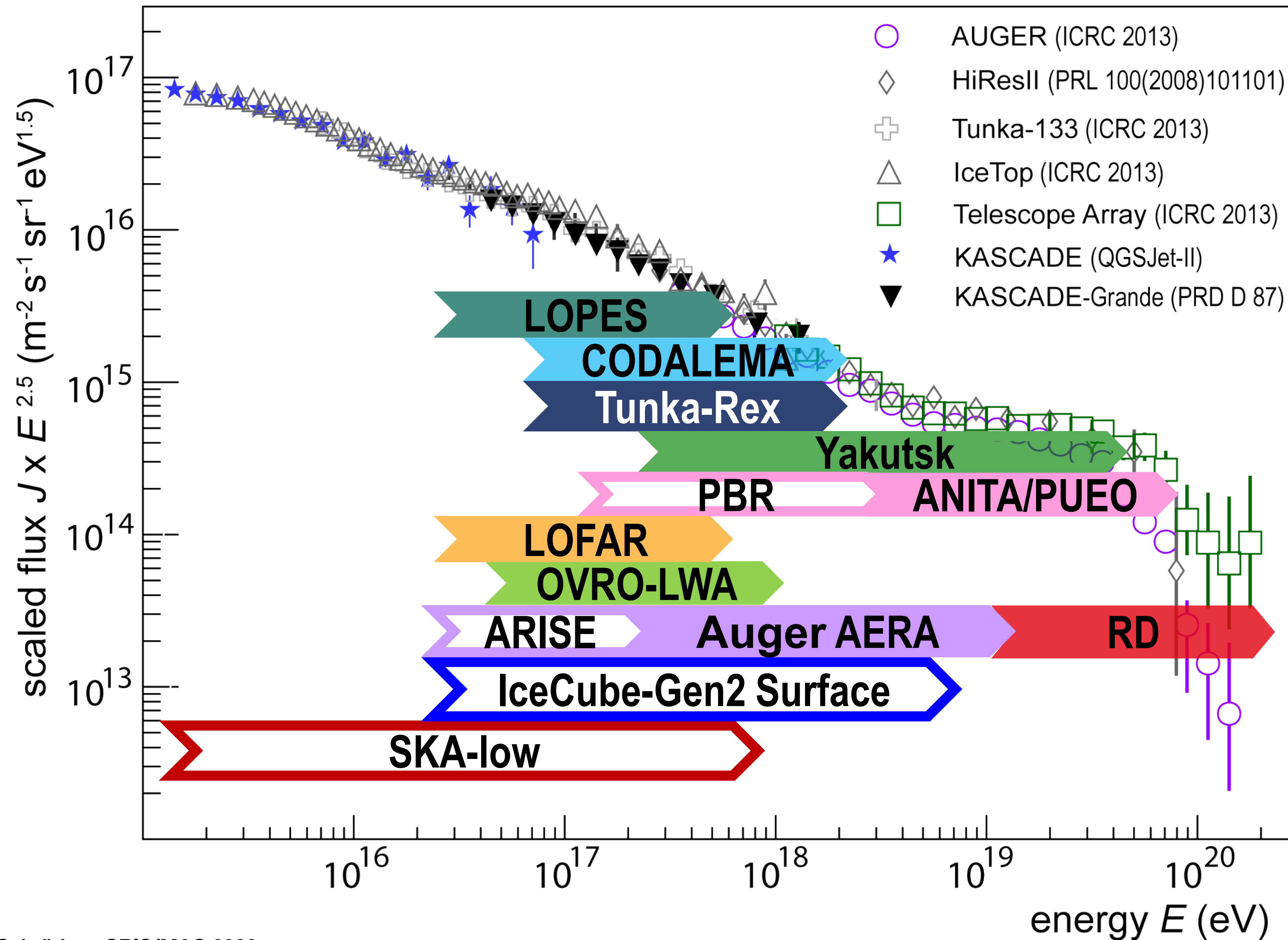
Radio detector arrays for air showers



Radio detector arrays for air showers



Energy range of Radio Detectors for Air Showers



**Radio Detector of
Pierre Auger Observatory**

Radio Detector of the Pierre Auger Observatory

radio antenna 30-80 MHz
two orthogonal polarizations
250 MHz sampling

 e/γ

plastic scintillator

120 MHz sampling

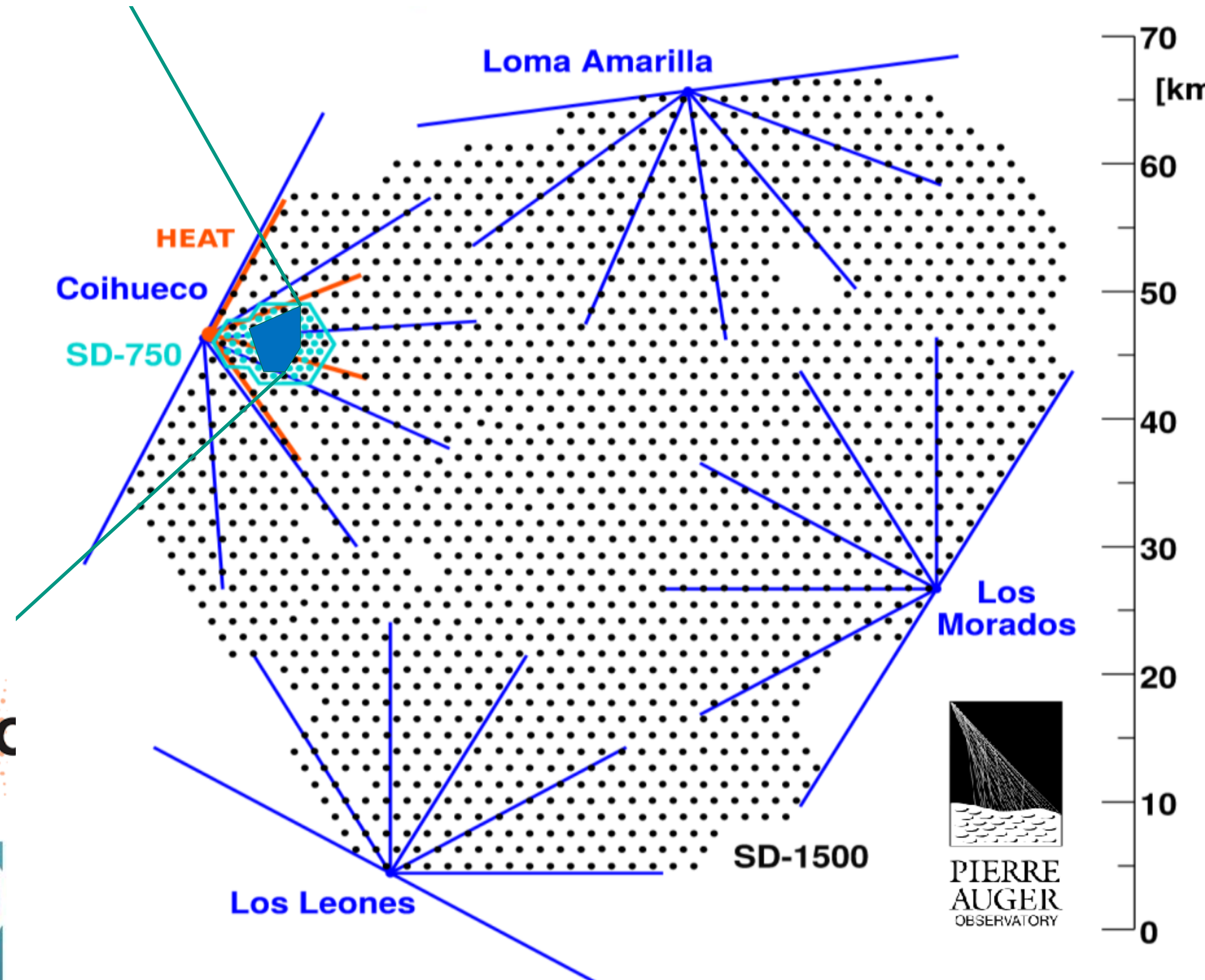


read-out electronics



water-Cherenkov detector

120 MHz sampling



Radio Detector of the Pierre Auger Observatory

radio antenna 30-80 MHz
two orthogonal polarizations
250 MHz sampling

e/γ

plastic scintillator
120 MHz sampling

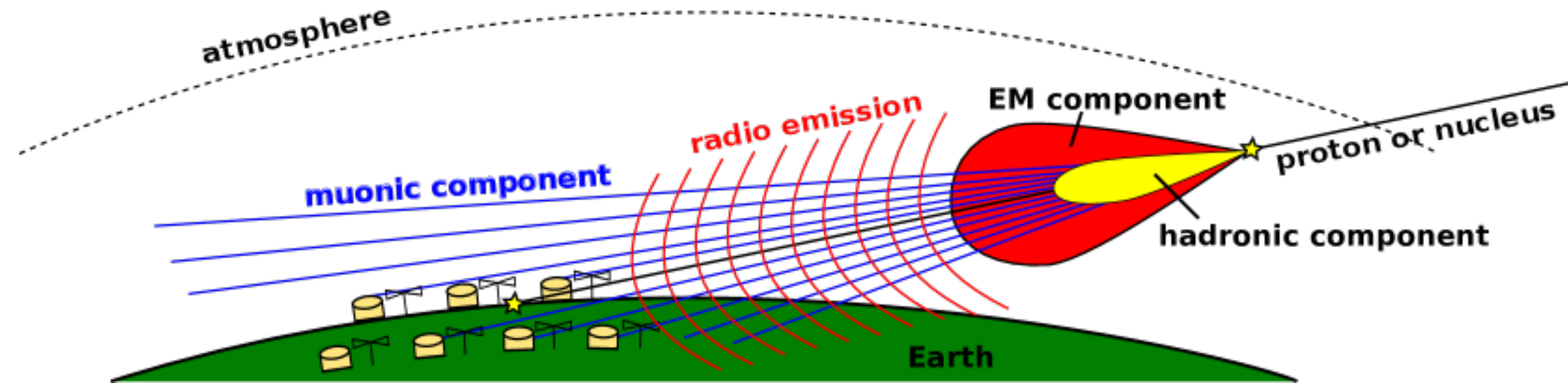
read-out electronics

e/γ

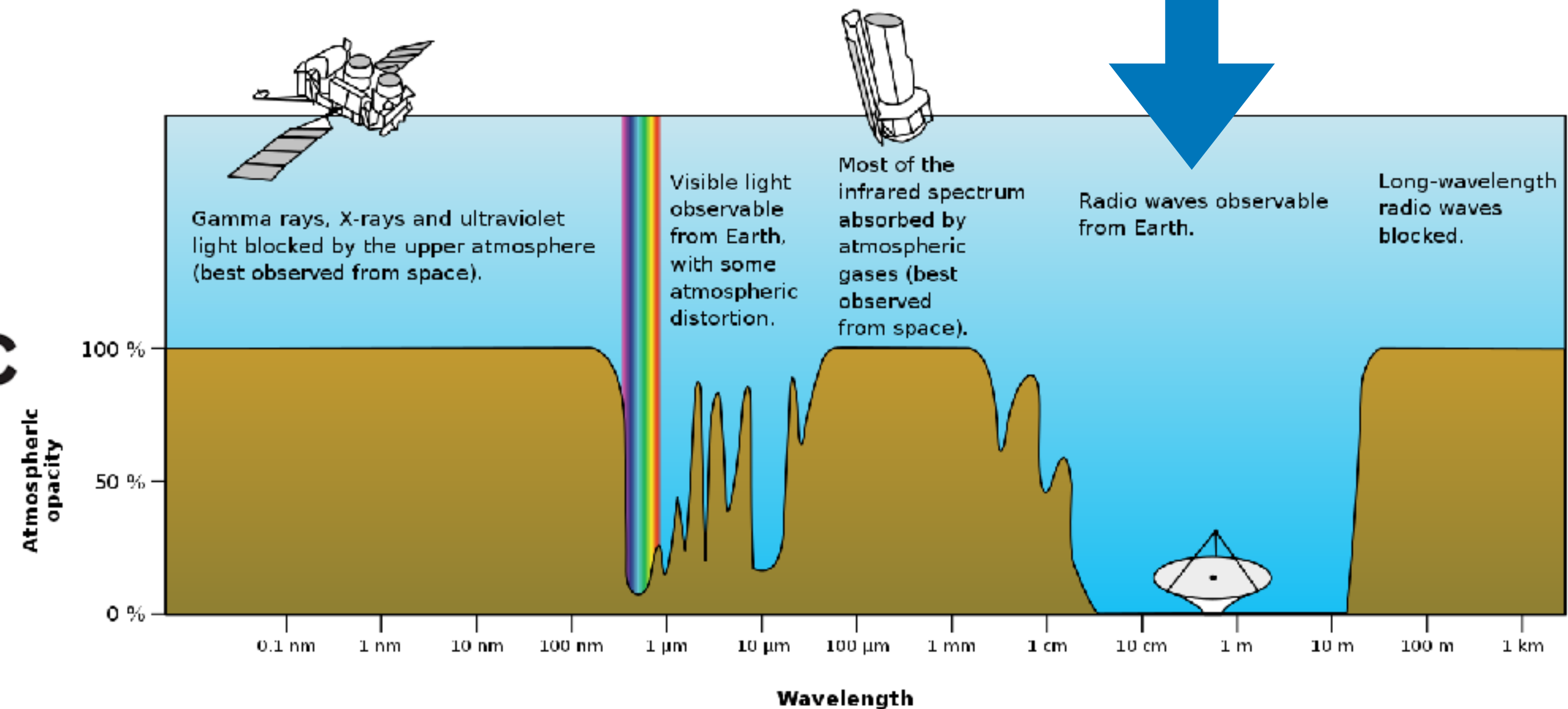
μ

μ

water-Cherenkov detector
120 MHz sampling

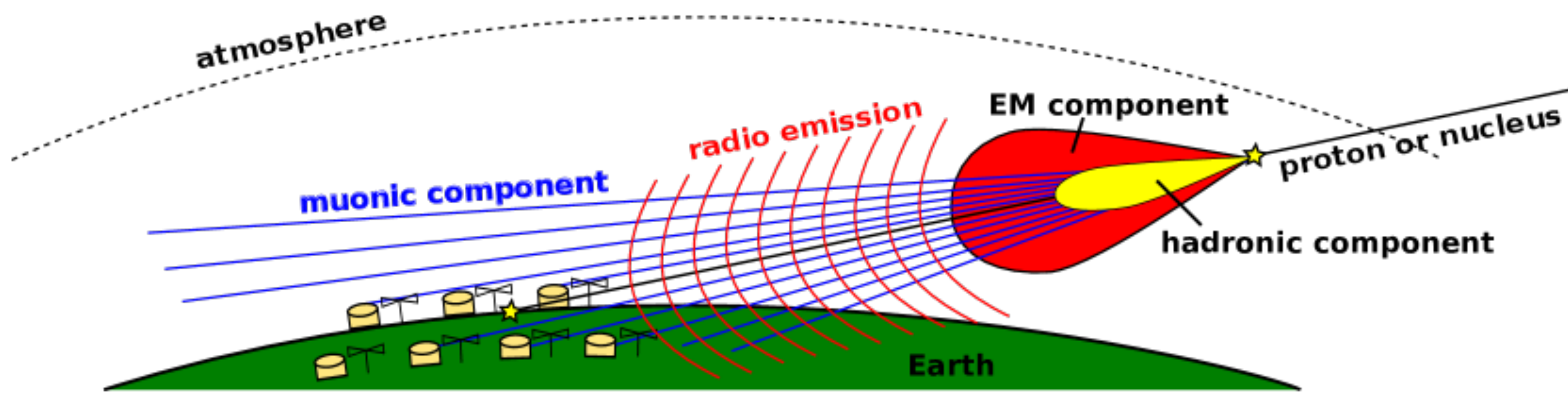
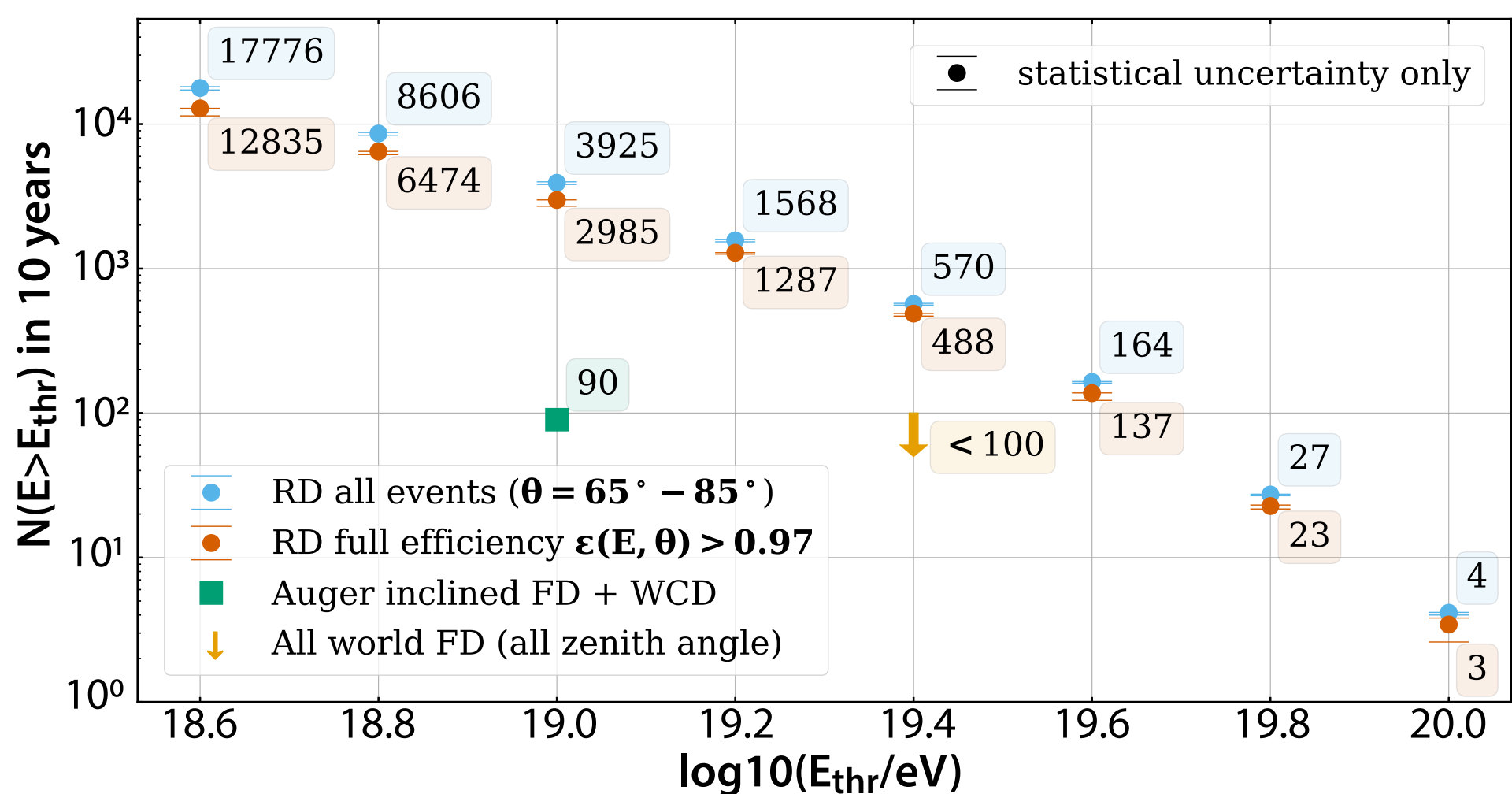


atmosphere of Earth is transparent in
30-80 MHz band



Radio Detector of the Pierre Auger Observatory

integrated # of cosmic rays



atmosphere of Earth is transparent in 30-80 MHz band

mass separation

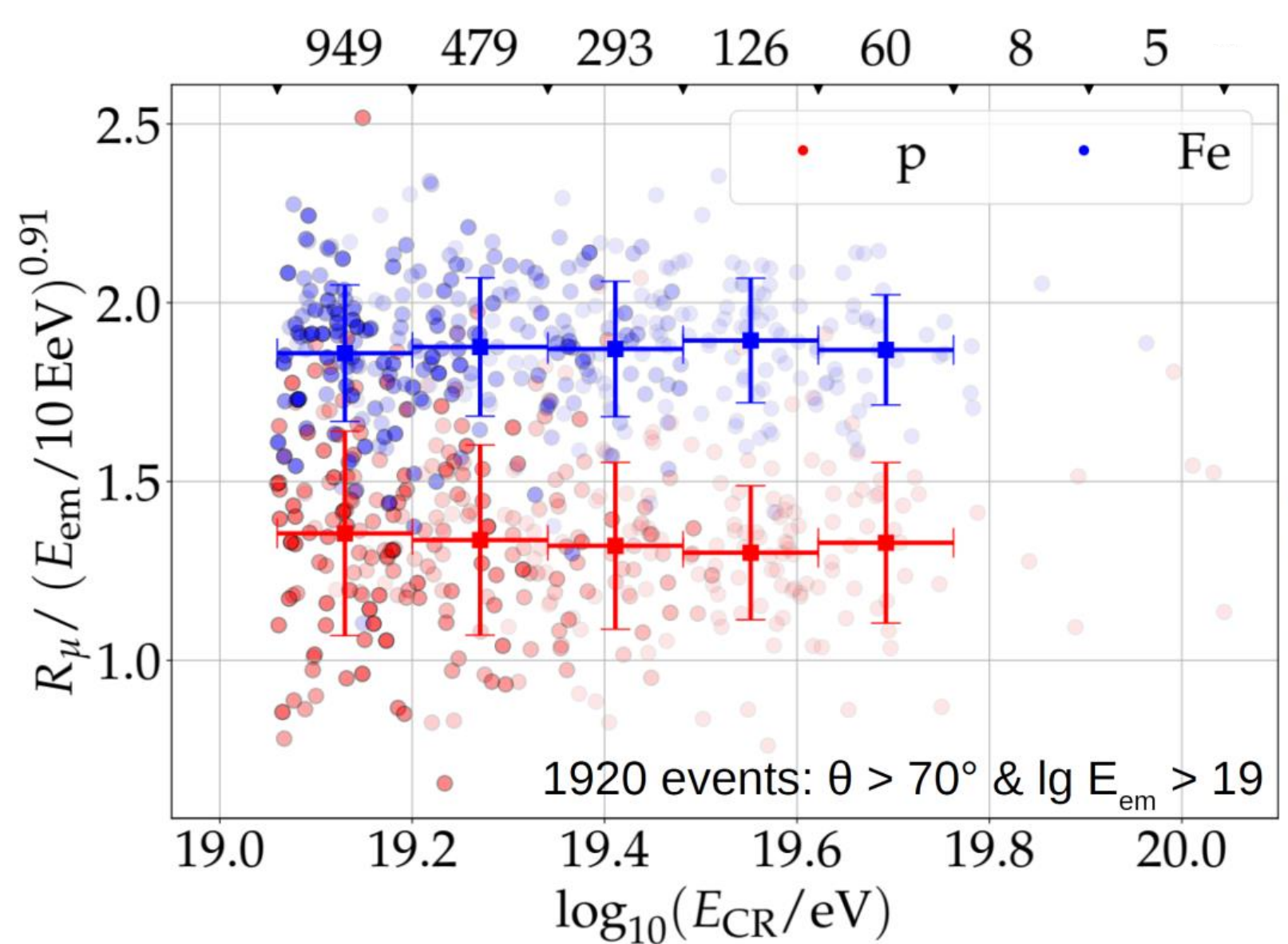


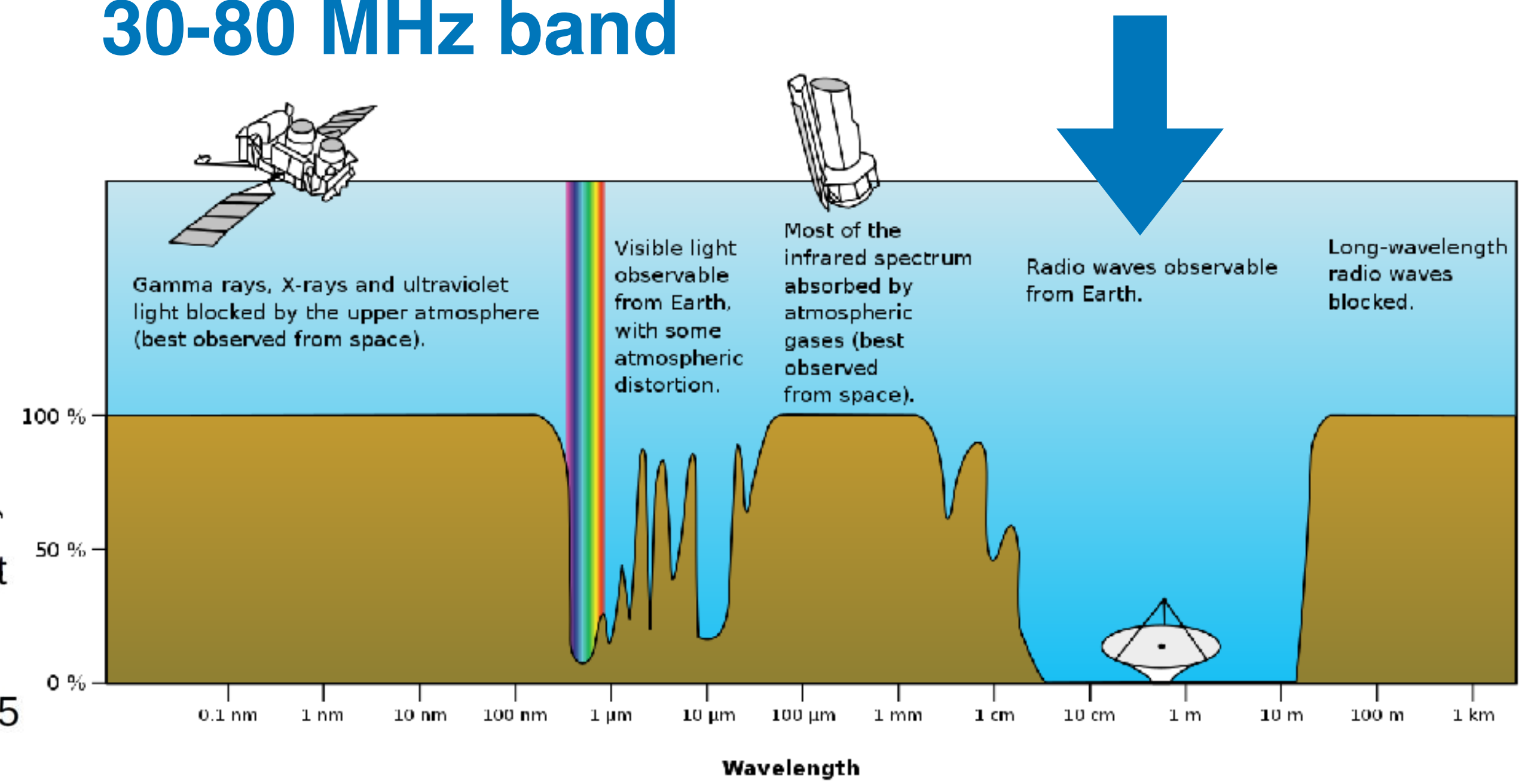
Figure of Merit:

$$\text{FOM} = \frac{|\langle r_p \rangle - \langle r_{Fe} \rangle|}{\sqrt{\sigma_{r_p}^2 + \sigma_{r_{Fe}}^2}}$$

$$\text{FOM} = 1.61 \pm 0.04$$

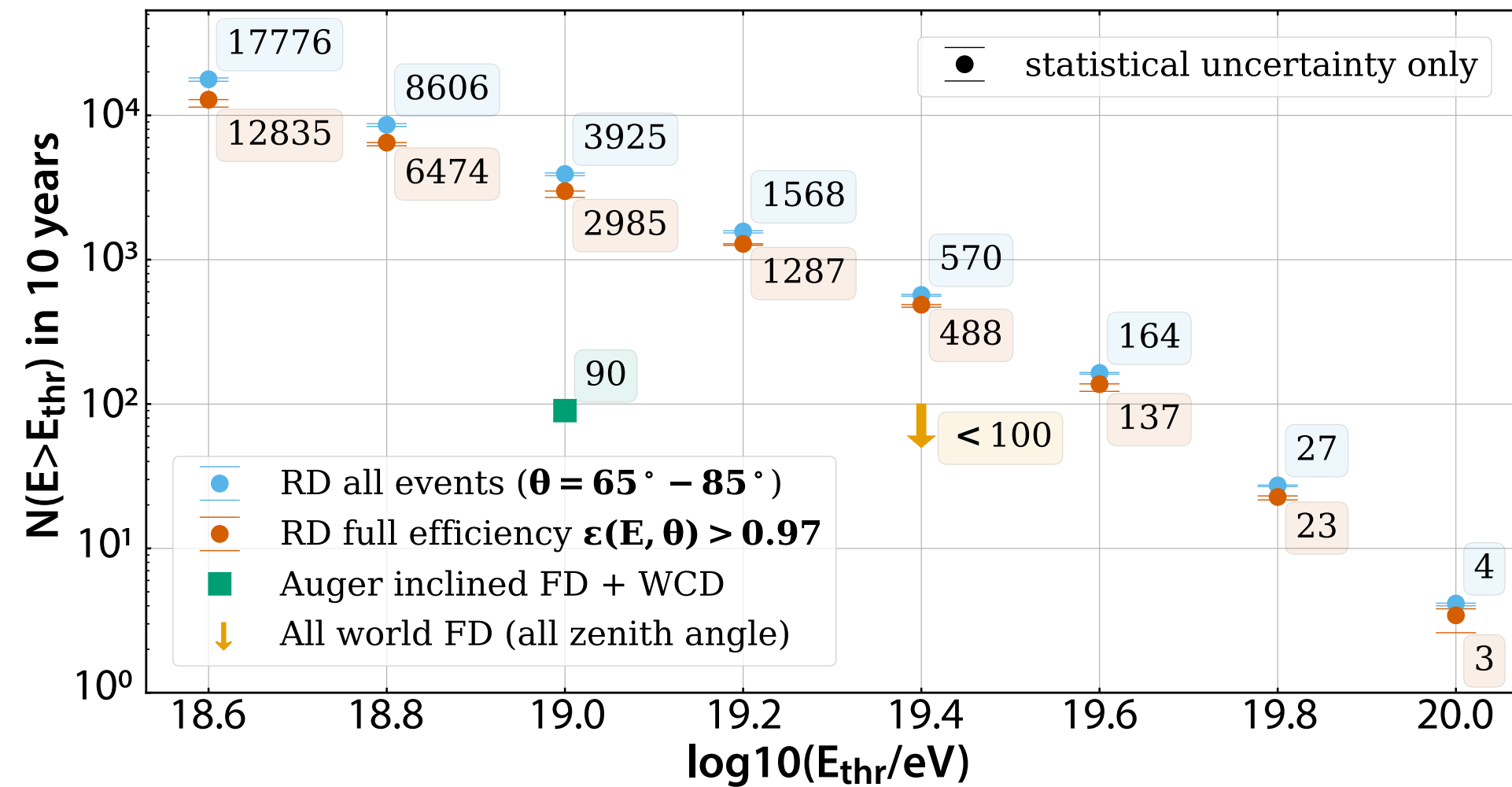
Equal to $X_{\max}$ with perfect resolution!

Goal for the Upgrade: 1.5

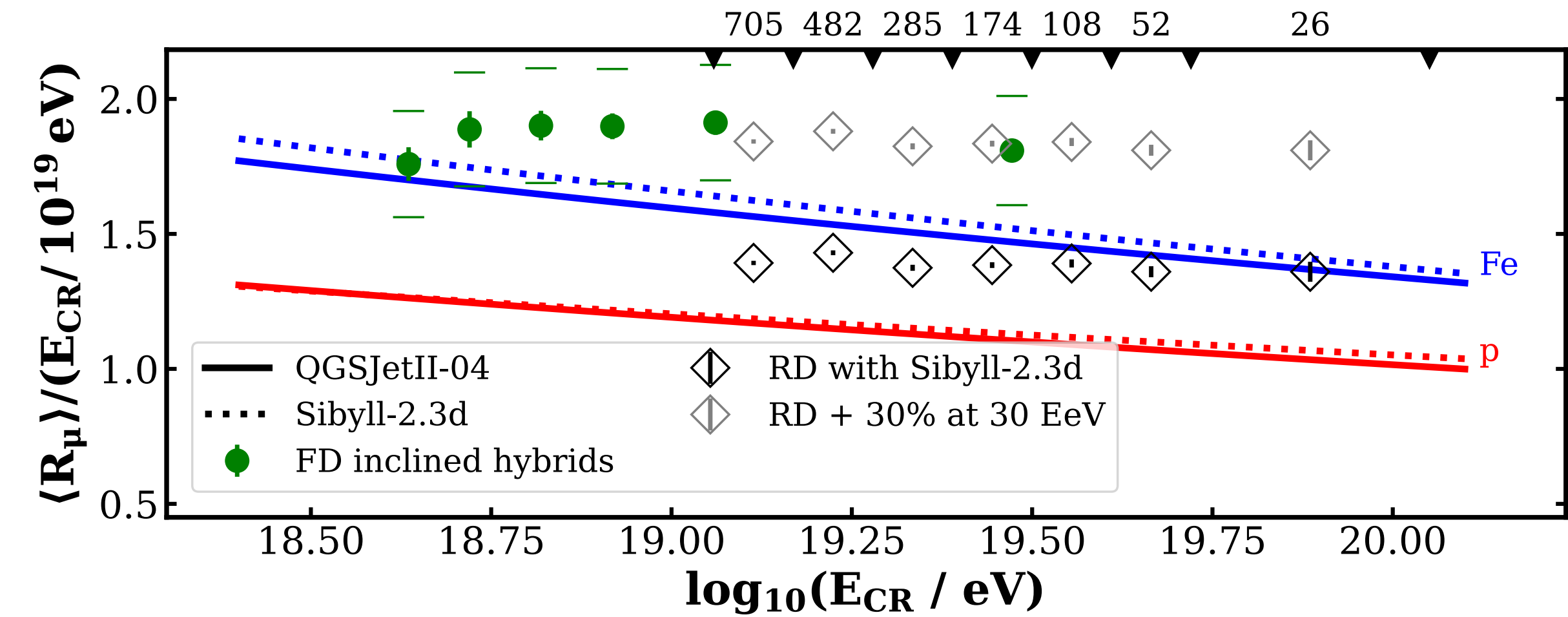


Radio Detector of the Pierre Auger Observatory

integrated # of cosmic rays



measurement quality combining RD & WCD



mass separation

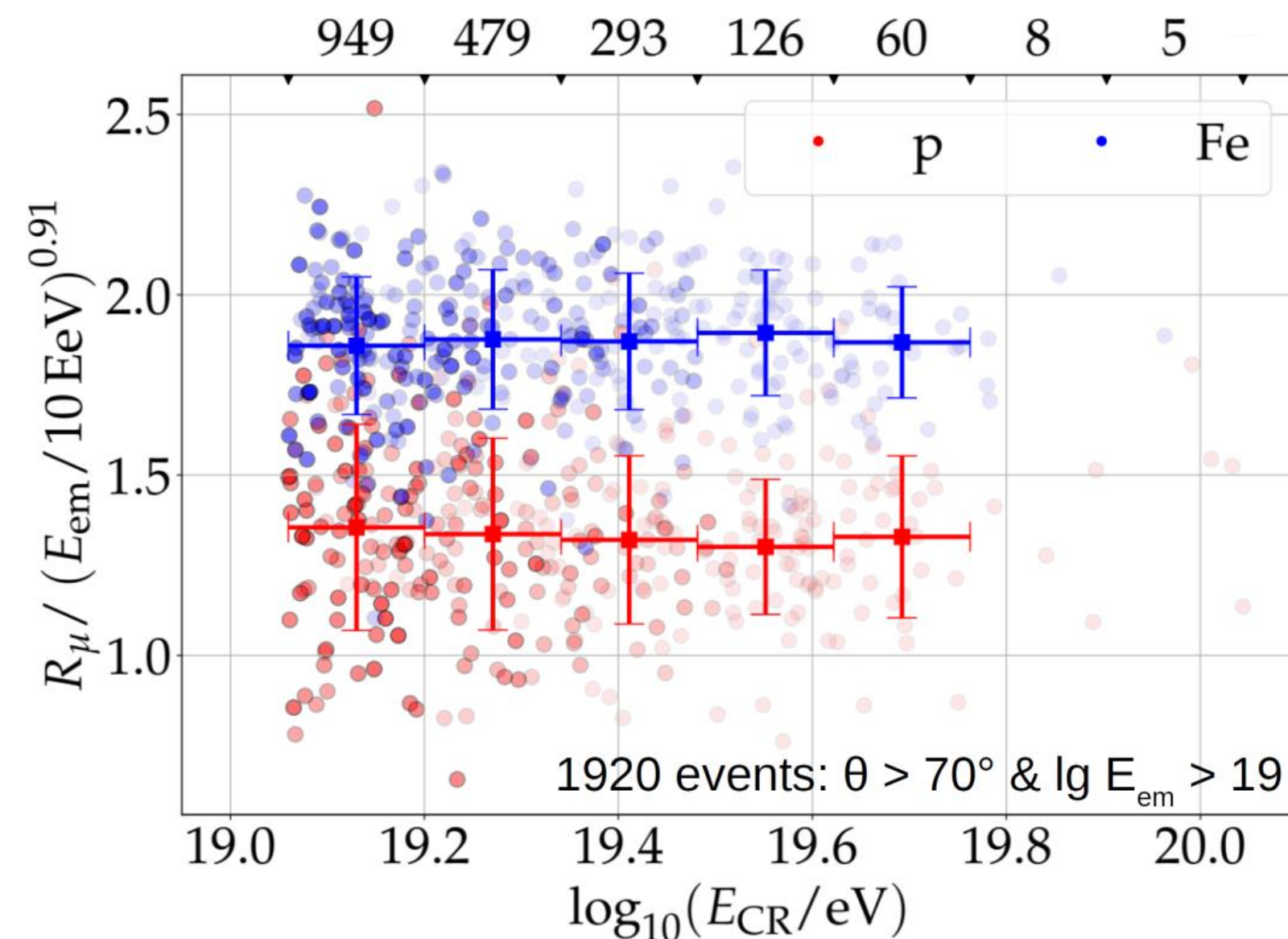


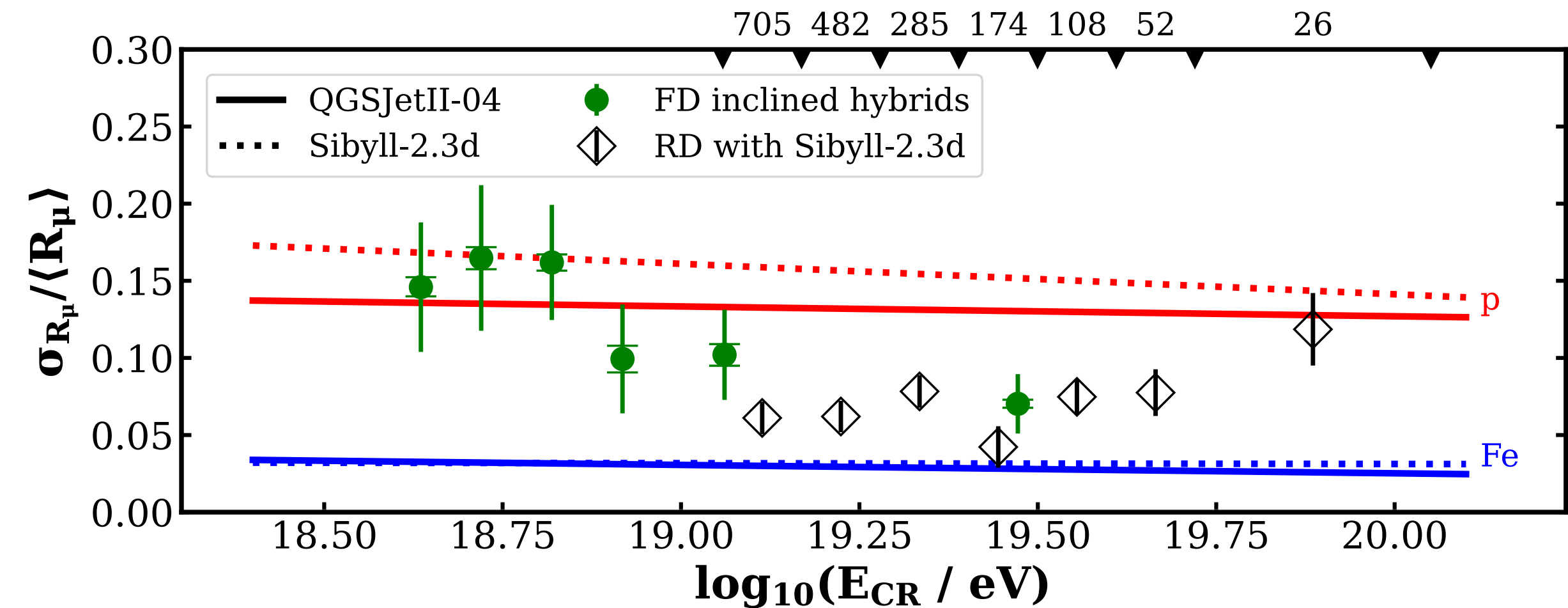
Figure of Merit:

$$\text{FOM} = \frac{|\langle r_p \rangle - \langle r_{Fe} \rangle|}{\sqrt{\sigma_{r_p}^2 + \sigma_{r_{Fe}}^2}}$$

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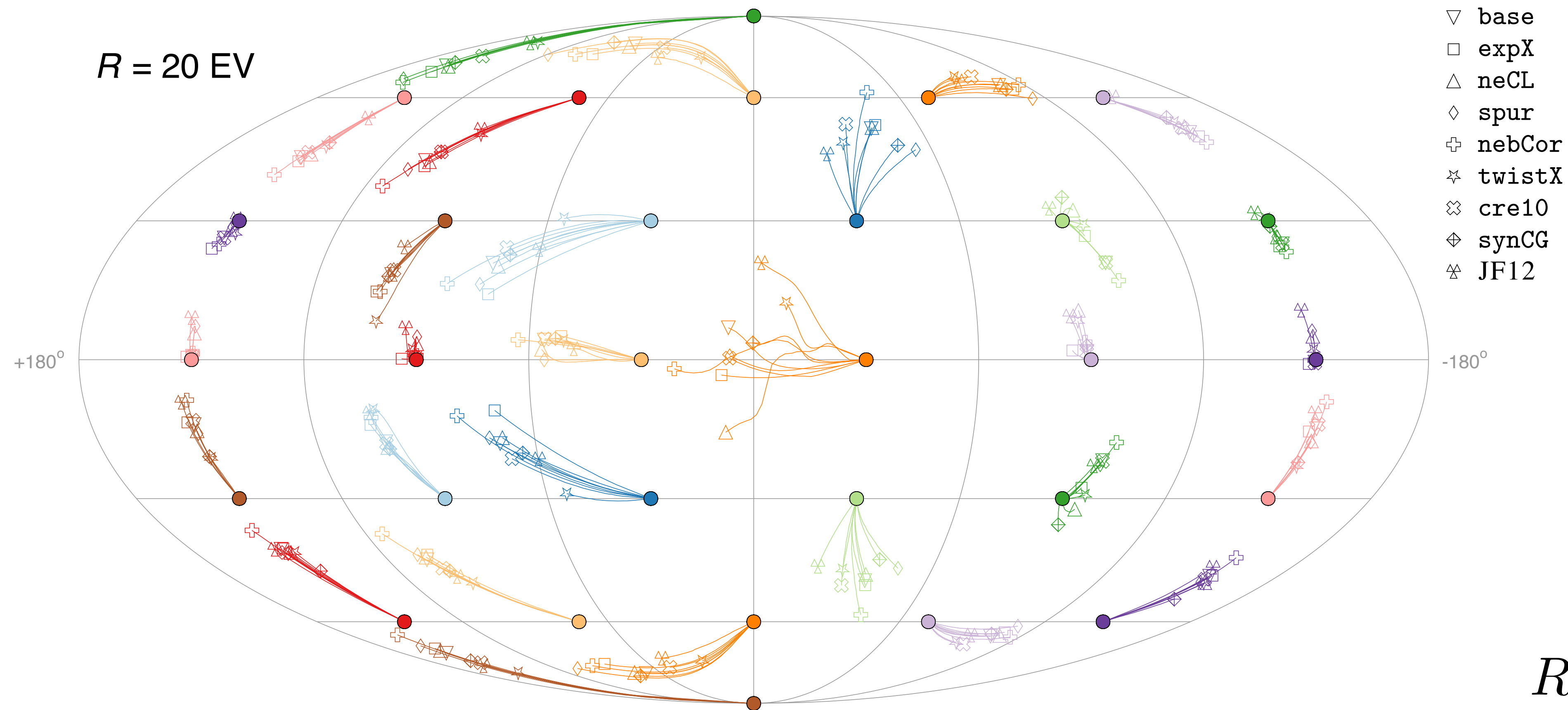
Equal to $X_{\max}$ with perfect resolution!

Goal for the Upgrade: 1.5



T. Huege et al, EPJ Web of Conf. 283 (2023) 06002

Deflection of cosmic rays in magnetic fields



$$R = \frac{E}{Z} \approx \frac{E}{A/2}$$

Figure 19. Angular deflections of ultrahigh-energy cosmic rays in the eight model variations derived in this paper and JF12. The cosmic-ray rigidity is 20 EV (2×10^{19} V). Filled circles denote a grid of arrival directions and the open symbols are the back-tracked directions at the edge of the Galaxy.

The Coherent Magnetic Field of the Milky Way

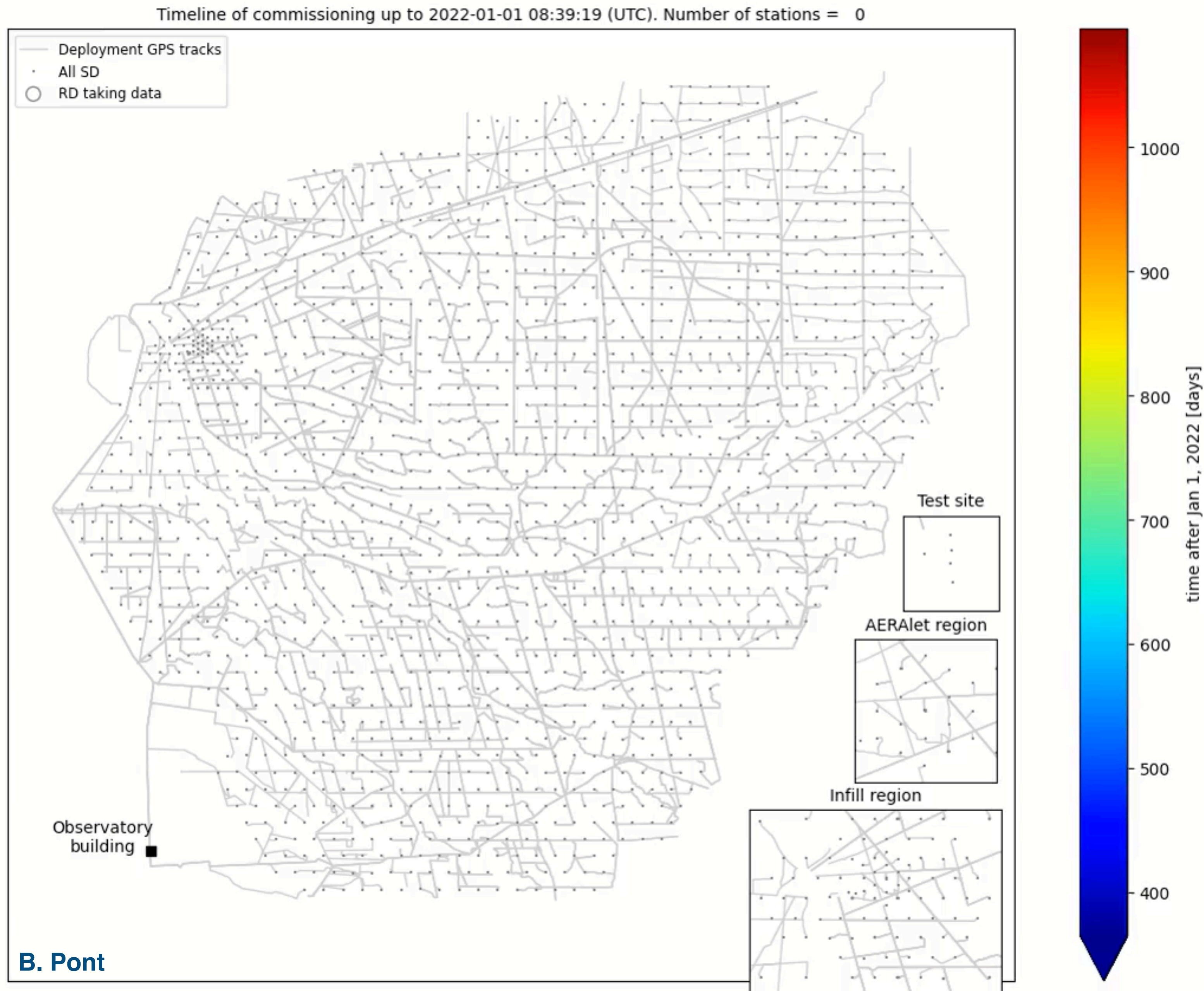
MICHAEL UNGER ^{1,2} AND GLENNYS R. FARRAR ³

**need to know rigidity (mass)
of incoming cosmic rays**

Radio Detector of the Pierre Auger Observatory



Radio Detector of the Pierre Auger Observatory



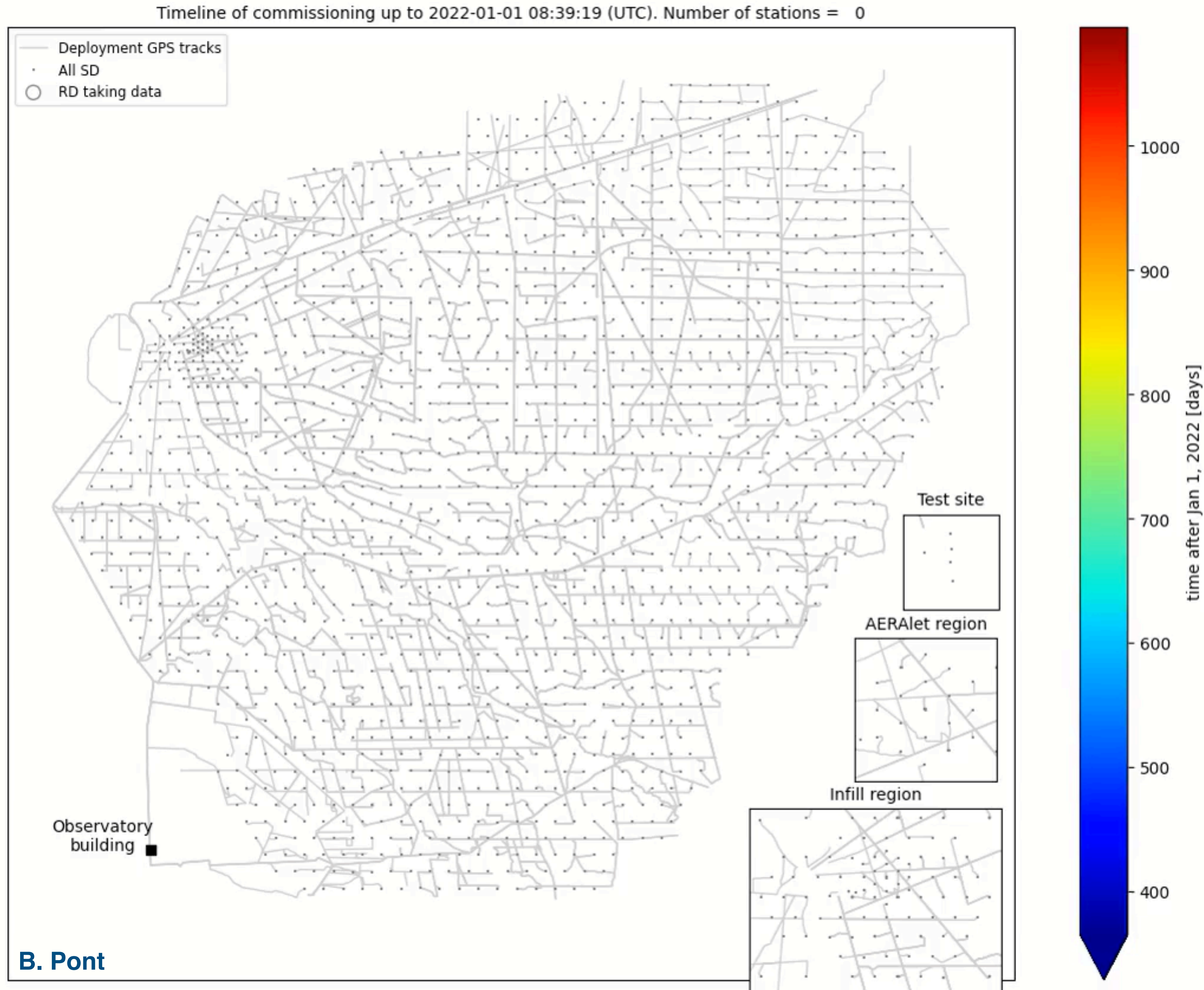
construction 2022 - 2024

followed by commissioning

**Radio Detector handed
over to Observatory
end of 2025**

**routinely measuring
cosmic rays until >2035**

Radio Detector of the Pierre Auger Observatory



B. Pont

construction 2022 - 2024

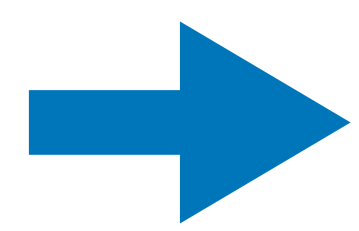
followed by commissioning

**Radio Detector handed
over to Observatory
end of 2025**

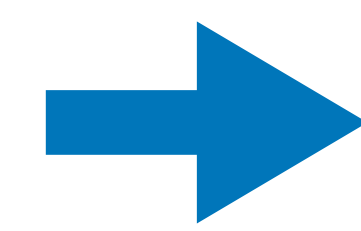
**routinely measuring
cosmic rays until >2035**

RD calibration concept

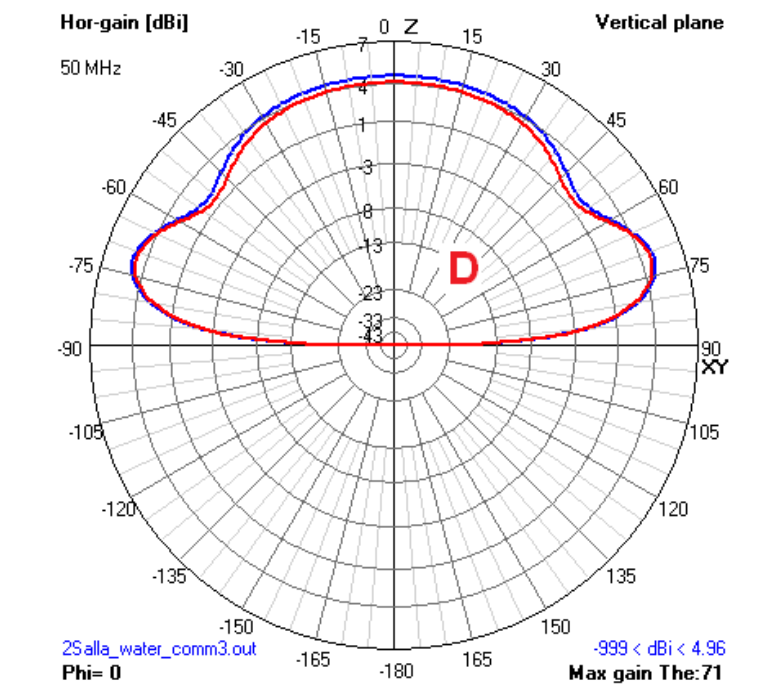
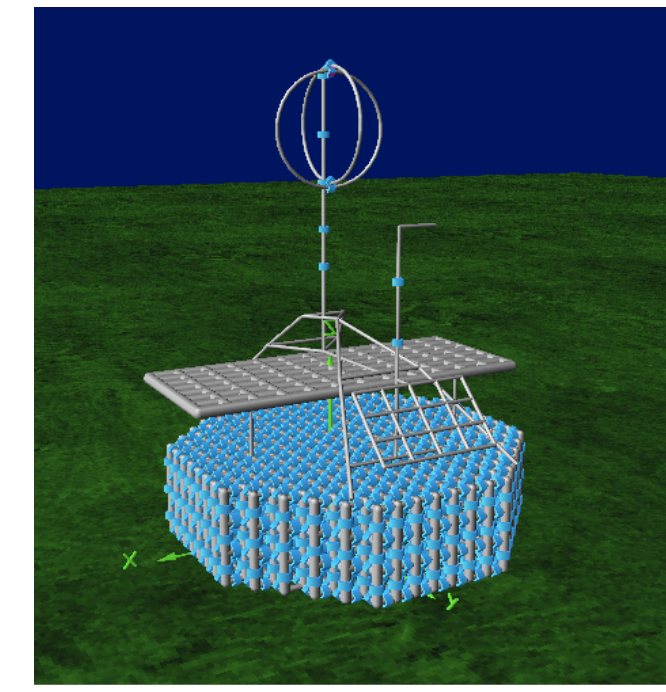
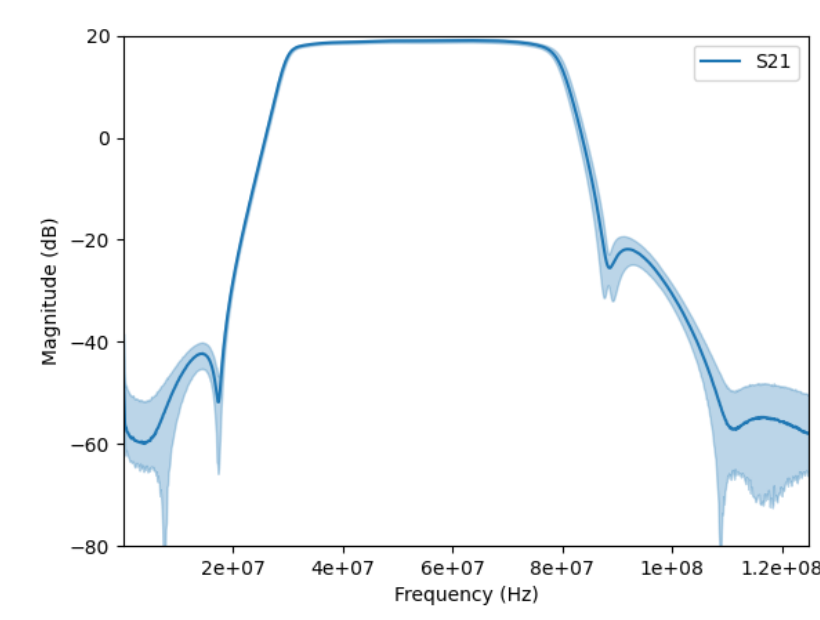
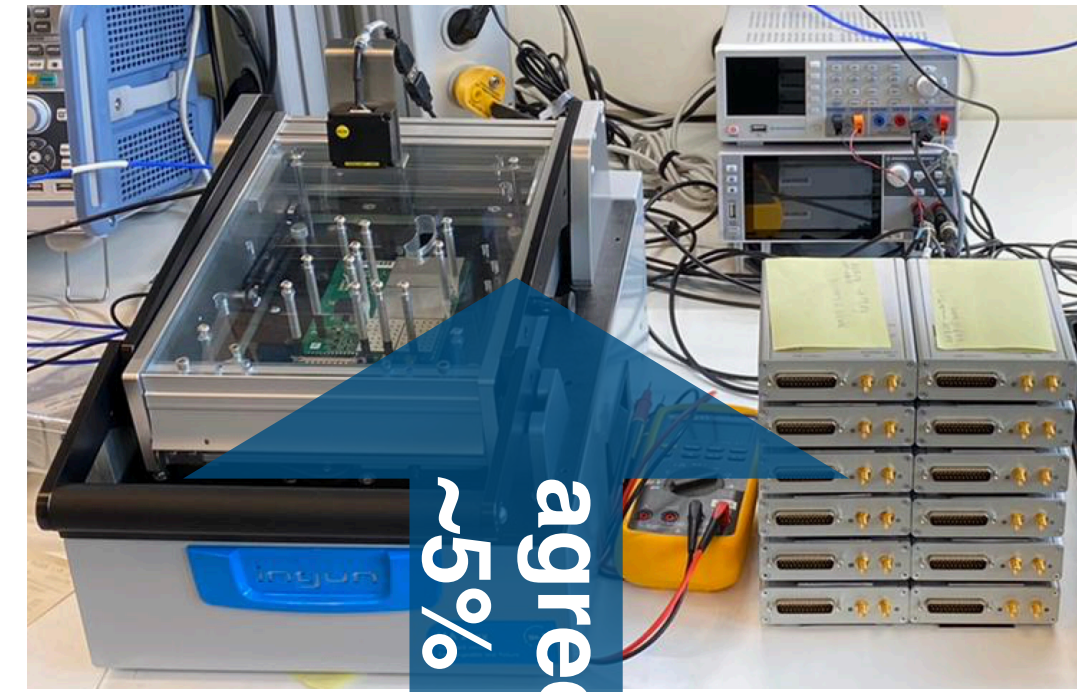
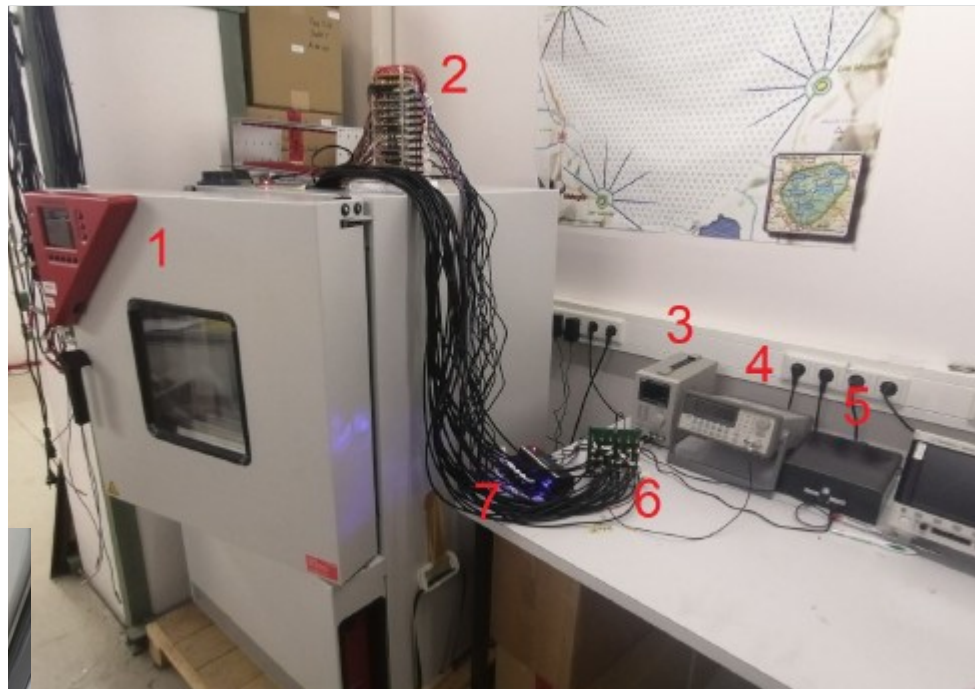
thermal cycling (aging)
LNA & digitizer



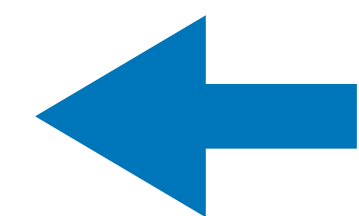
end-to-end calibration in lab
LNA & digitizer



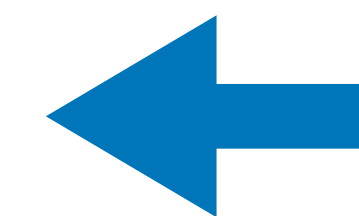
simulation of antenna pattern
NEC



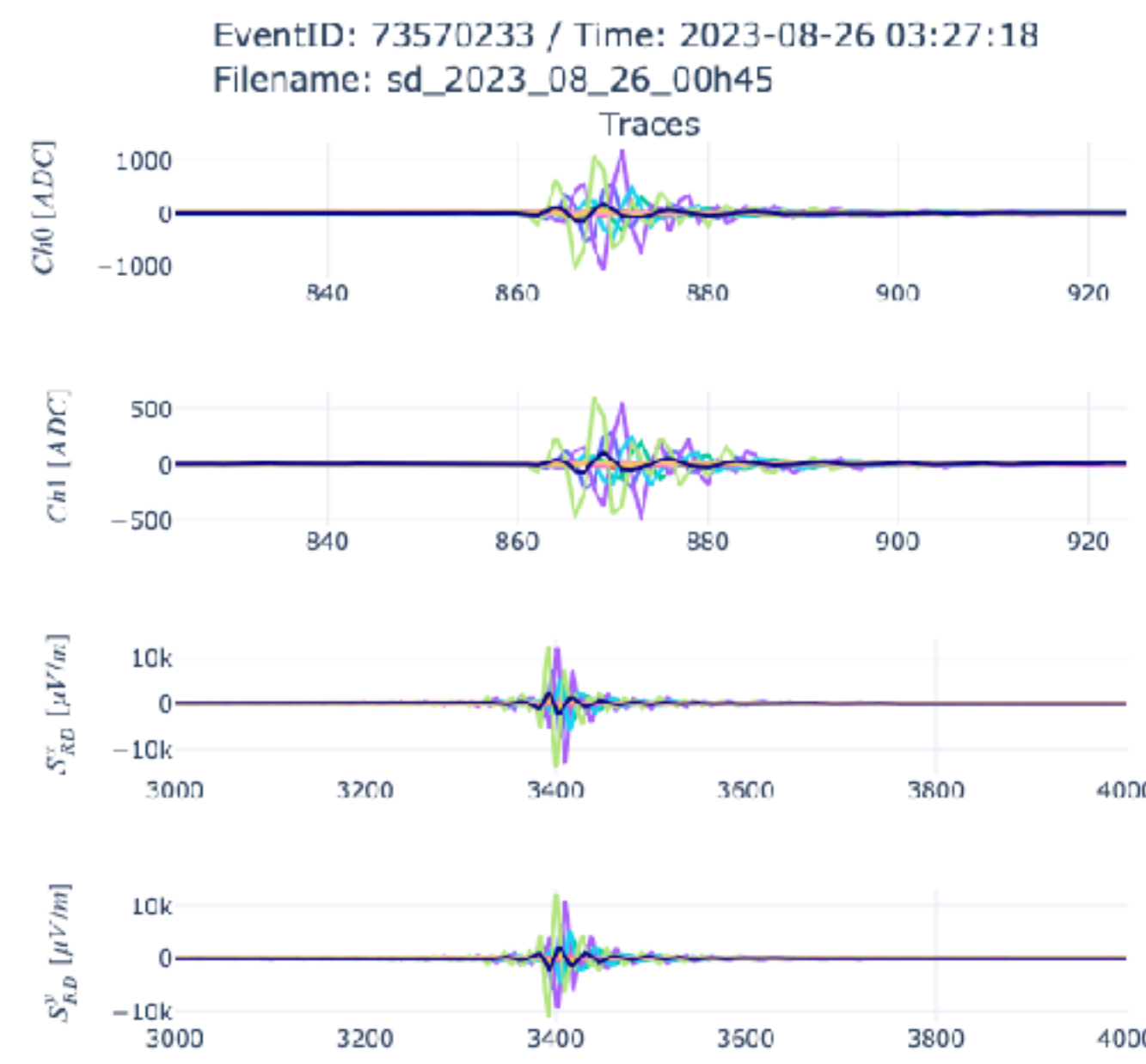
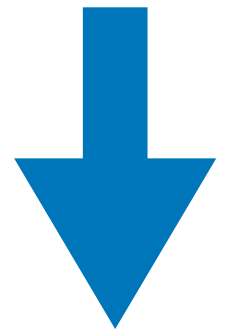
absolutely calibrated signals



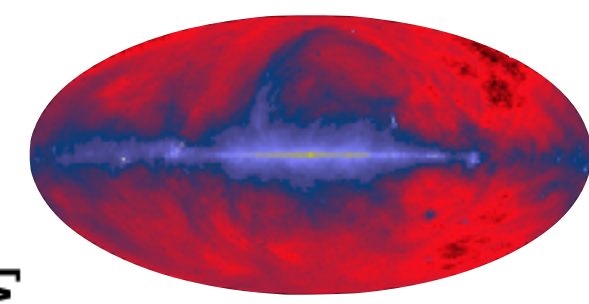
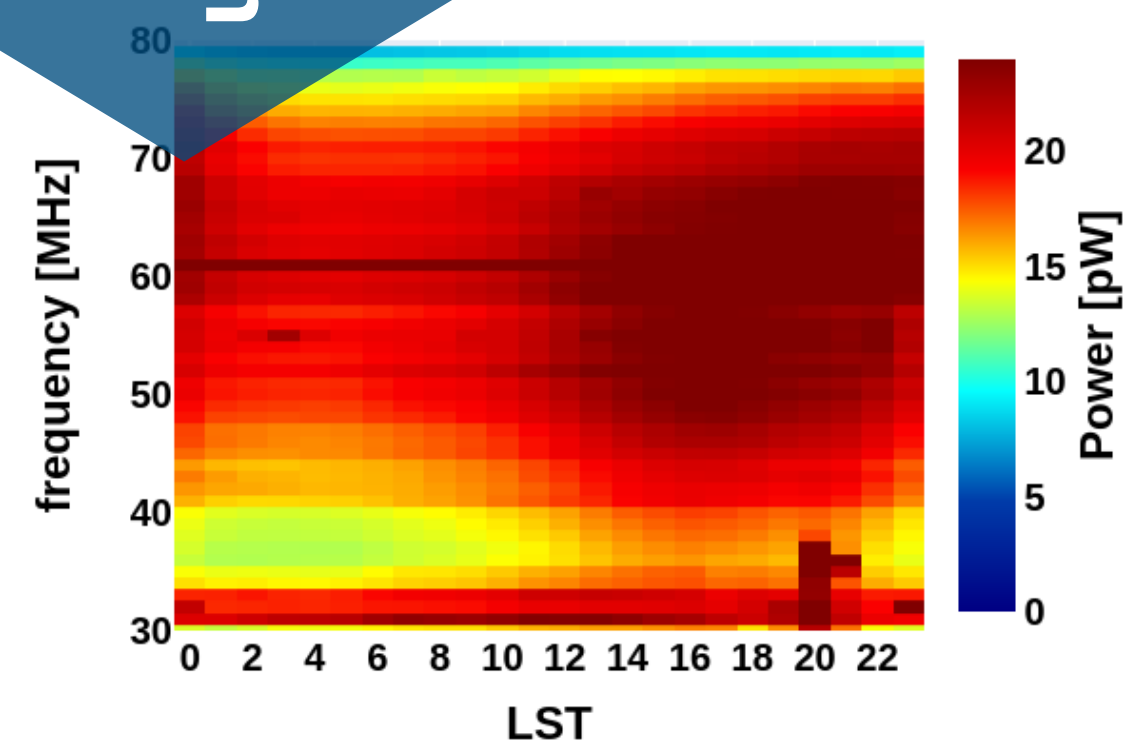
Galactic emission



in-situ calibration with
reference antenna

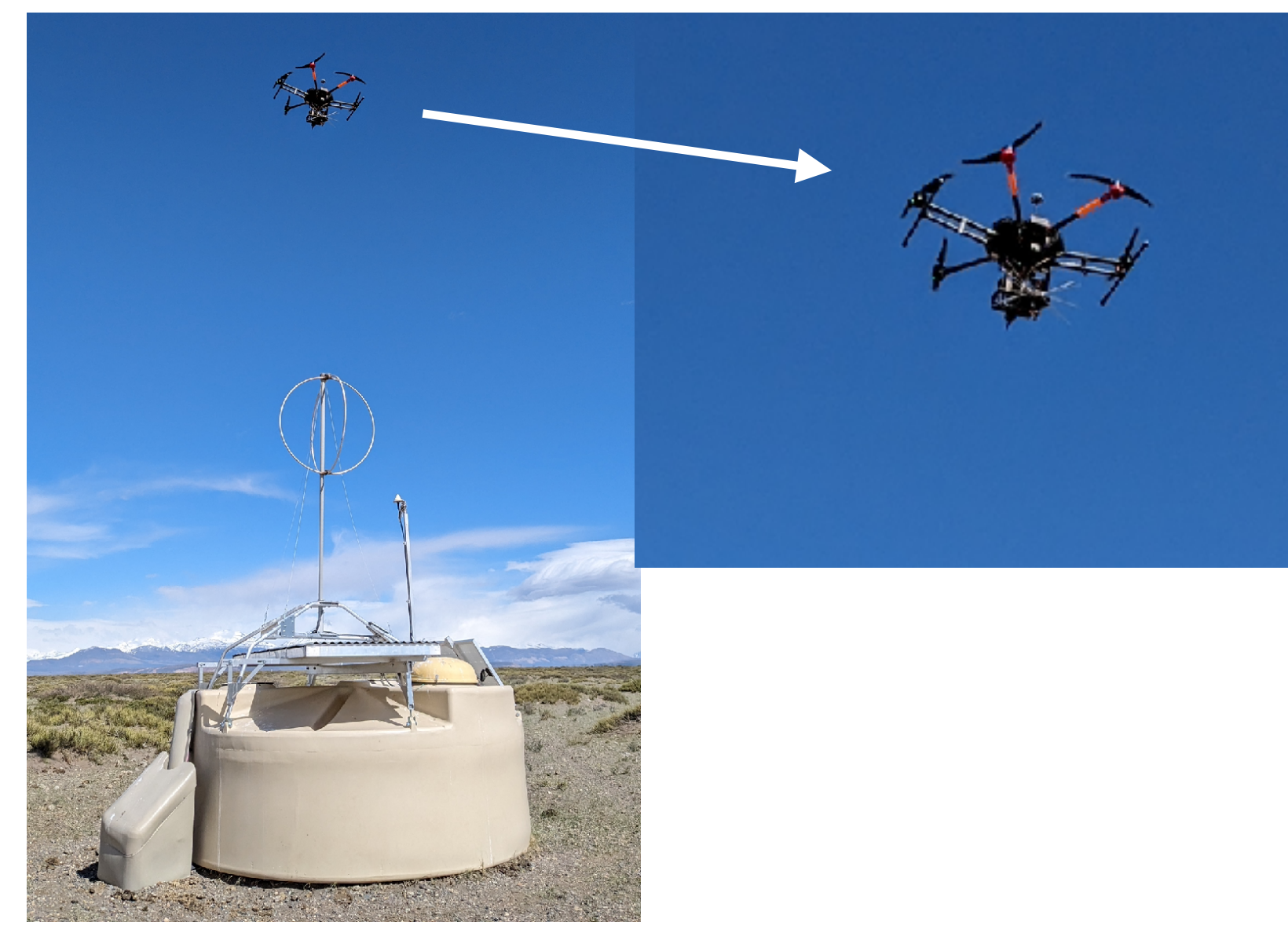
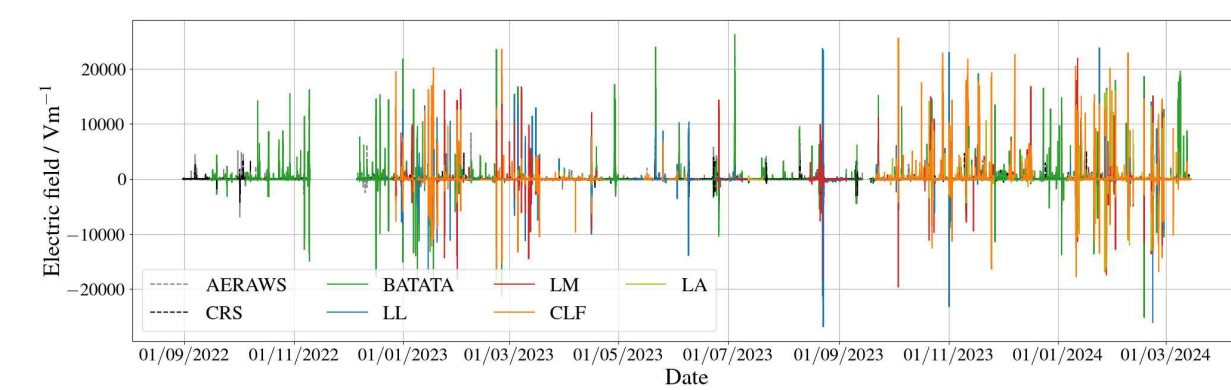


Measured power dataset:

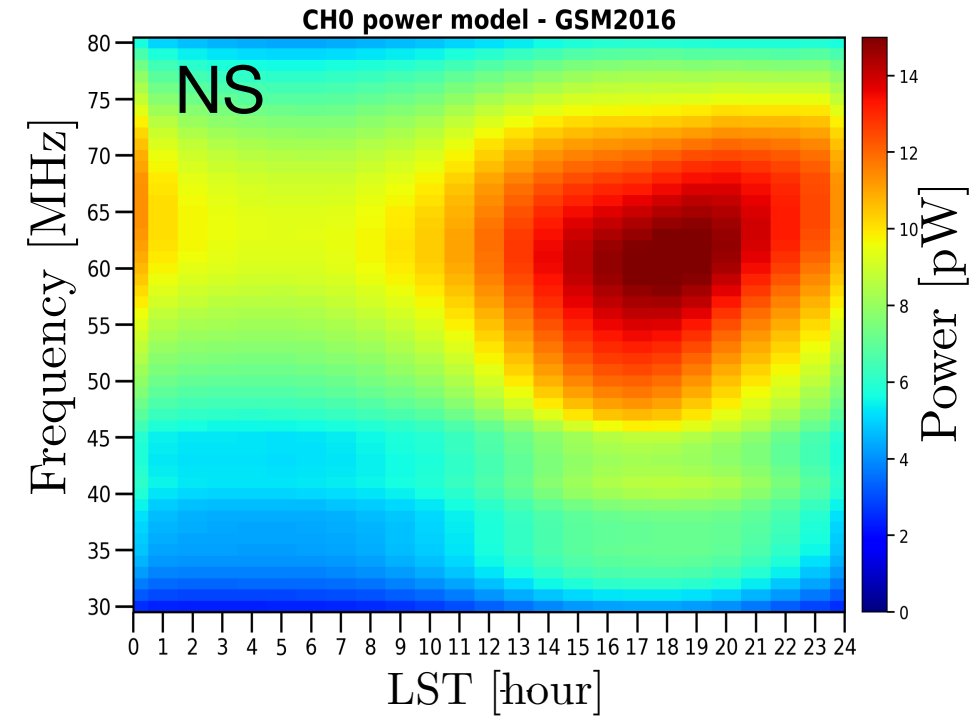


the „muon
peak“ for
radio

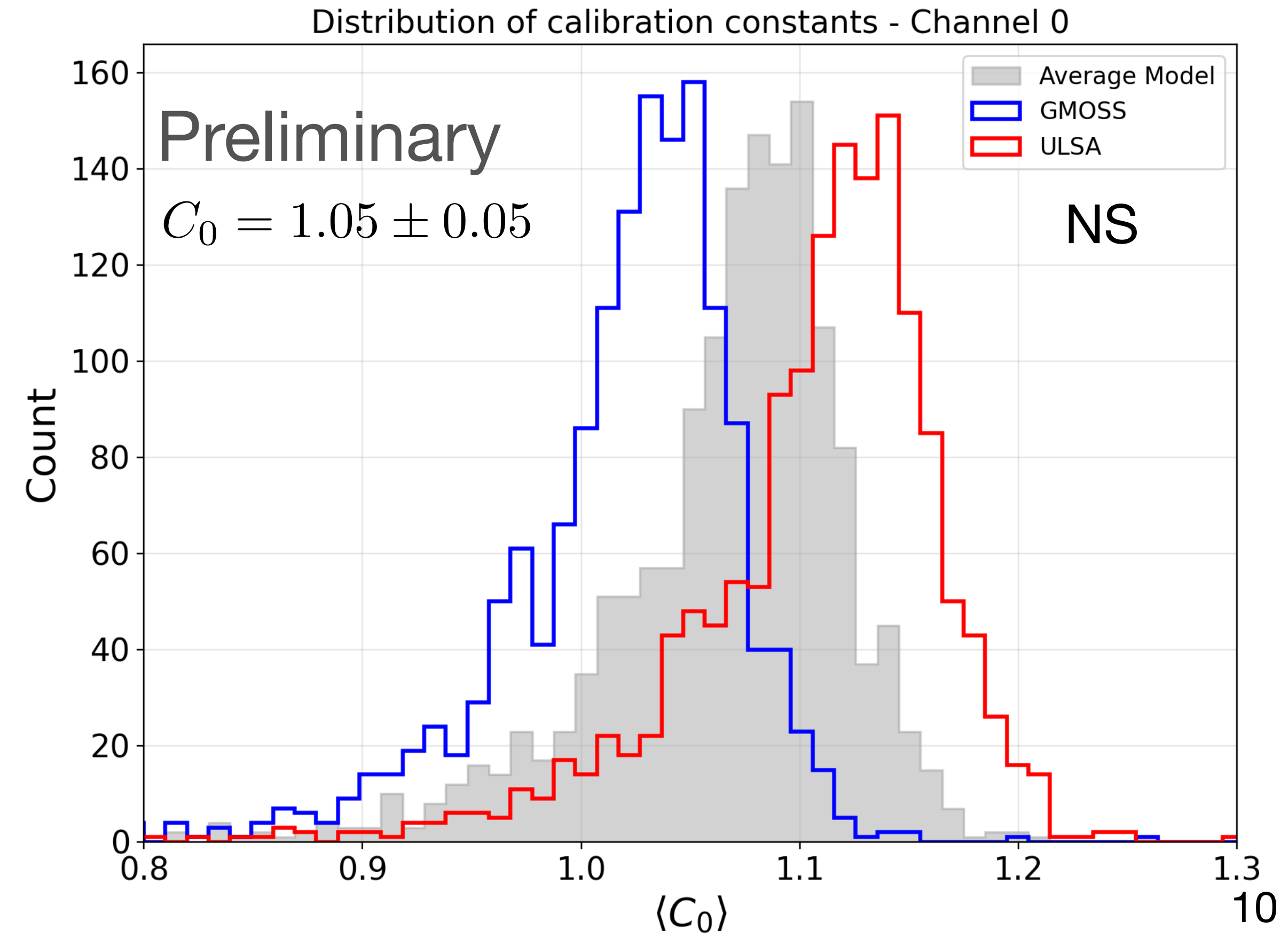
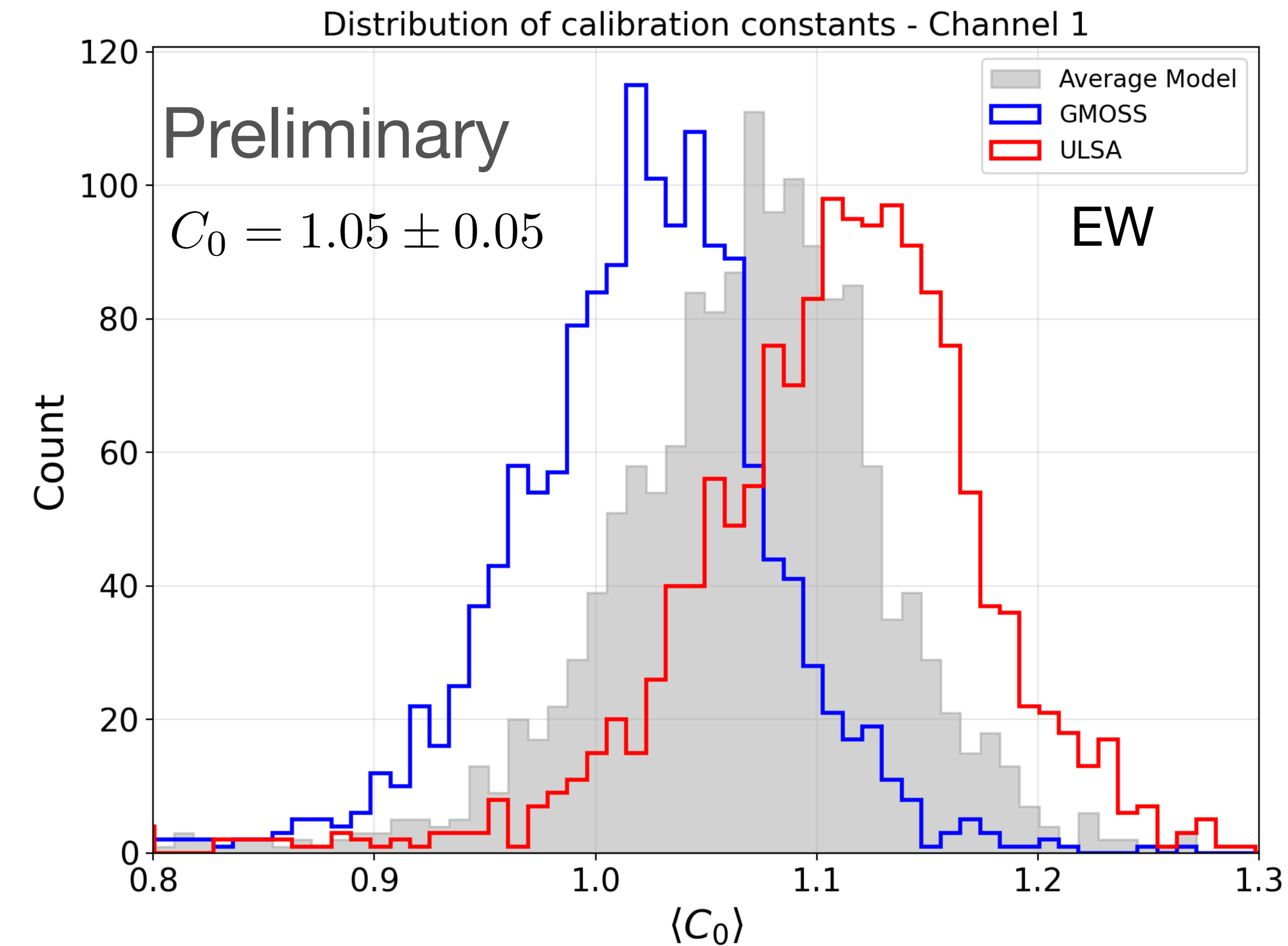
atmospheric electric field



Absolute calibration with galactic emission



- average of different models of Galactic emission
- systematic uncertainty $\sim 5\%$
- excellent agreement with lab calibration

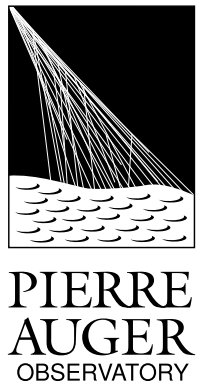


RECEIVED: November 25, 2025

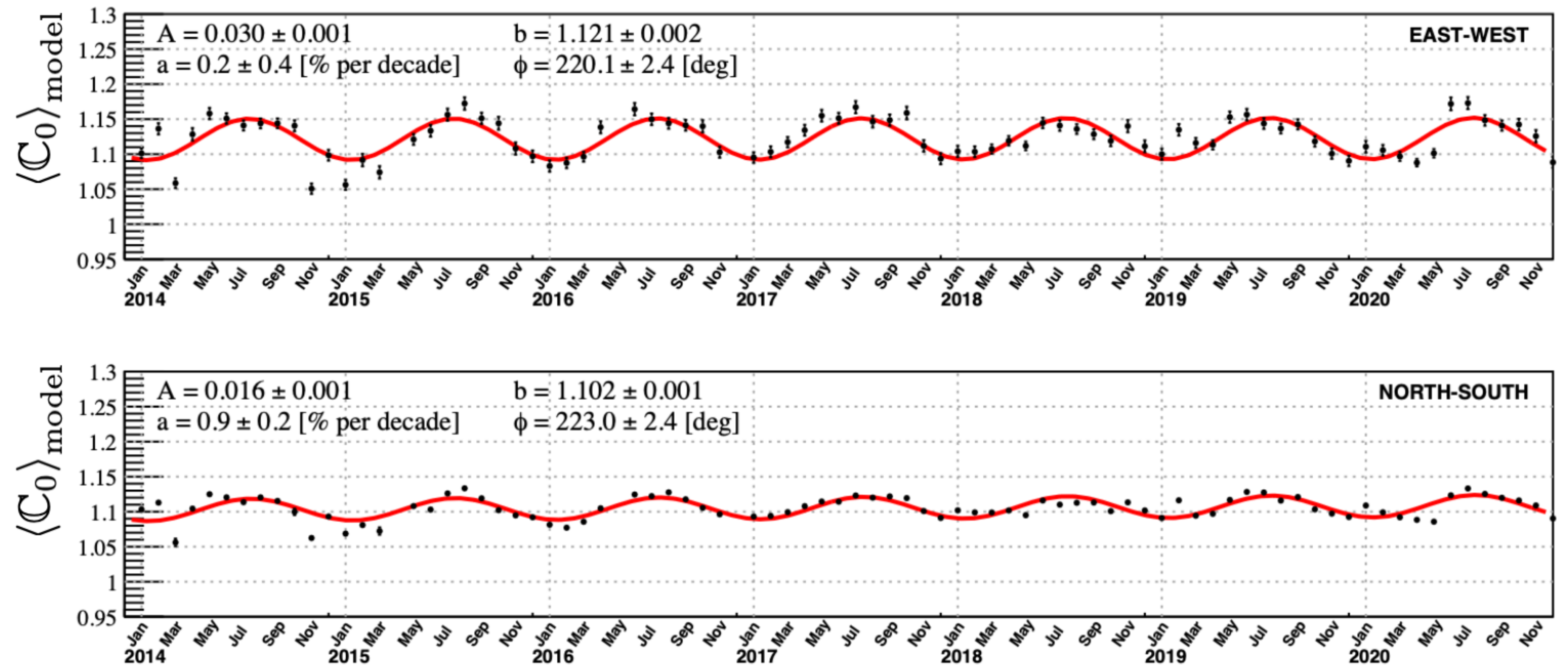
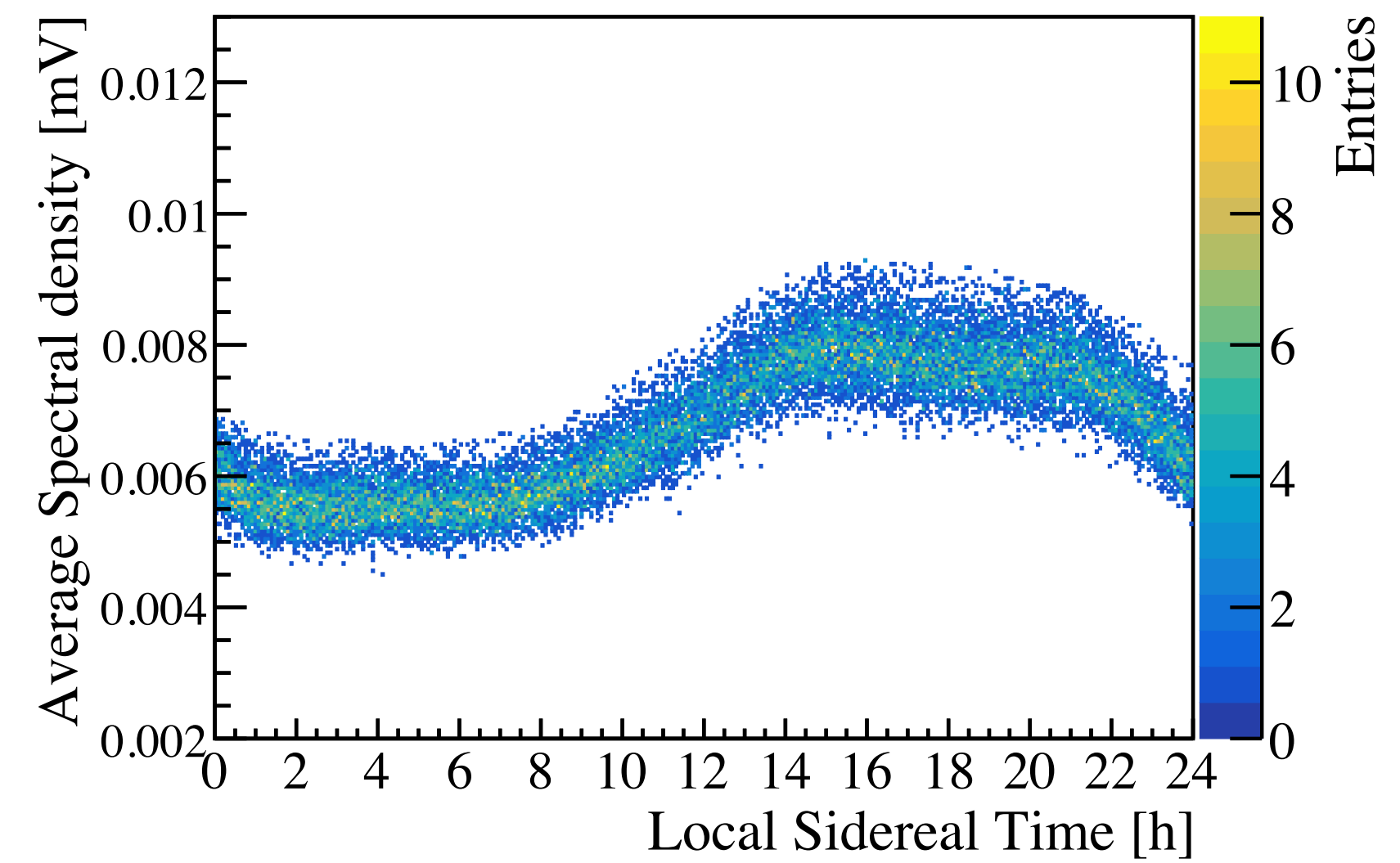
ACCEPTED: December 1, 2025

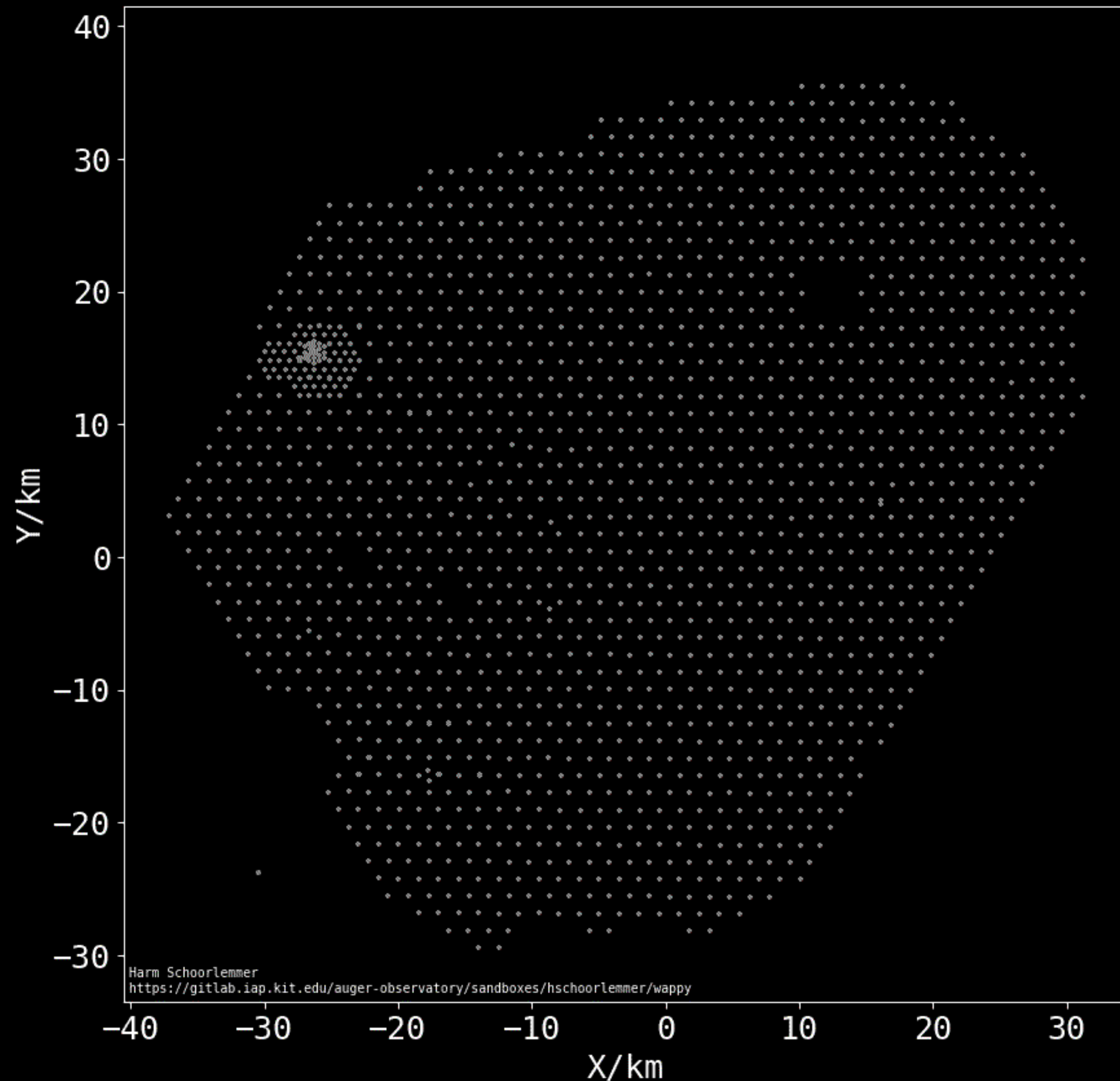
PUBLISHED: December 11, 2025

Long-term calibration and validation of stability of the Auger Engineering Radio Array using the diffuse Galactic radio emission



The Pierre Auger collaboration

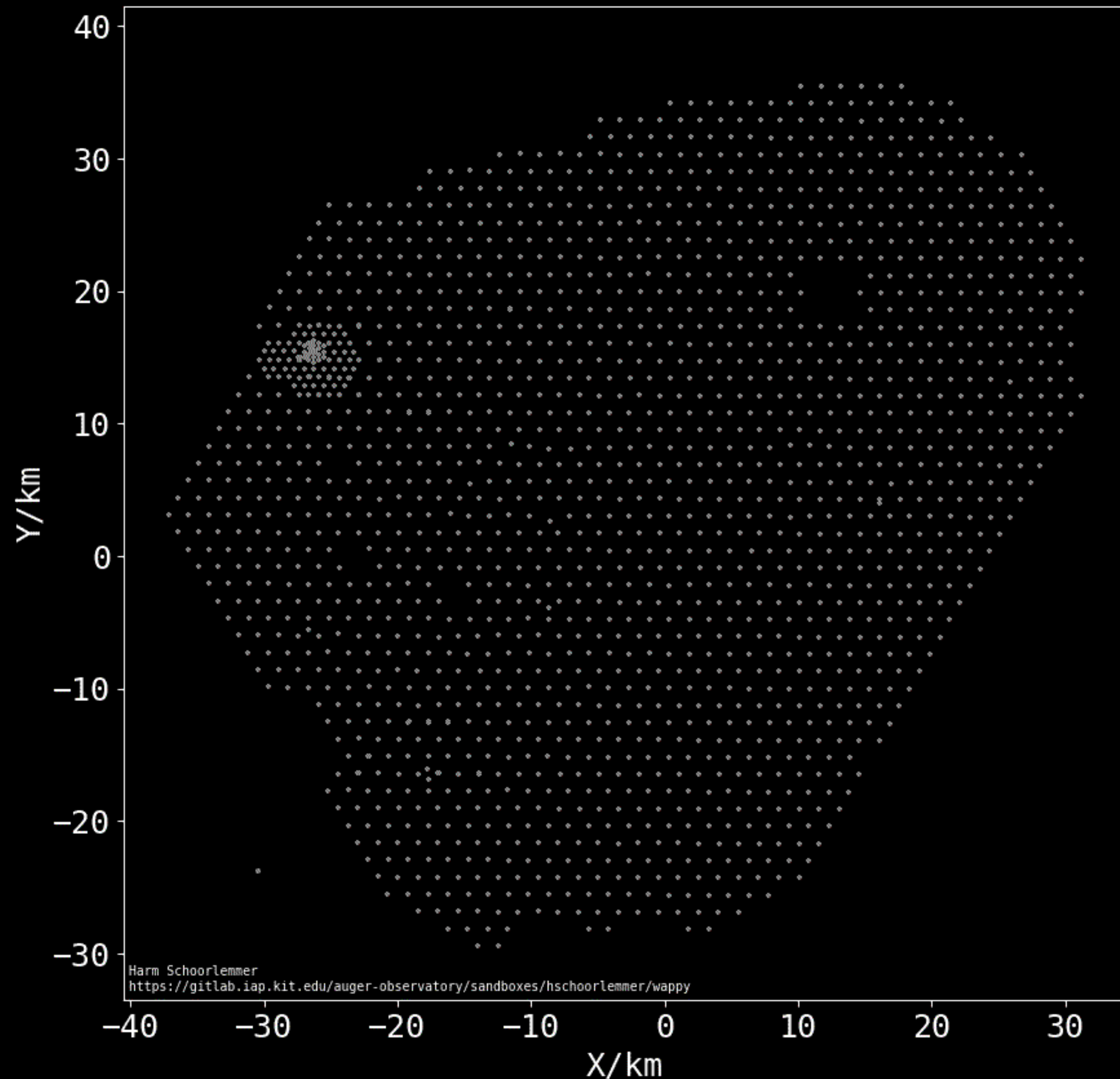




Air showers measured with the Radio Detector

air showers with more than 40 detection units above threshold

1.10.2024 - 30.9.2025

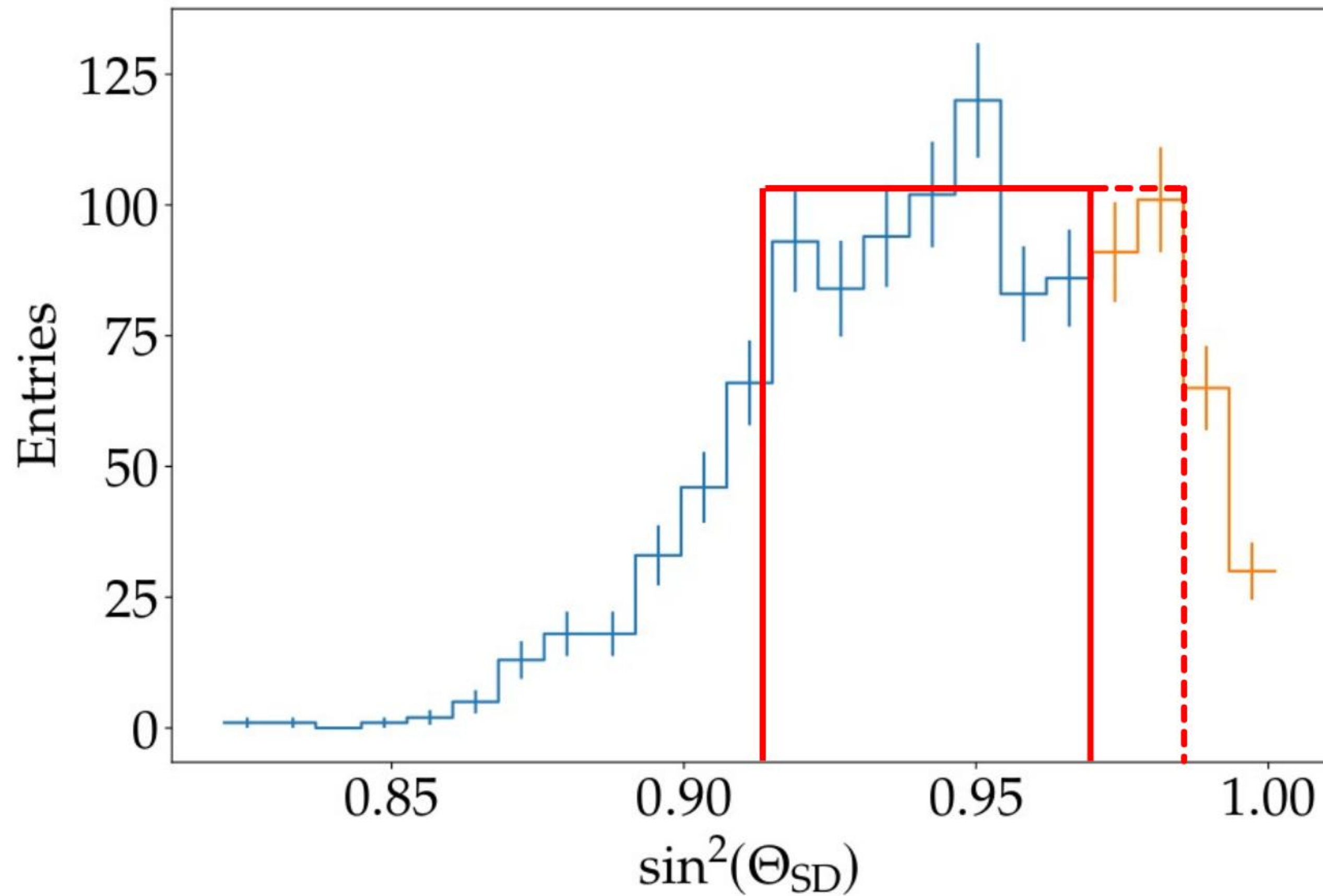


Air showers measured with the Radio Detector

air showers with more than 40 detection units above threshold

1.10.2024 - 30.9.2025

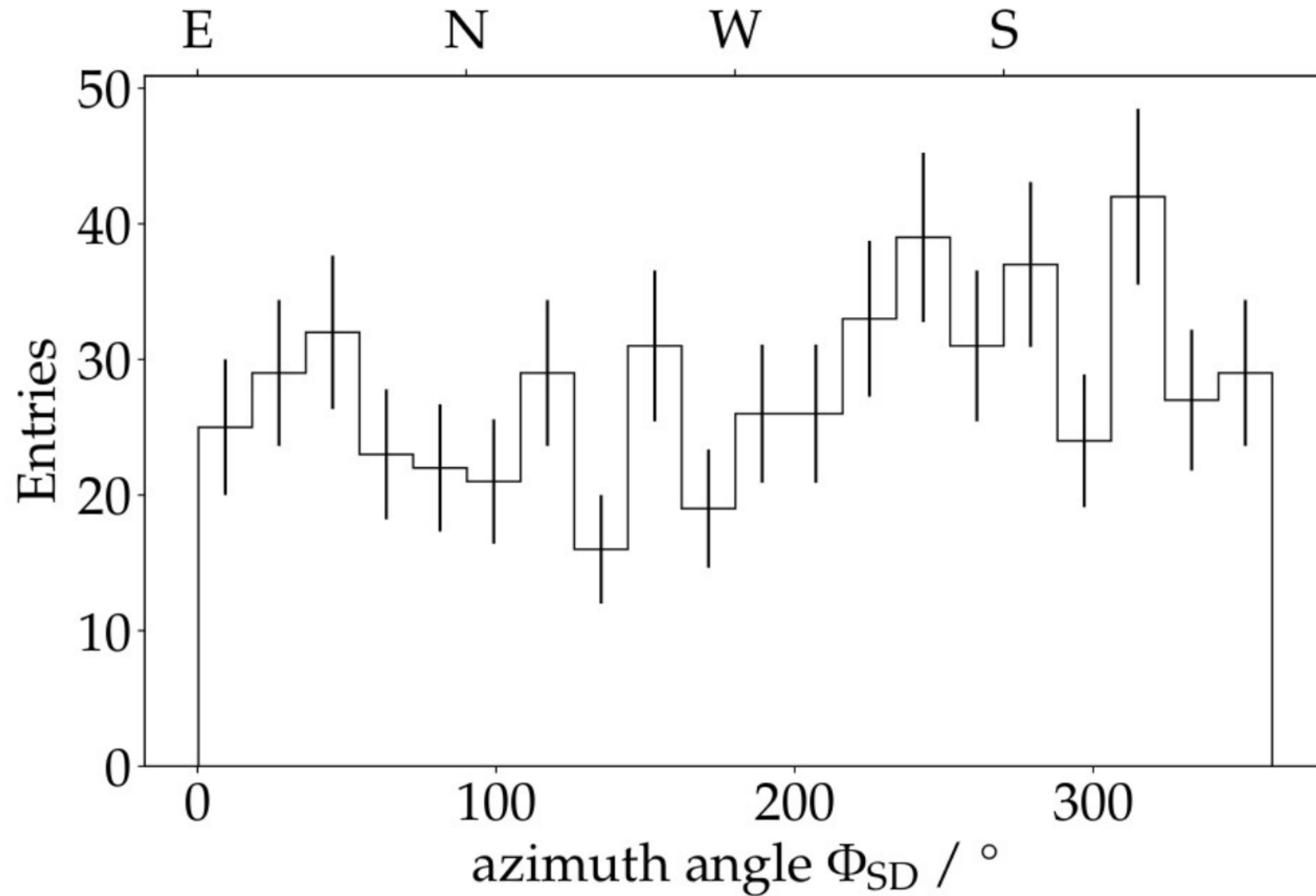
An initial look at 13 months of data



- Dec 2024 - Jan 2026
- 1172 showers after cuts
- in agreement with expectations
- „flat“ $\sin^2(\theta)$ distribution for $74^\circ < \theta < 80^\circ$

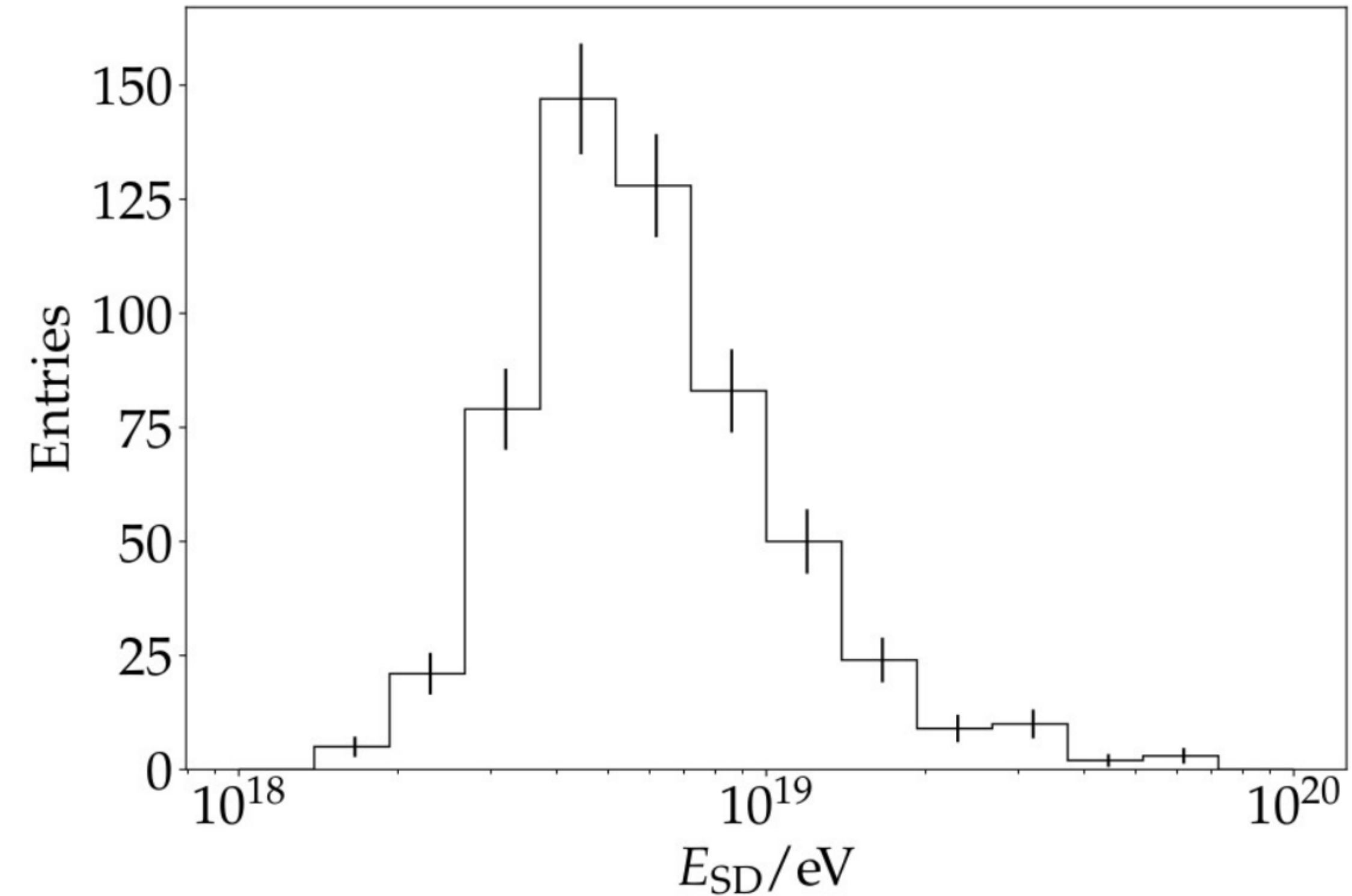
A closer look at “fully efficient” zenith angle range

azimuth angle



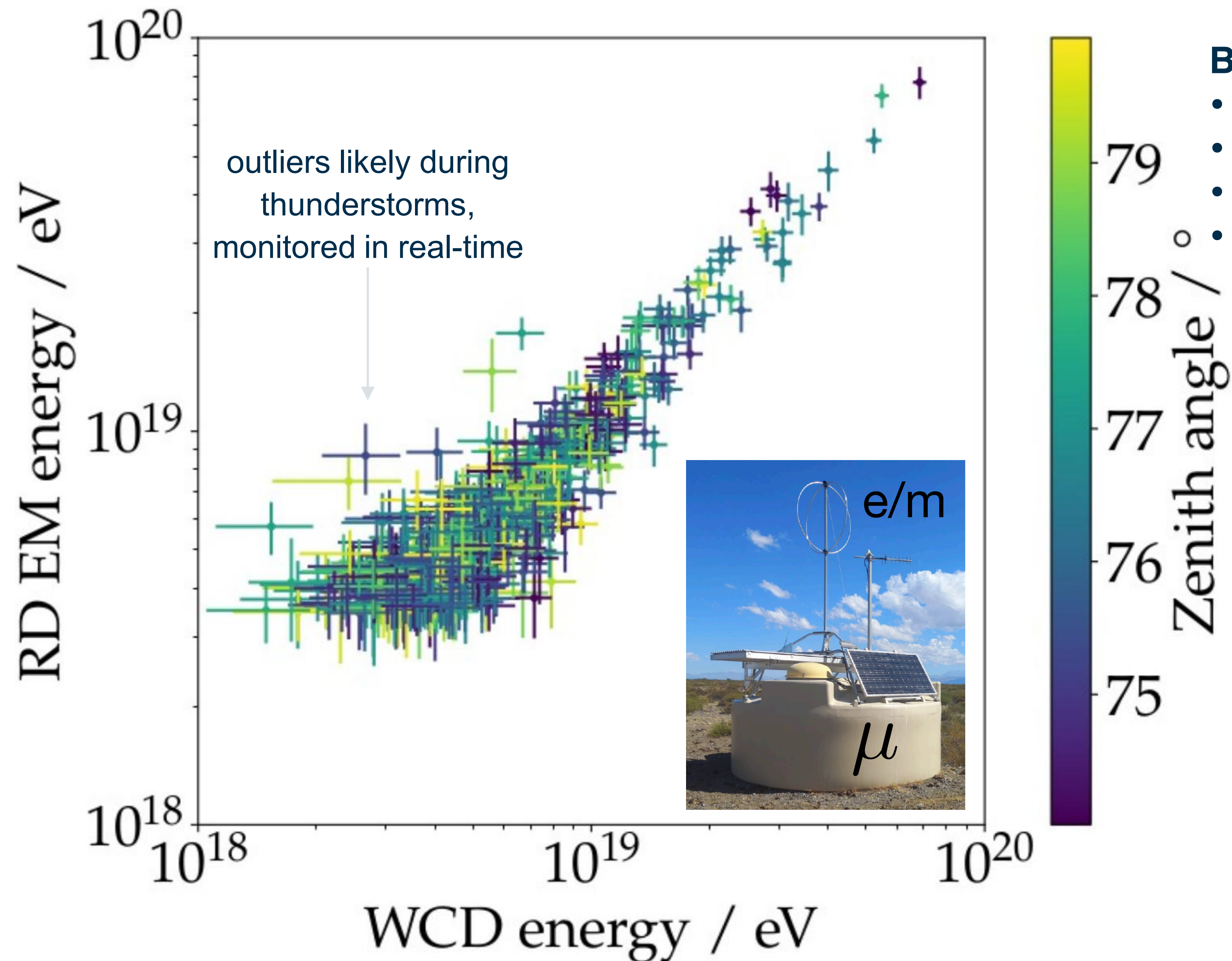
„flat“ distribution above threshold

energy



air showers with $E \sim 10^{20}$ eV -
world record for radio detection

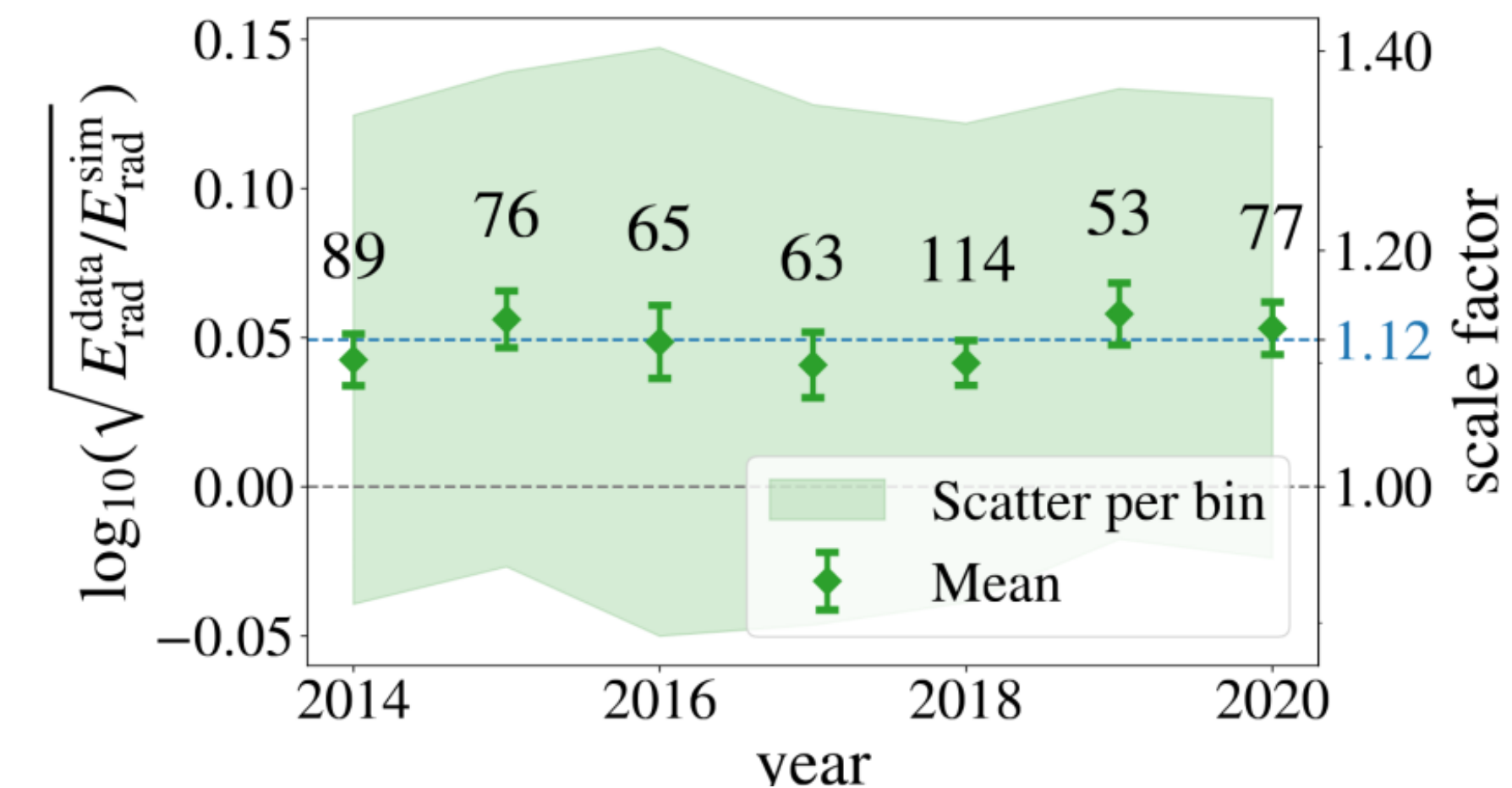
Correlation of energy measured with RD and WCD



Beautiful data set usable for

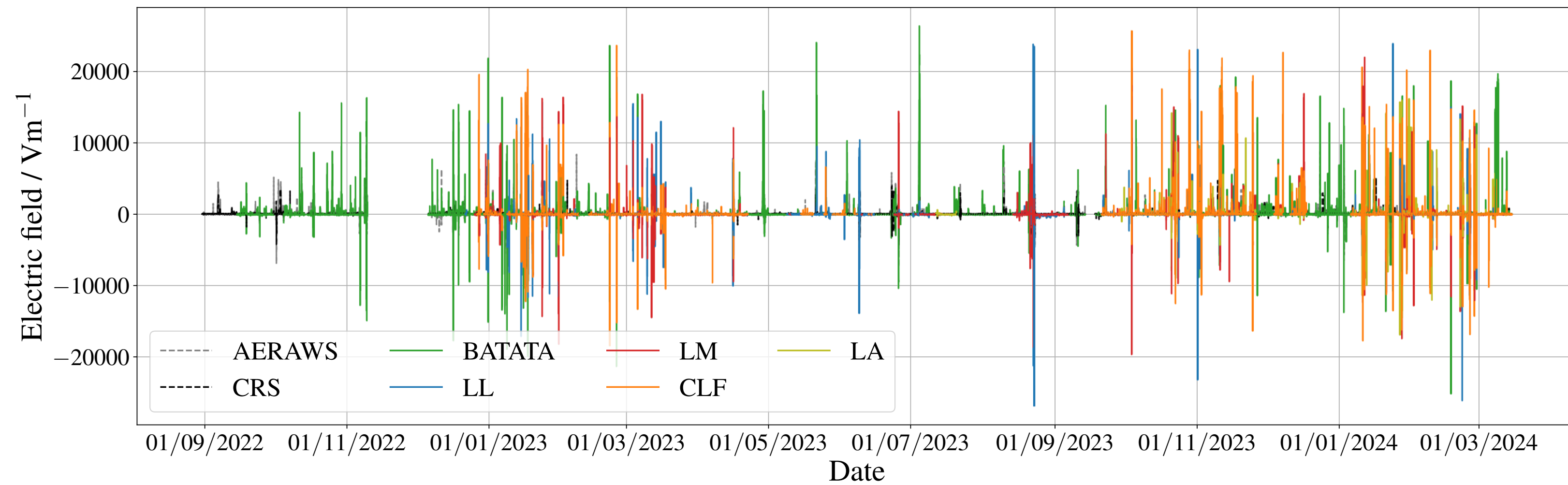
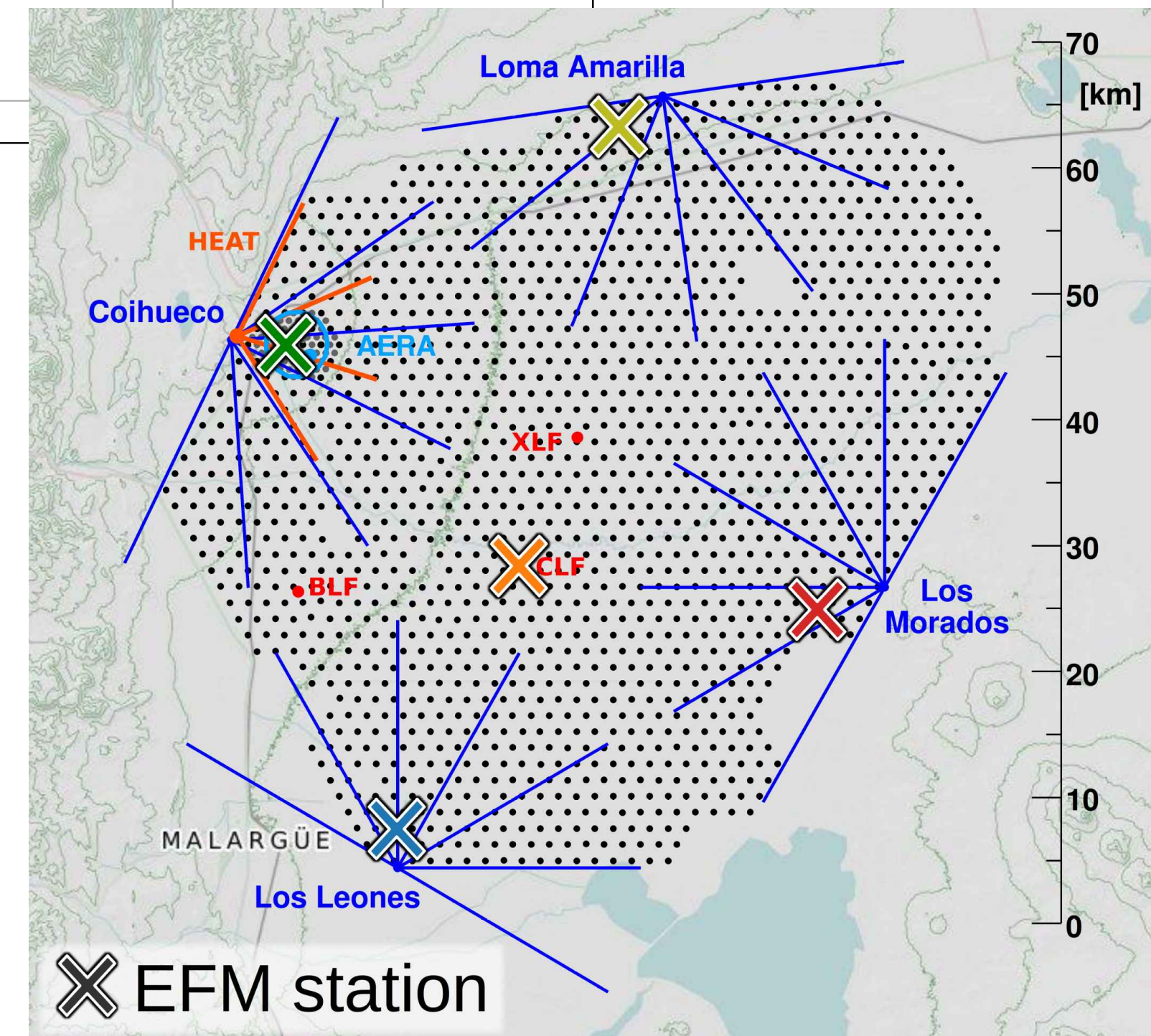
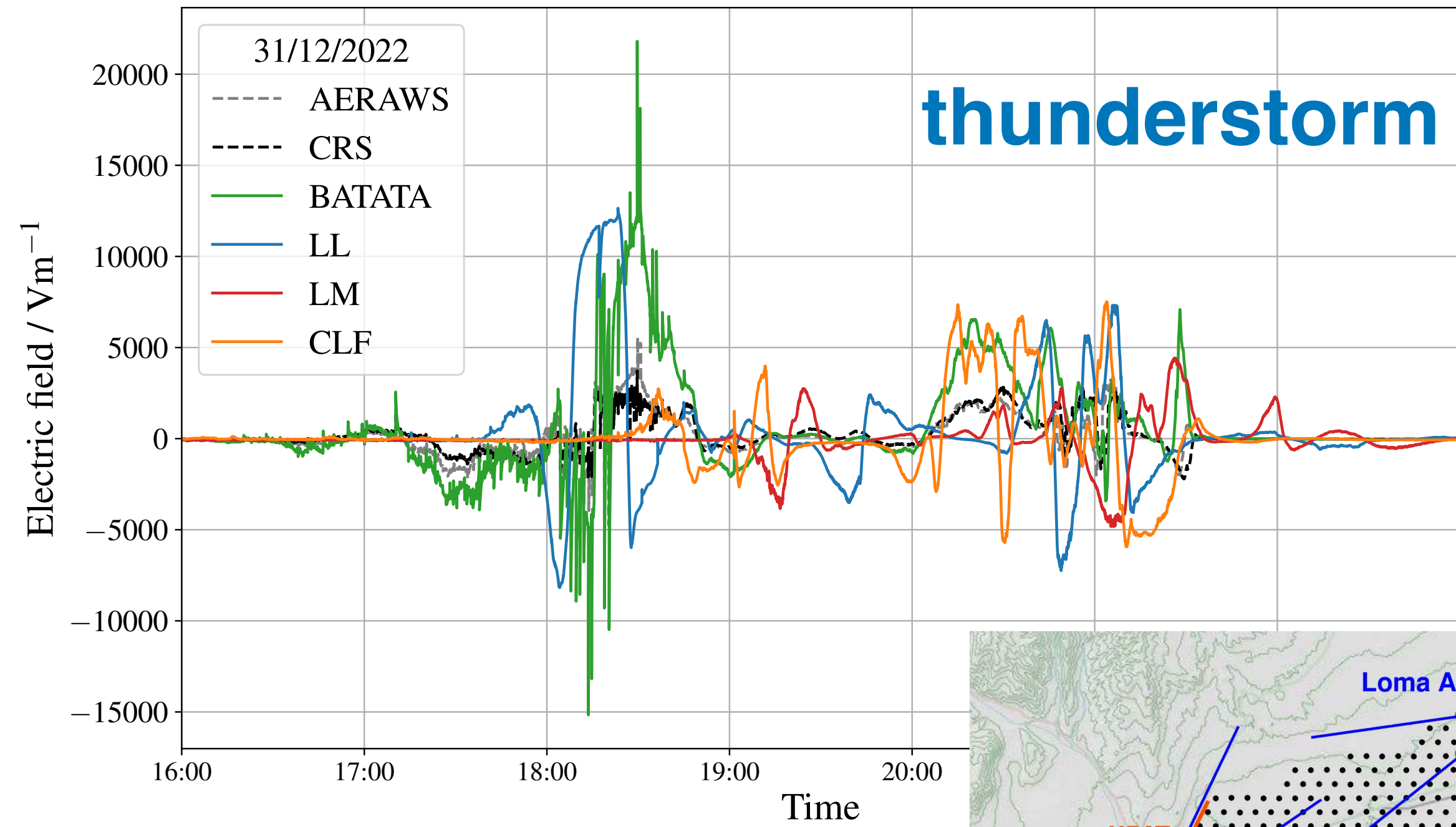
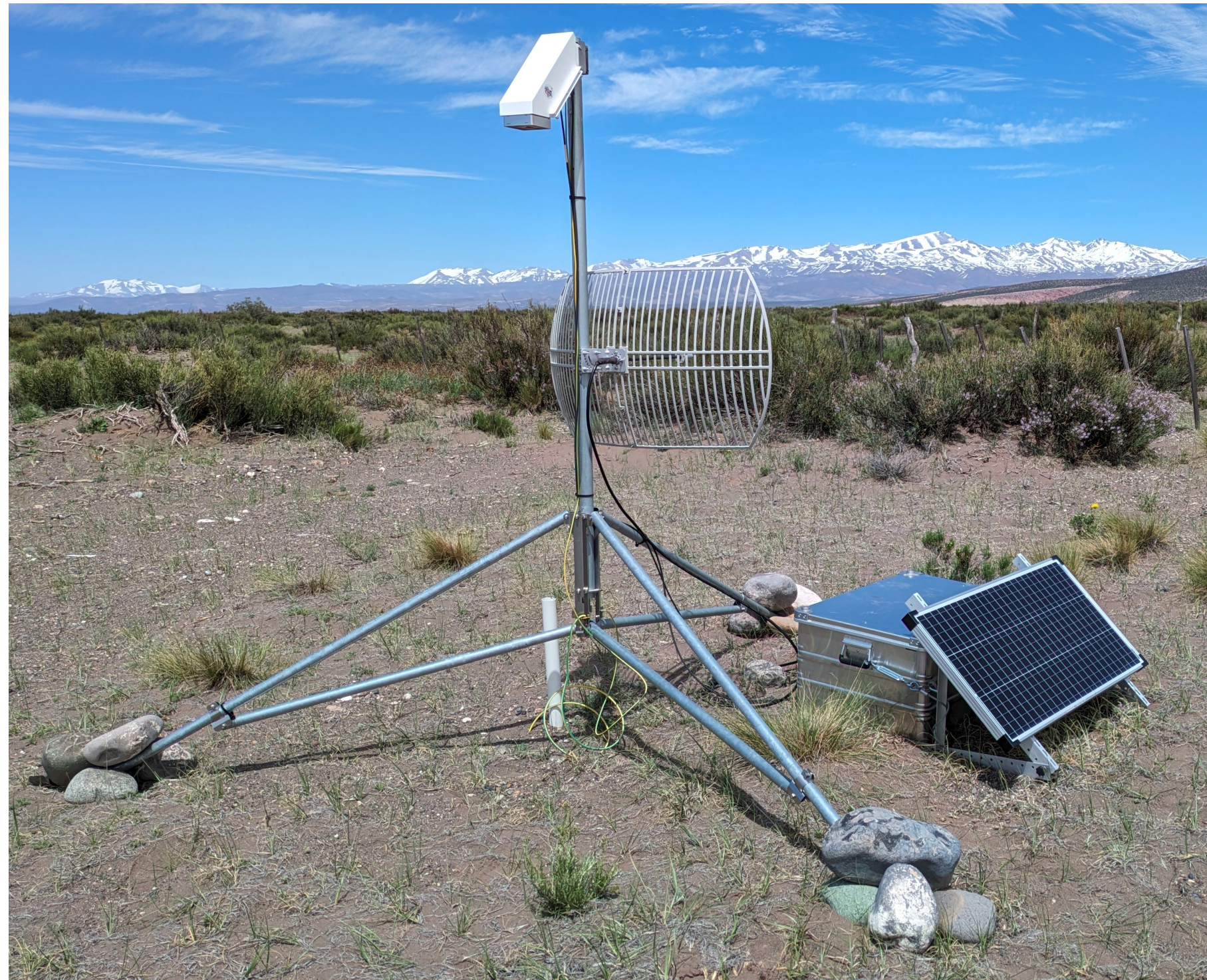
- Energy scale with Radio Detector
- Muon number measurements
- Photon searches
- Later interferometry

Aside: energy scale with AERA in agreement with Fluorescence Detector



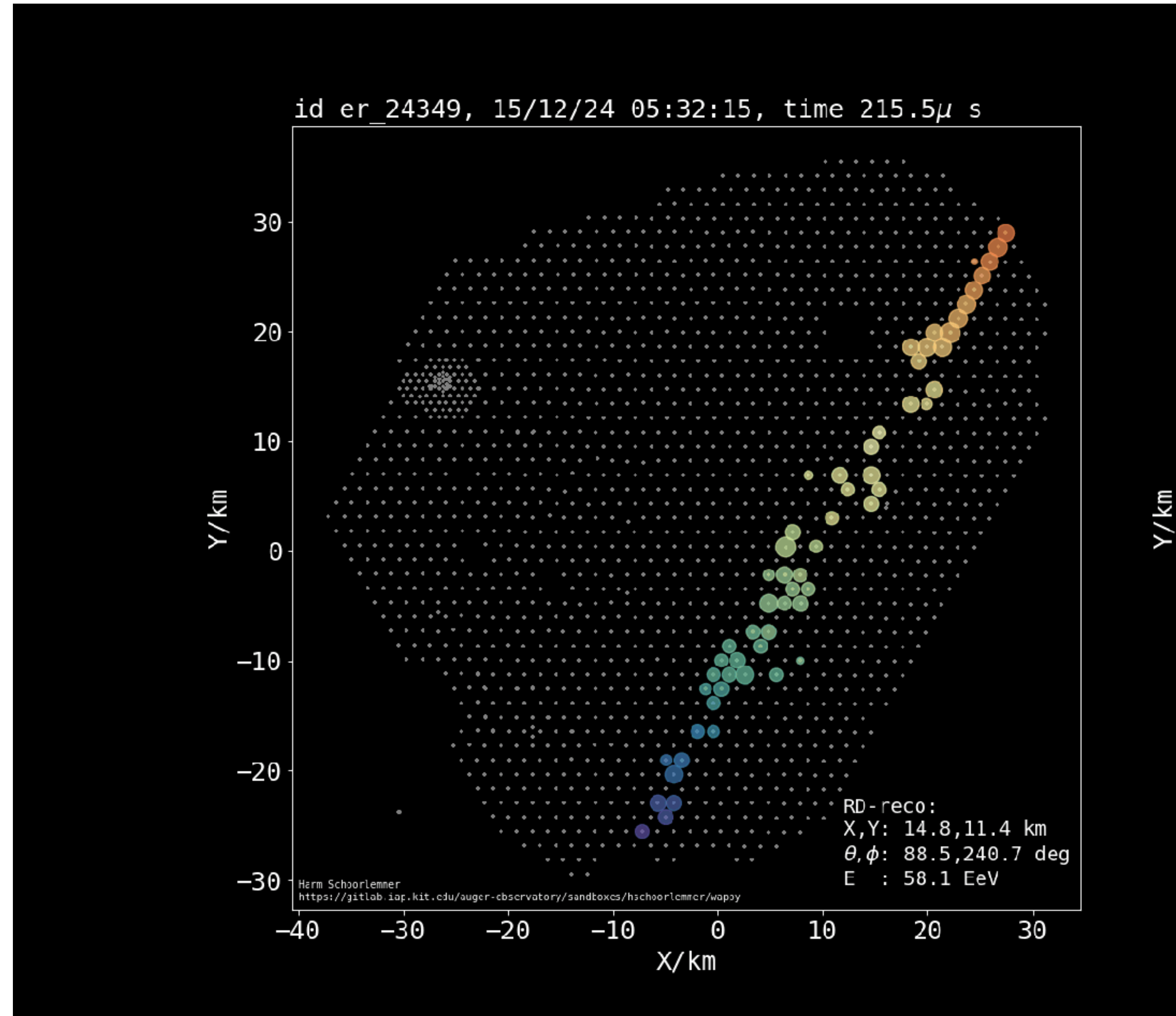
PoS ICRC2025 (2025) 292

In-situ monitoring of atmospheric electric fields



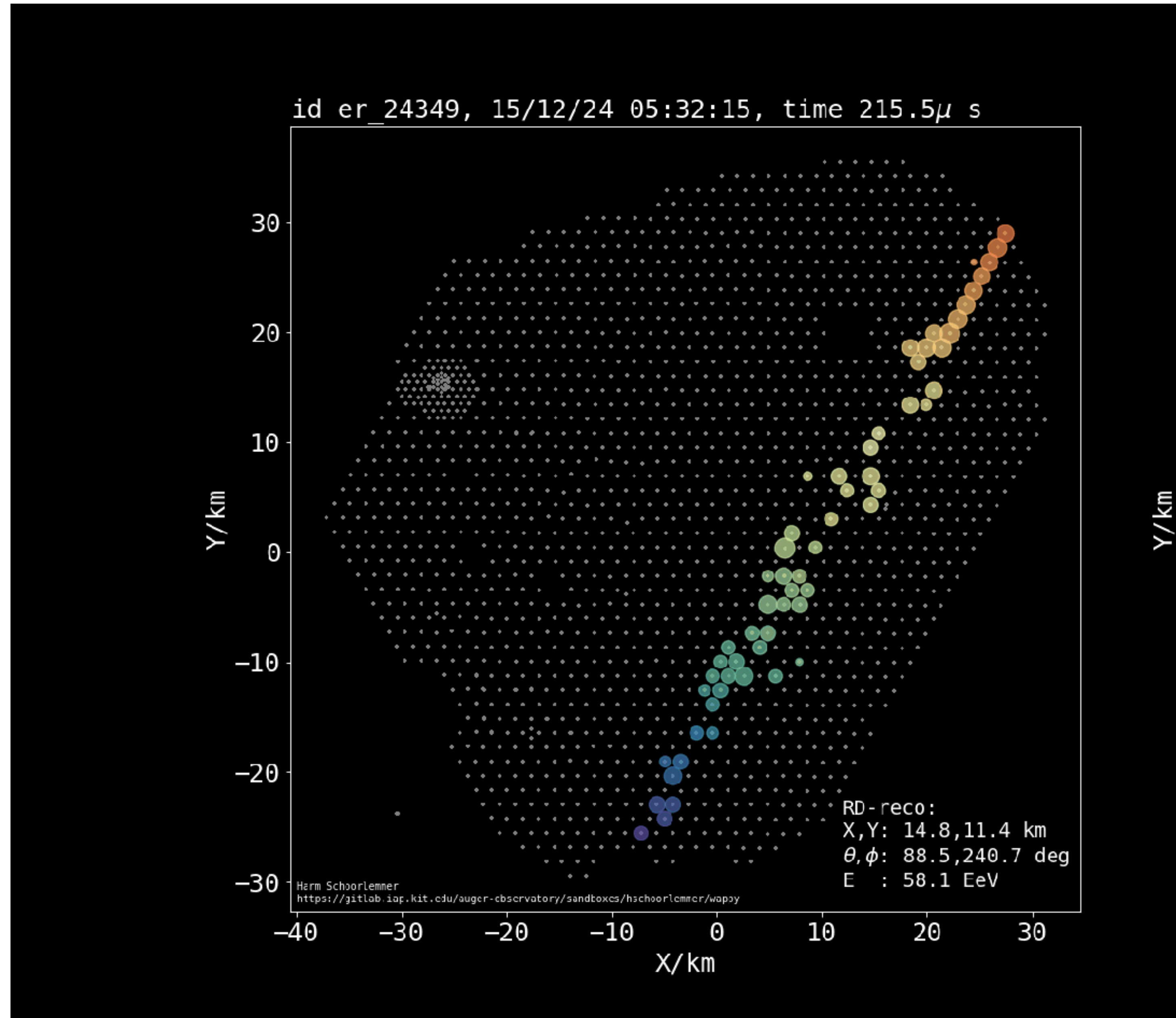
Earth-skimming potential

- 65 km footprint
- Nearly from the horizon: 89°
- around 2×10^{19} eV



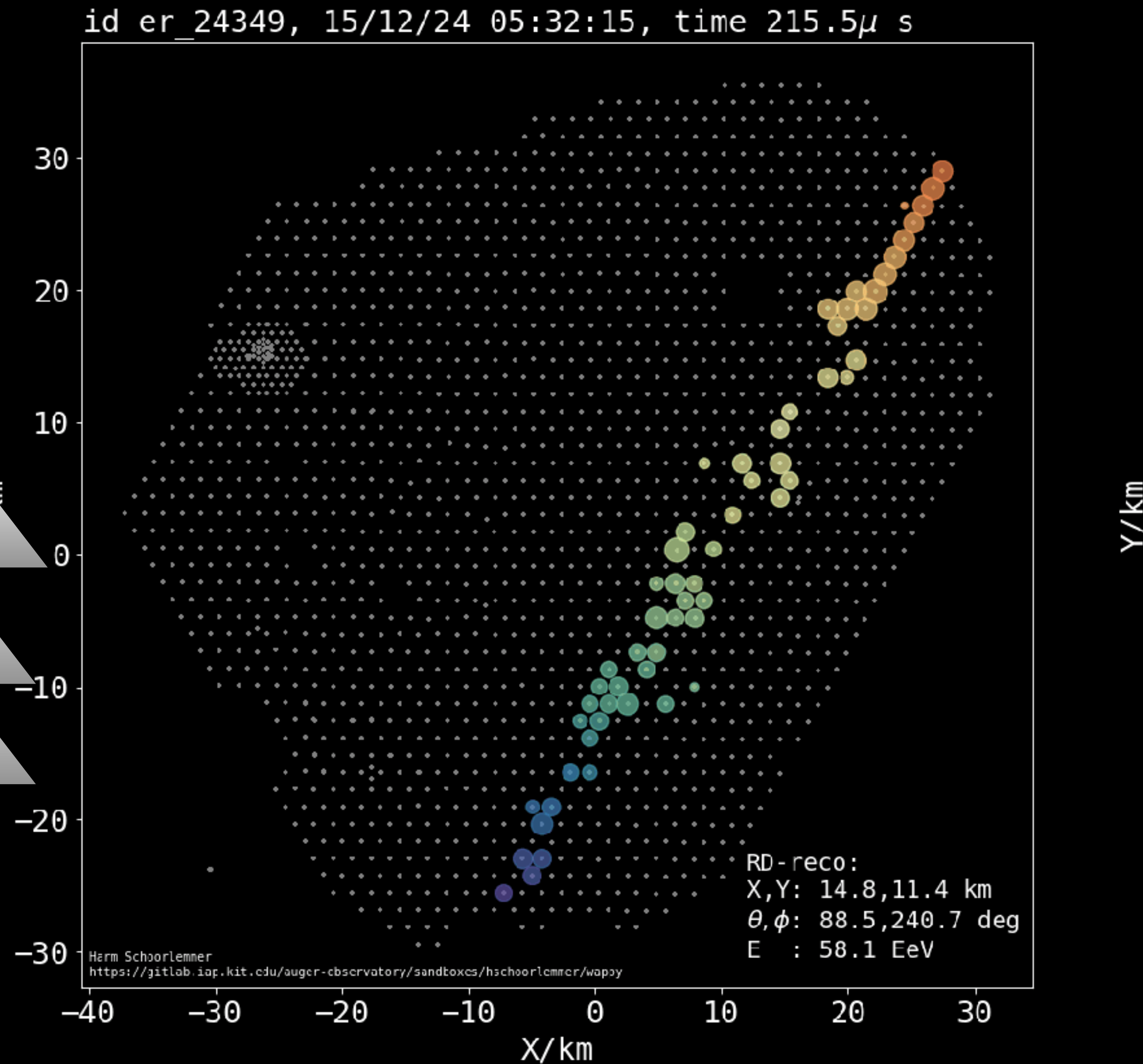
Earth-skimming potential

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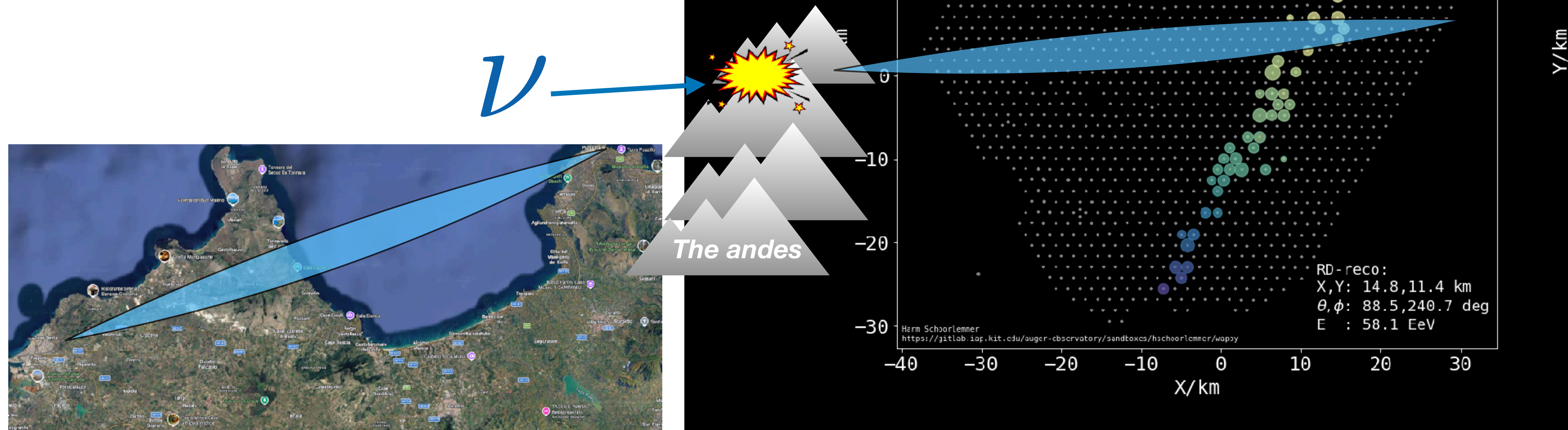
Earth-skimming potential

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- completely new domain for radio
—> illustrates the case for detecting Earth-skimming neutrinos (e.g. hitting the Andes)



Earth-skimming potential

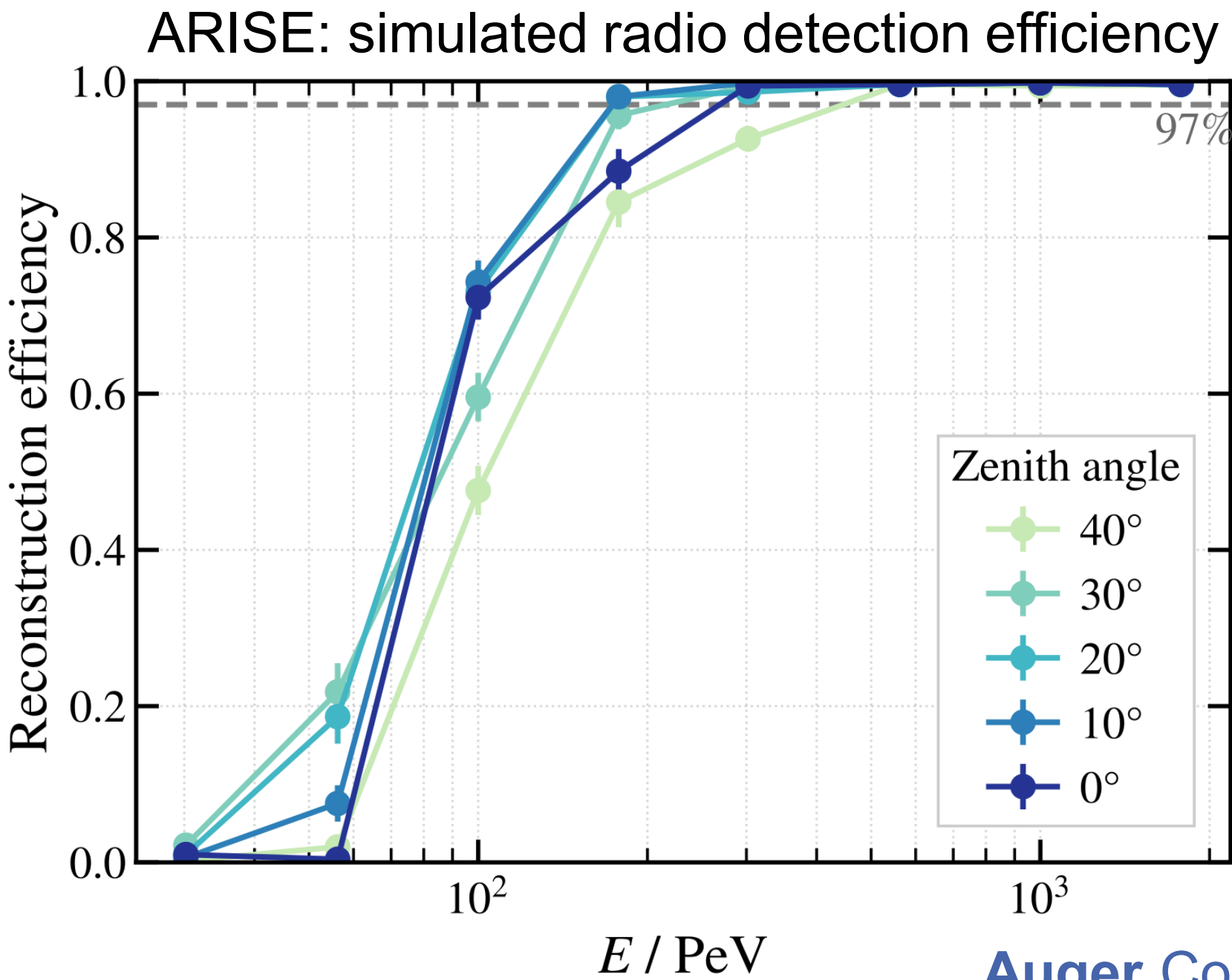
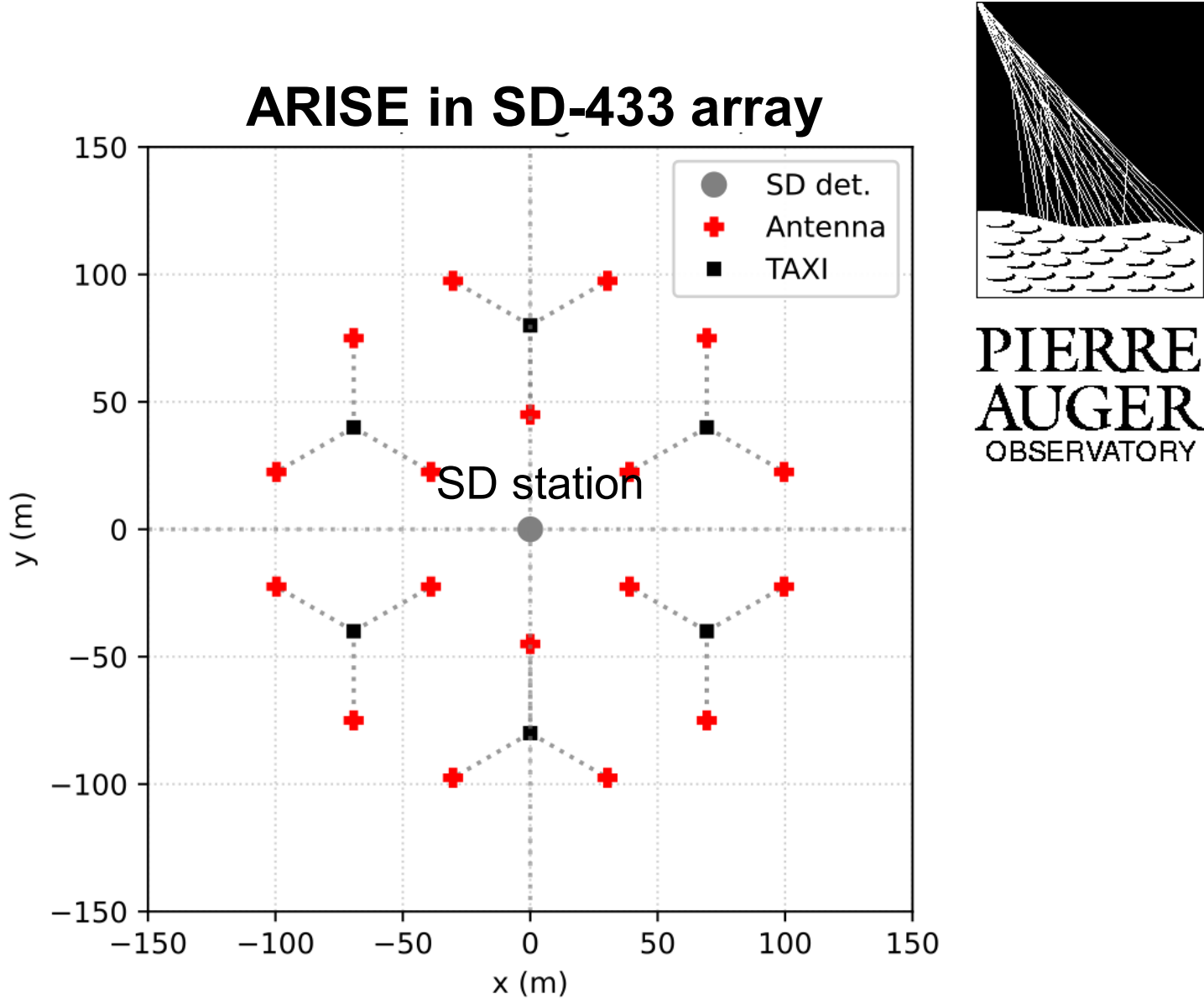
- 65 km footprint
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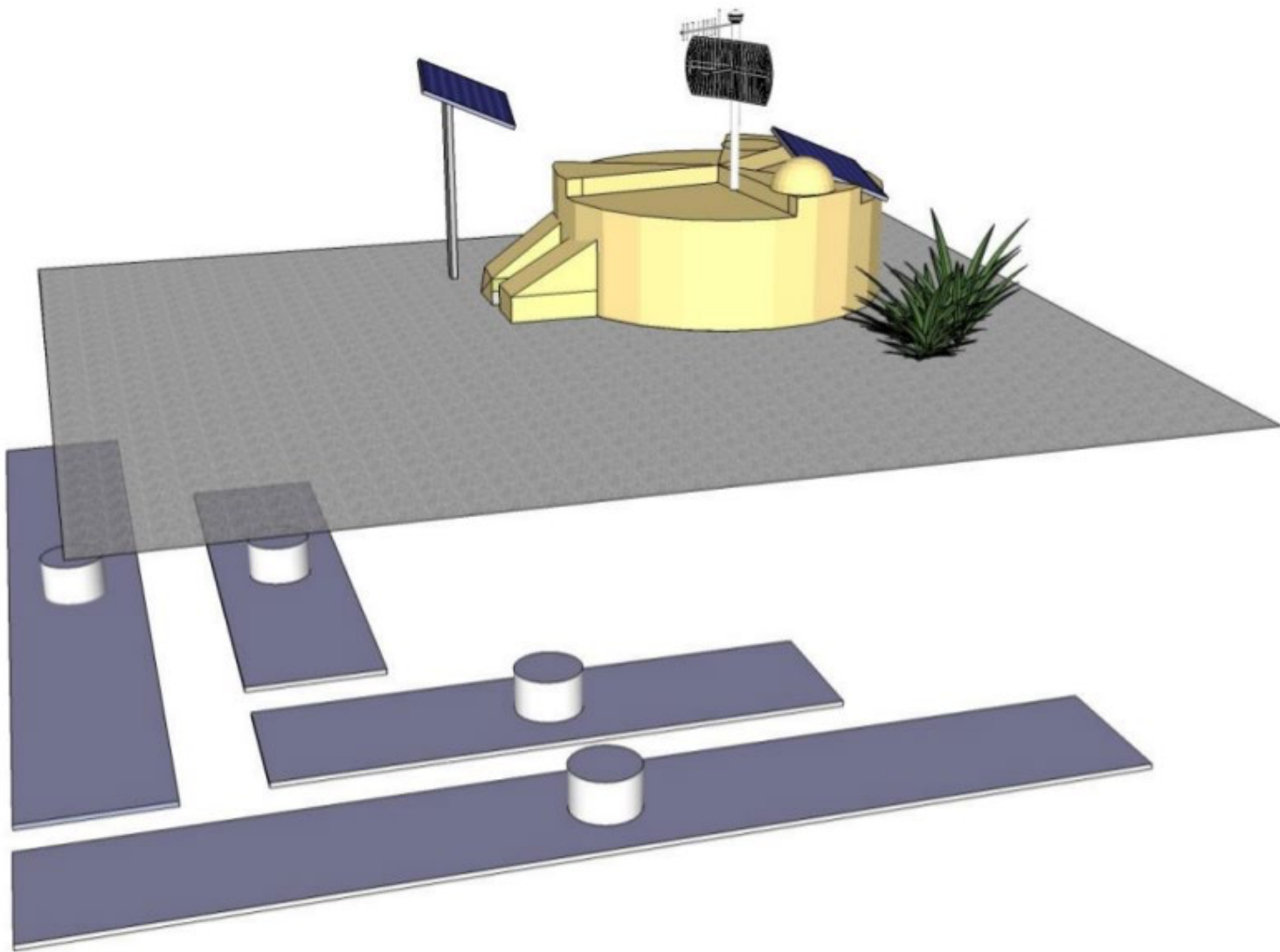
some future projects

Auger Radio Infill SKALA Enhancement (ARISE)

- 18 SKALAs triggered by Surface Detector aiming at:
 - demonstrating full efficiency for vertical showers
 - combined analysis with underground muon detectors
 - cross-calibration of energy scale with SKALA antennas



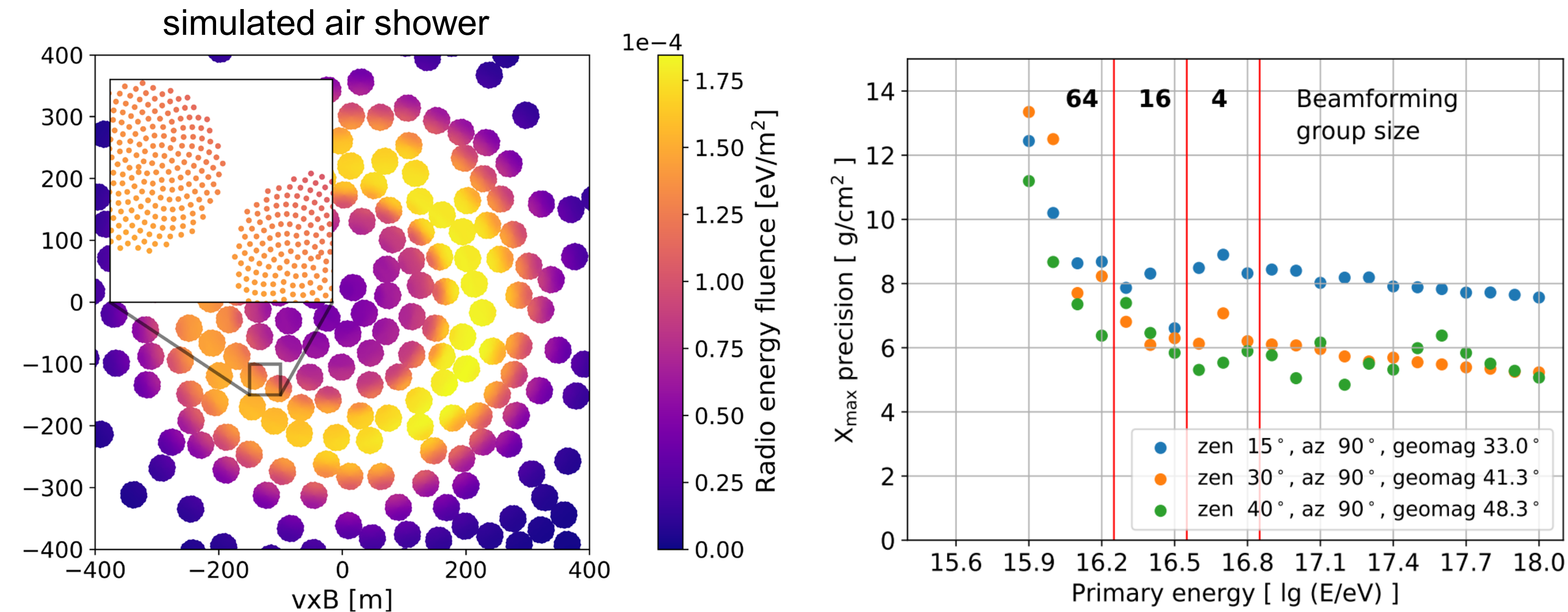
Surface Detector with Underground Muon Detector



The Square-Kilometer Array (SKA)



- SKA-low under construction in Australia
 - 10,000's of antennas on 1 km², 50-350 MHz
 - triggering scintillator array for air showers to be installed
 - building on LOFAR experience
- Unprecedented precision for air showers above 10¹⁶ eV

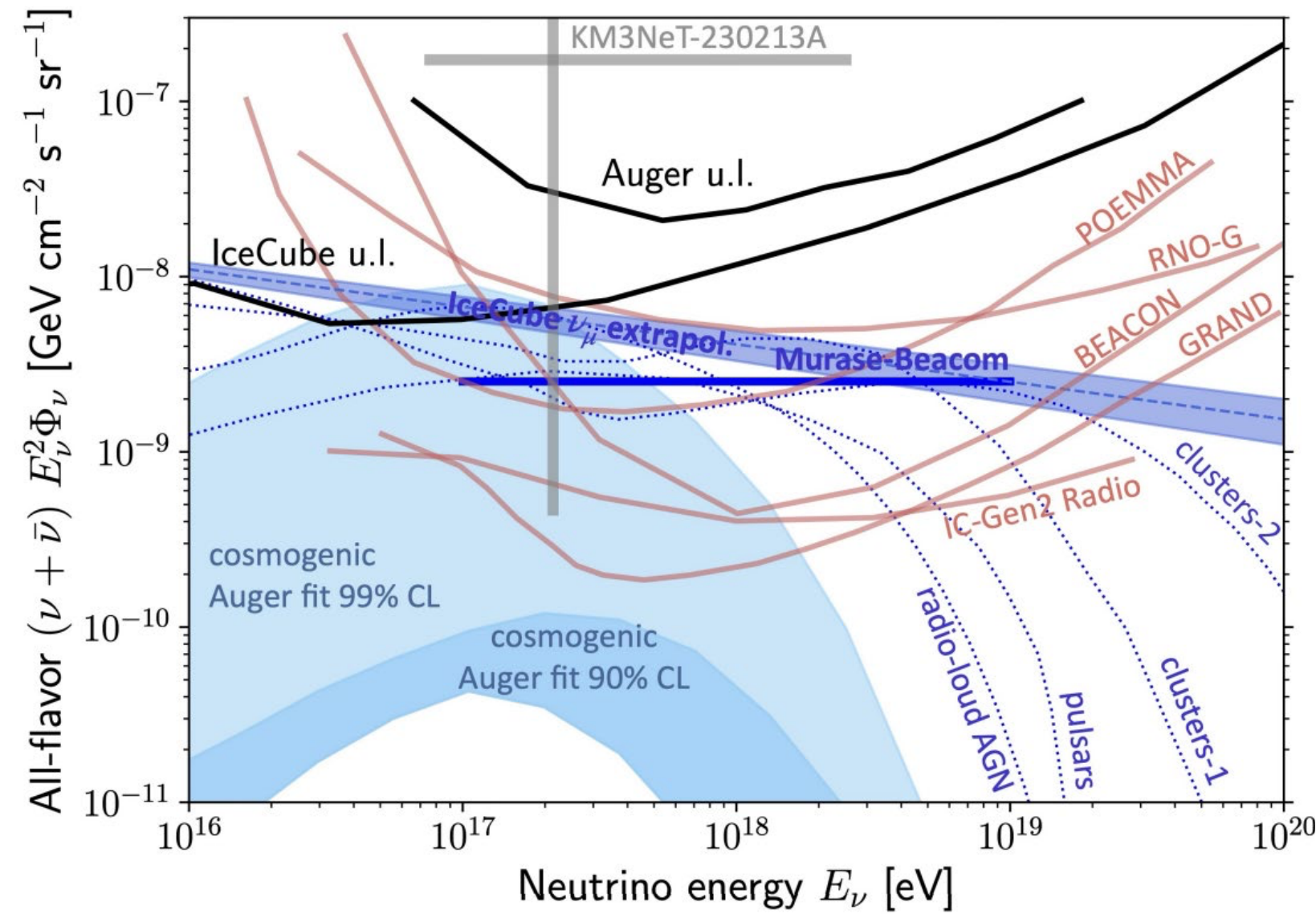
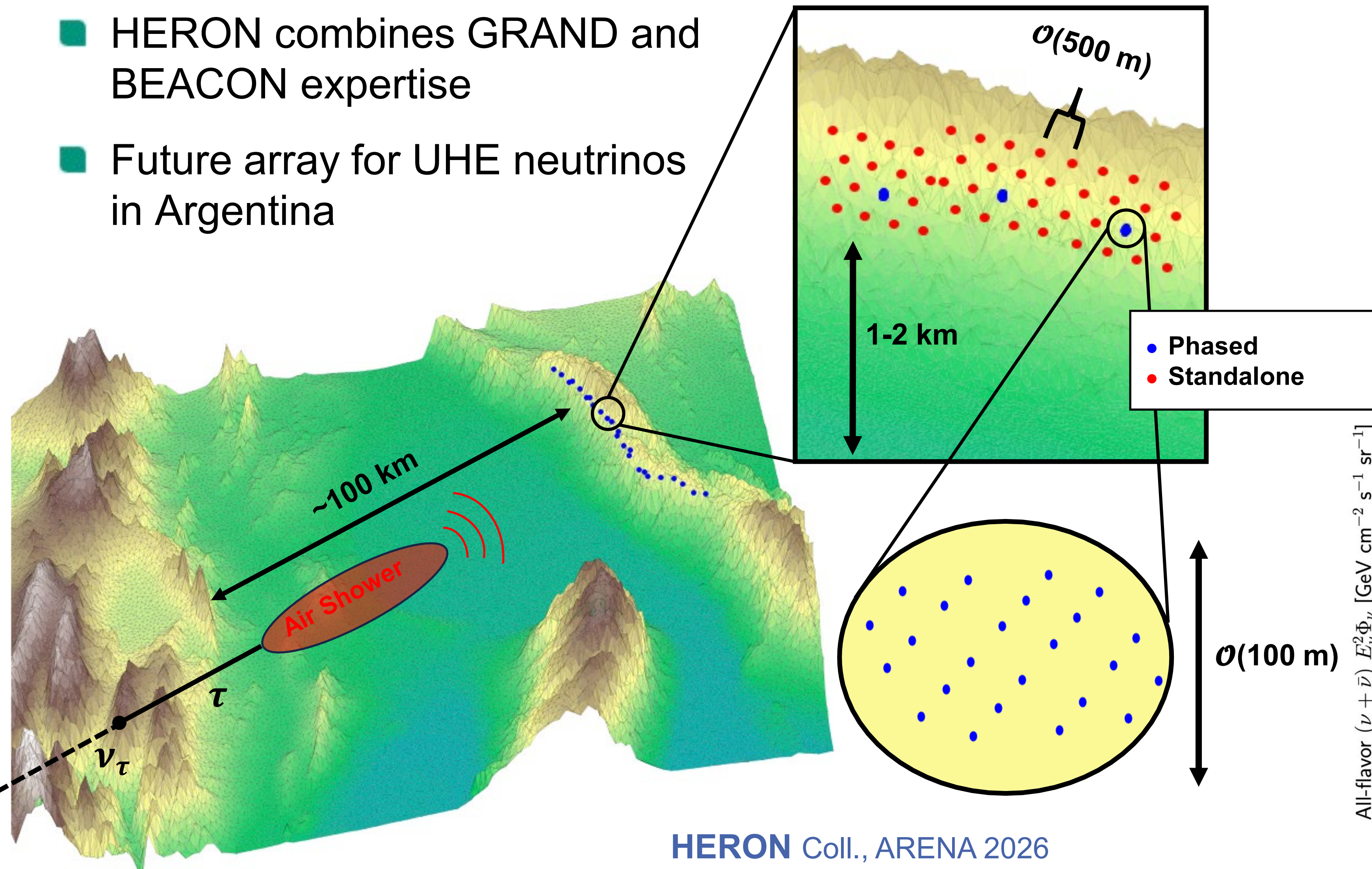


SKA Focus Group on High-Energy Cosmic Particles, ARENA 2026

Hybrid Elevated Radio Observatory for Neutrinos (HERON)

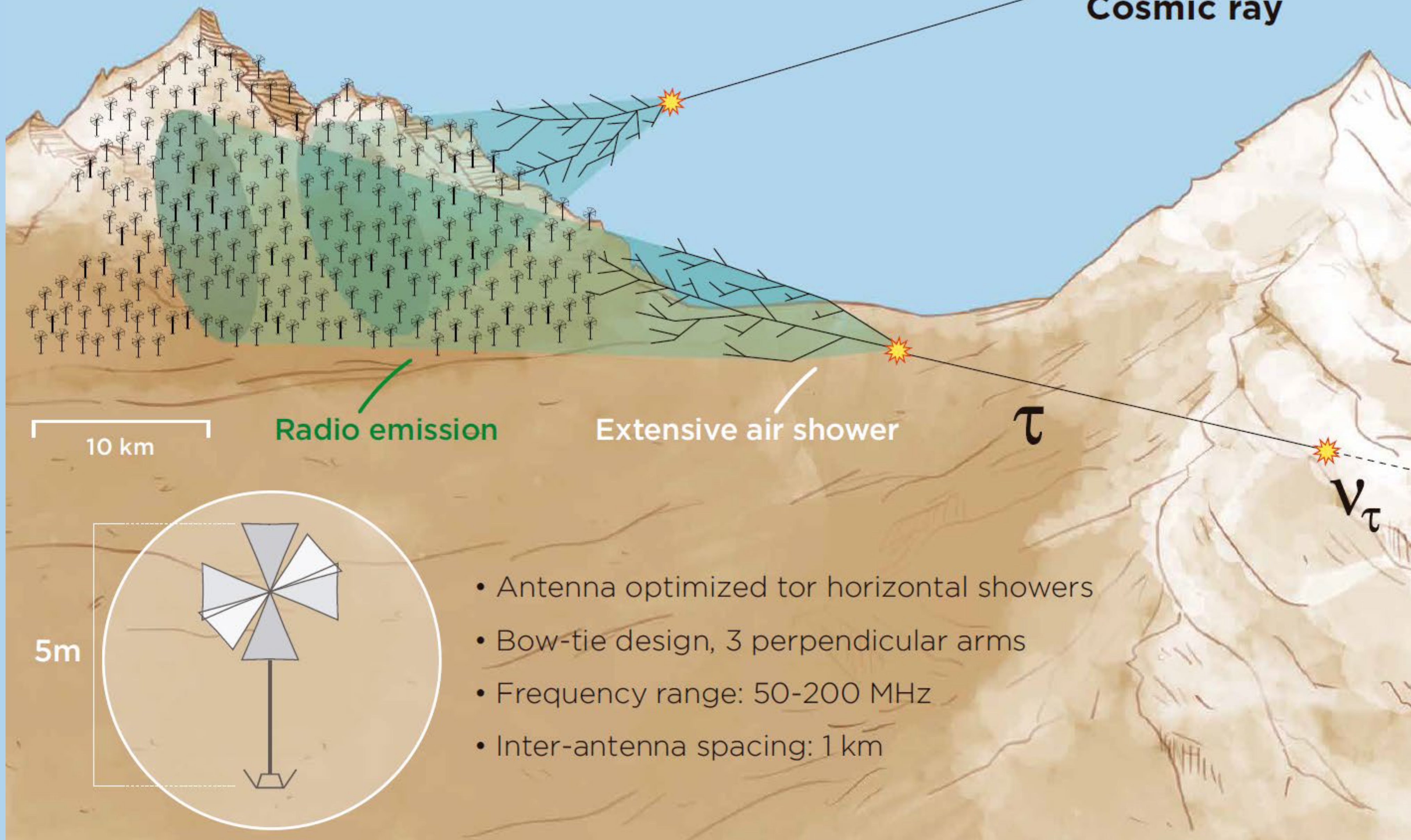


- HERON combines GRAND and BEACON expertise
- Future array for UHE neutrinos in Argentina





Giant Radio Array for Neutrino Detection



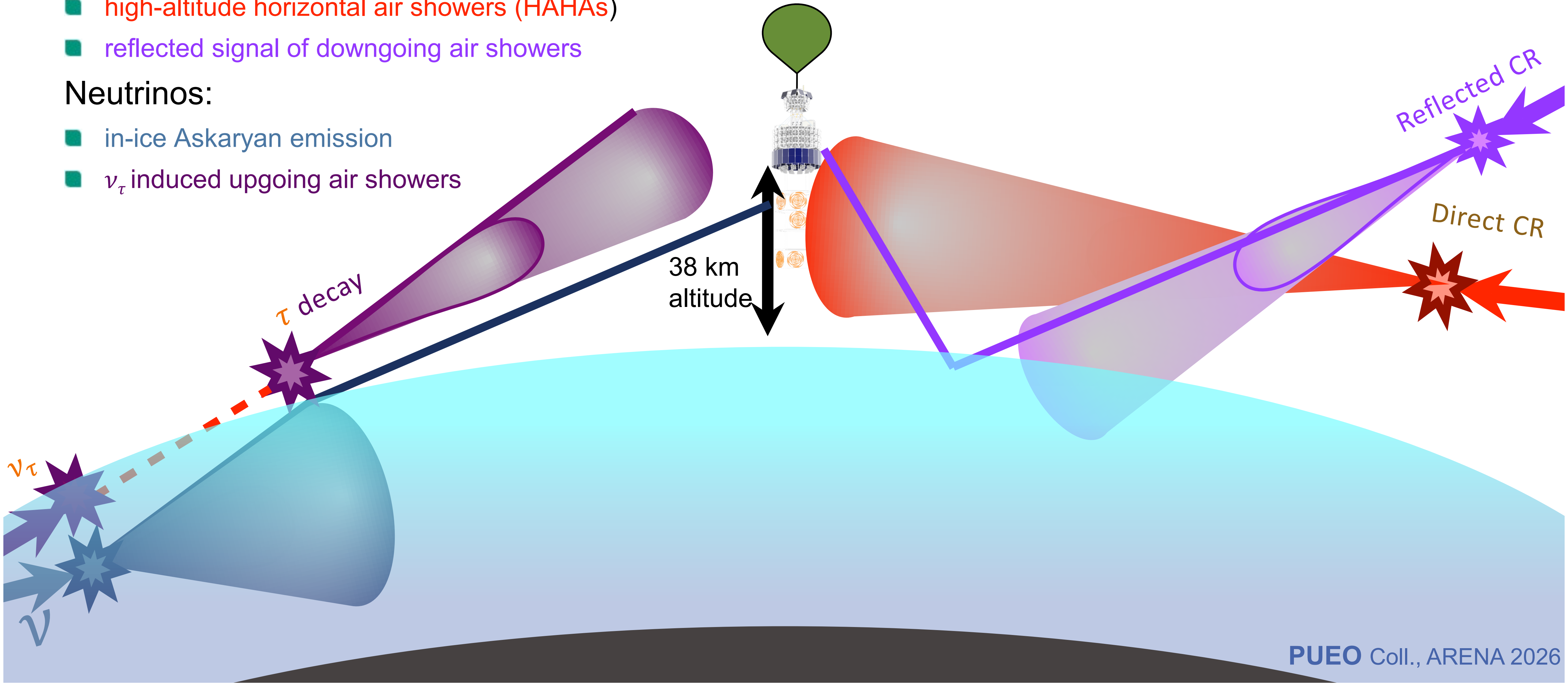
Concepts for Radio Detection on Balloons

Cosmic Rays:

- high-altitude horizontal air showers (HAHAs)
- reflected signal of downgoing air showers

Neutrinos:

- in-ice Askaryan emission
- ν_τ induced upgoing air showers



POEMMA-Balloon with Radio (PBR)

PBR Team,
JCAP07(2026)001
→ talk by B. Panico

Ultra-High-Energy
Cosmic Rays
(UHECRs)
UV Fluorescence

High Altitude Horizontal
Airshowers (HAHAs)
Optical+Radio

Cosmic Rays $E > \text{PeV}$

Cherenkov Emission

EAS

Tau Neutrino
Optical+Radio

Tau Neutrino

Tau lepton decay

Atmosphere

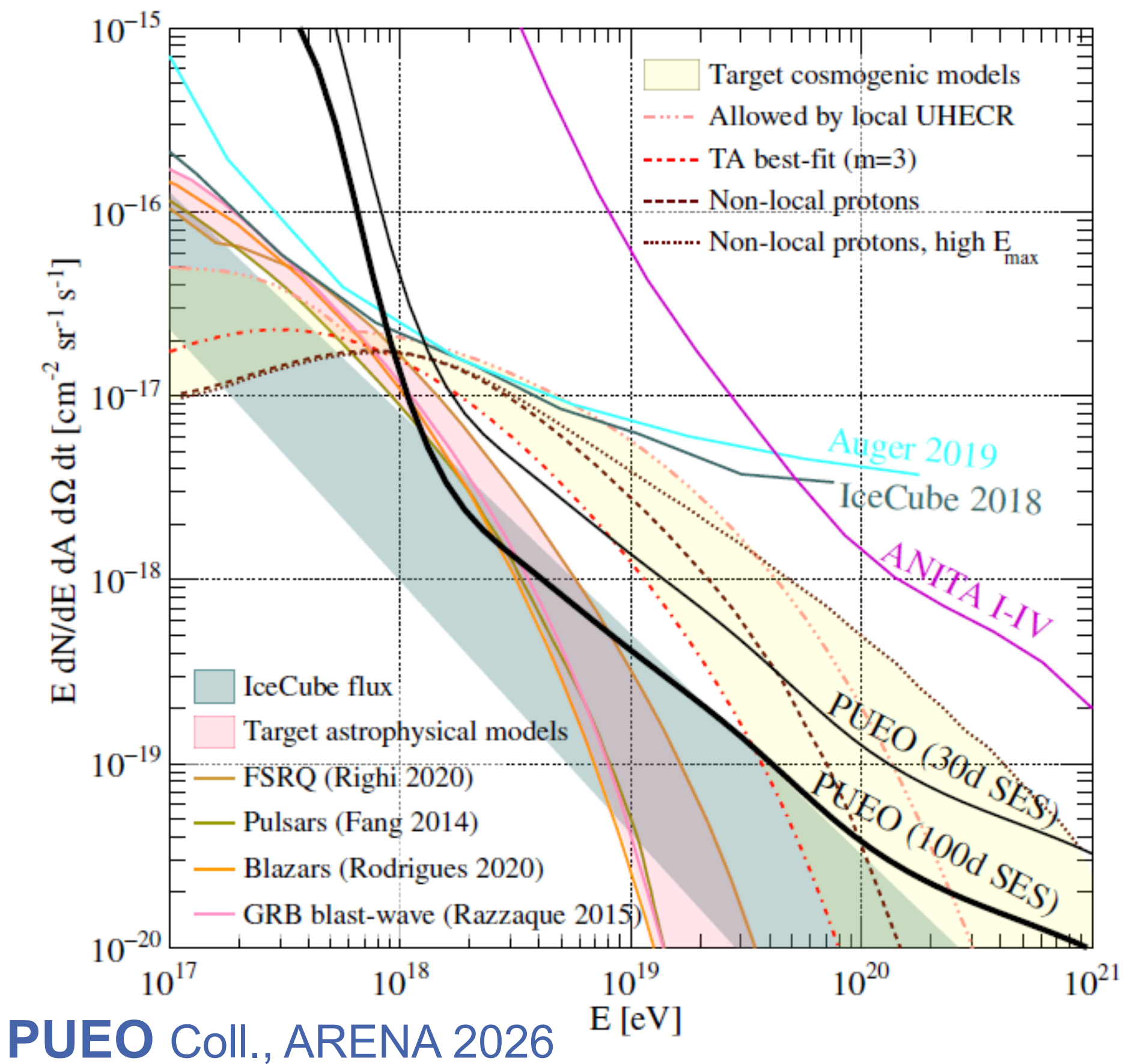
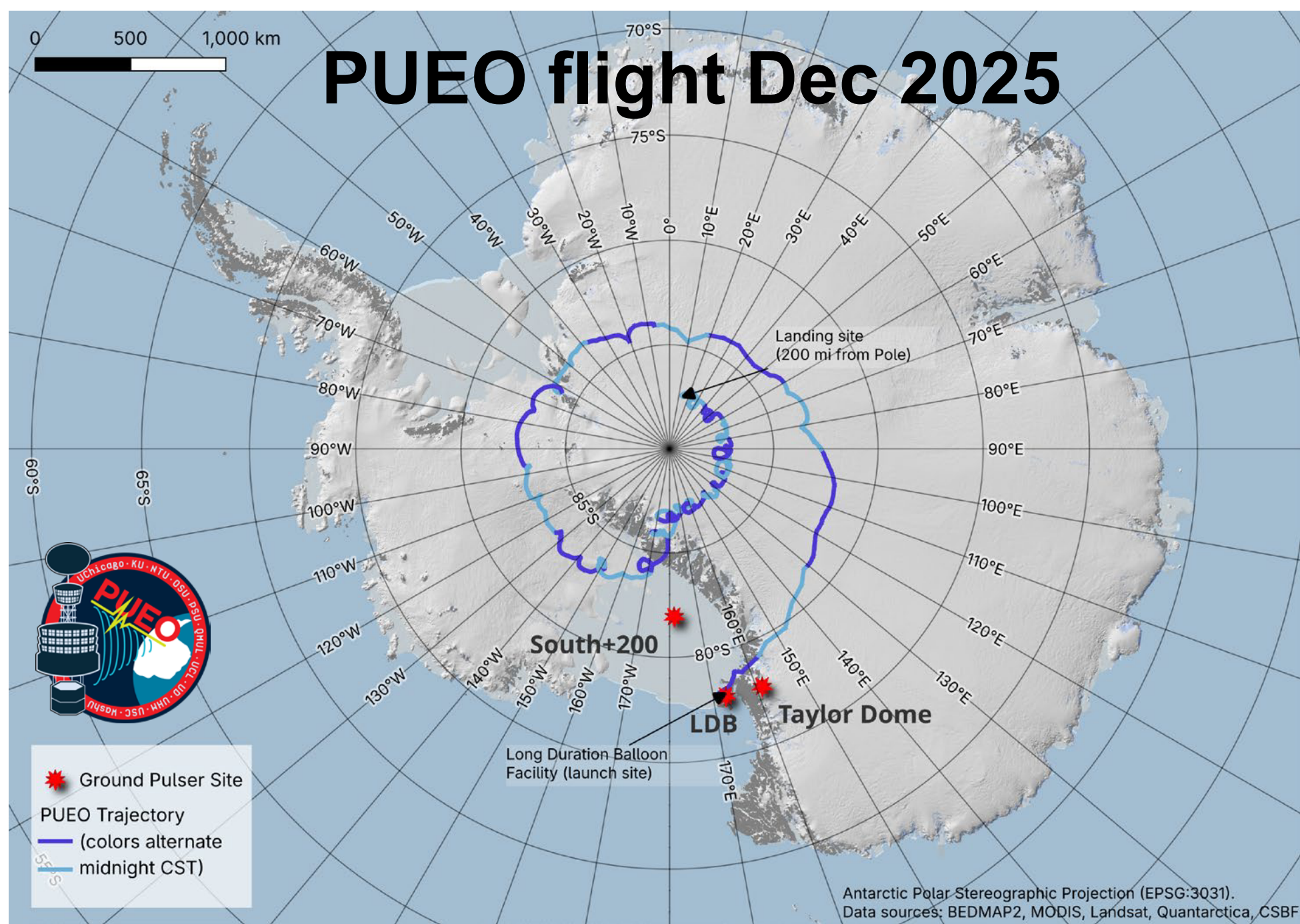
EAS

Southern Ocean

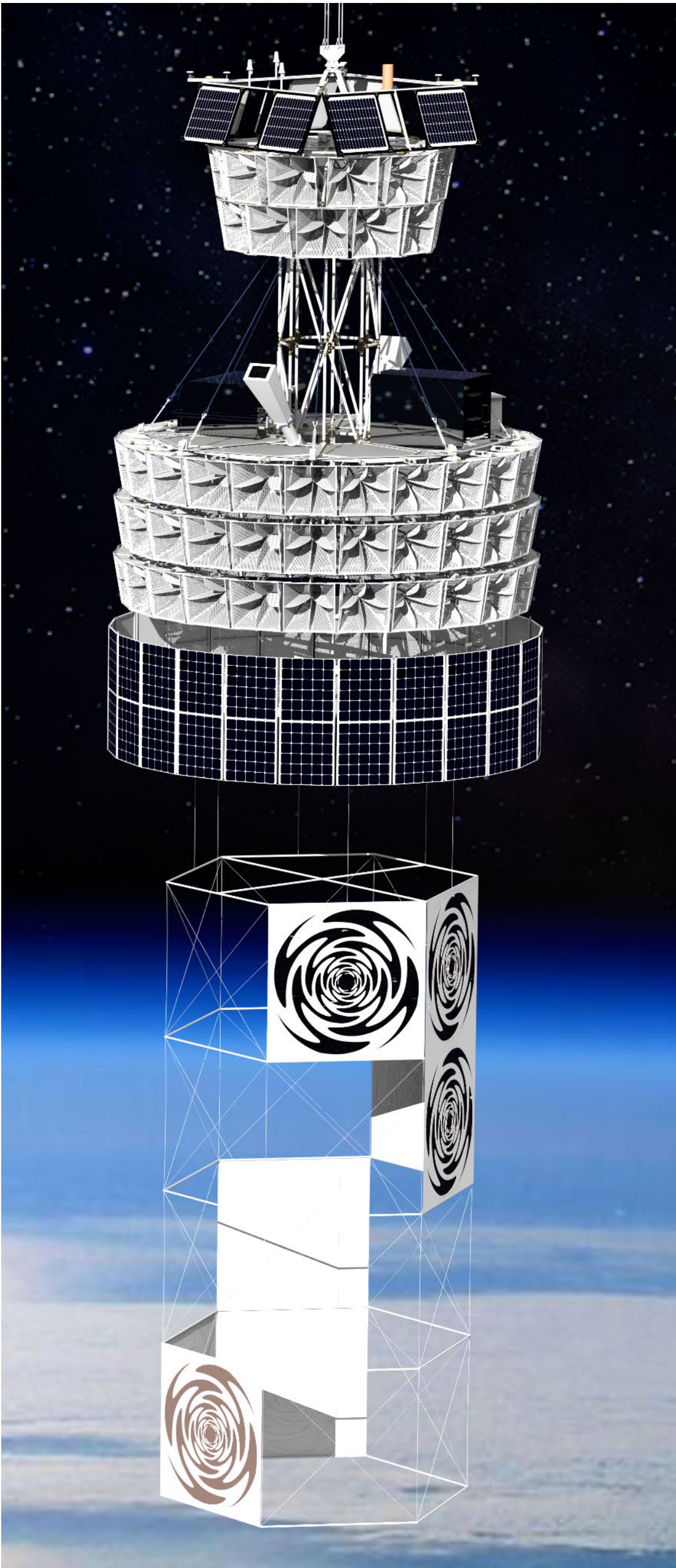
Payload for Ultrahigh Energy Observations (PUEO)

PUEO is the successor of ANITA with higher sensitivity

- search for neutrino-induced air showers in the Antarctic ice
- improvement of cosmic-ray detection due to additional low-frequency instrument

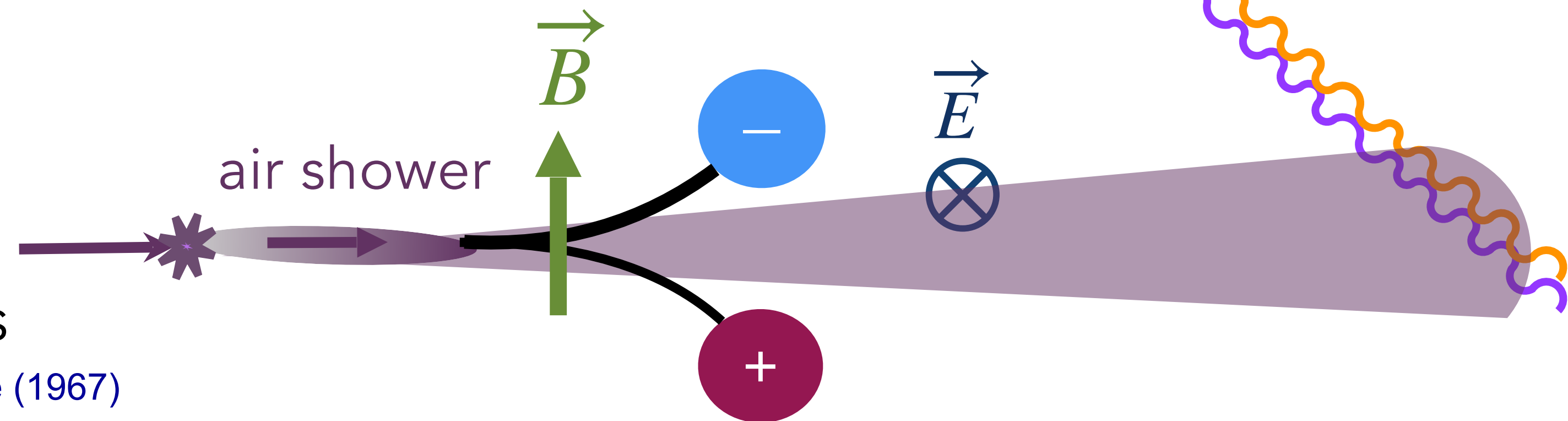
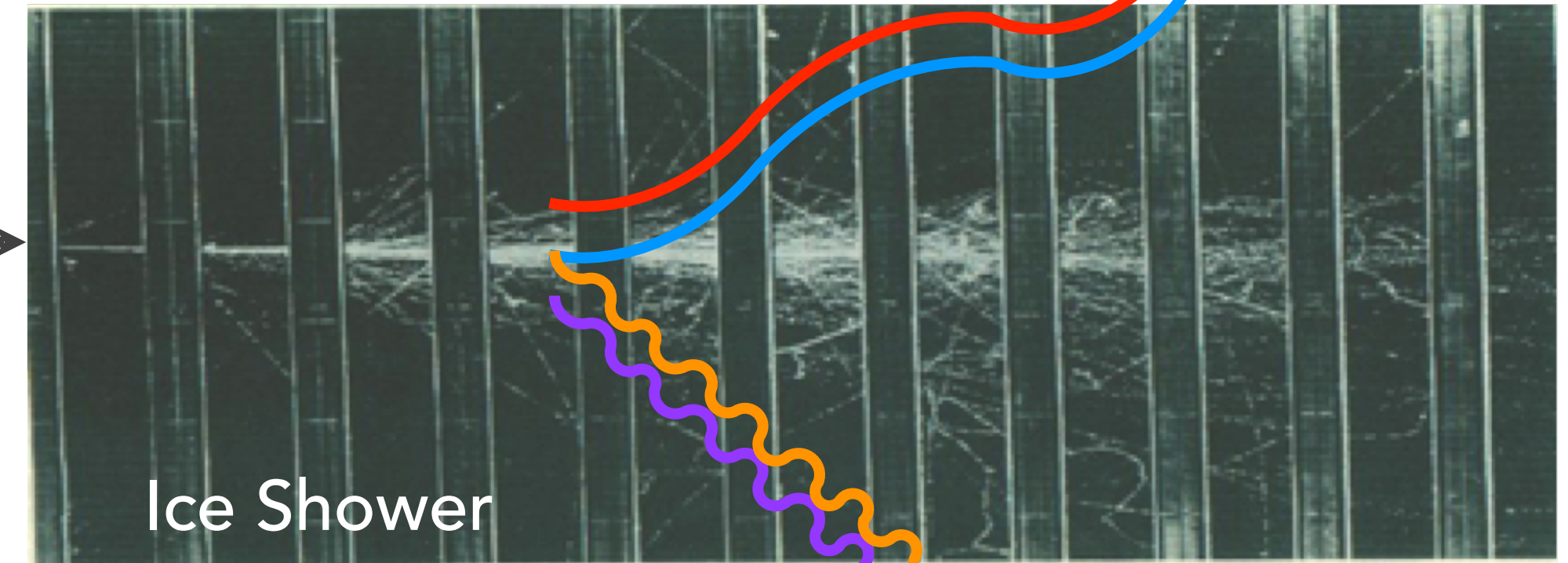
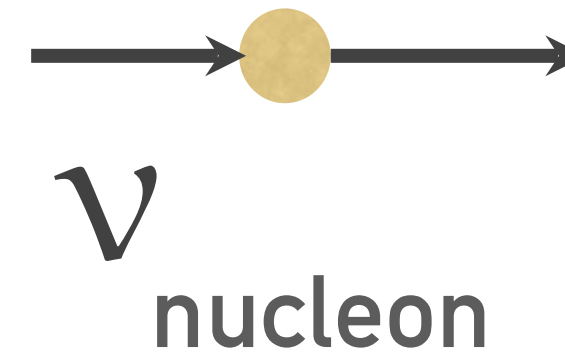


PUEO Coll., ARENA 2026



Radio Emission in air and in dense media

Askaryan 1969,
Saltzberg, PRL, 2001



Kahn & Lerche (1967)

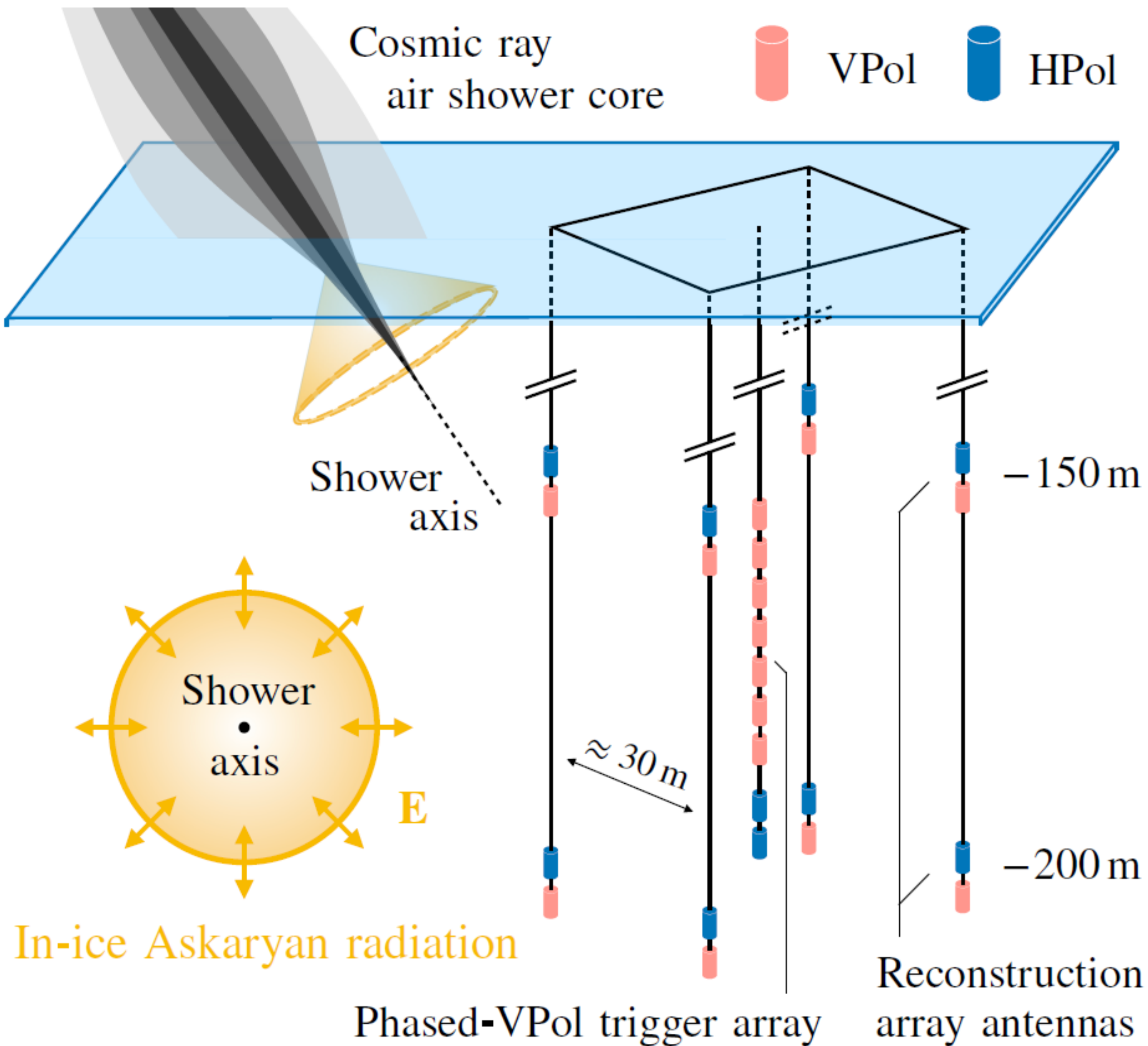
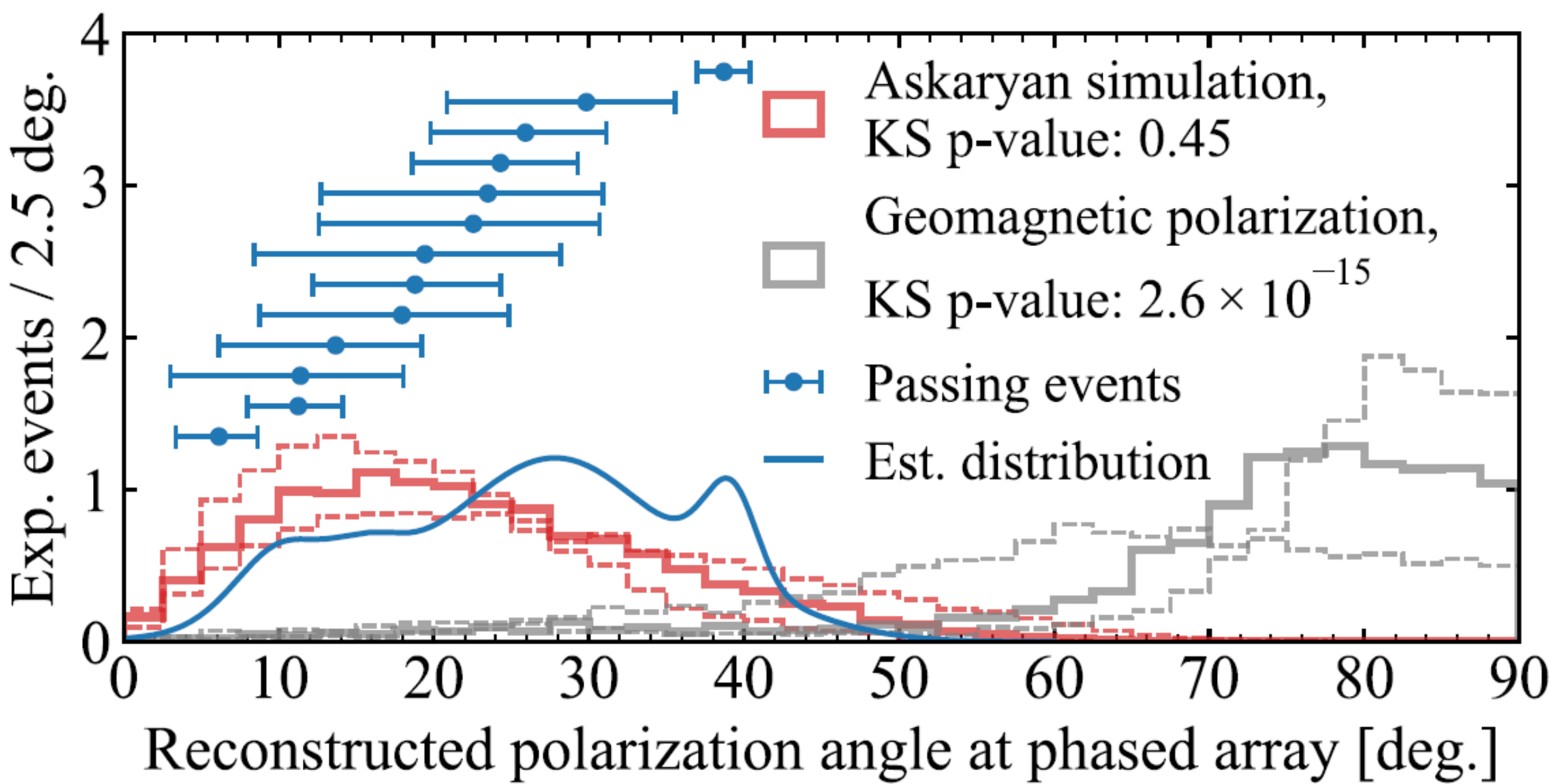
- **Askaryan emission:** radiation from time-varying net negative charge excess in shower. Dominant for ***in-ice*** showers
- **Geomagnetic emission:** time-varying current due separation of positive and negative charges in shower due to Lorentz force. Dominant for ***air*** showers
- Both benefit from boost due to coherence effects near the Cherenkov angle

Askaryan Radio Array (ARA) at the South Pole

Recent result:

validation of in-ice Askaryan emission from cosmic-ray air showers continuing in the ice

Polarization estimate is quite distinct from expected geomagnetic signals

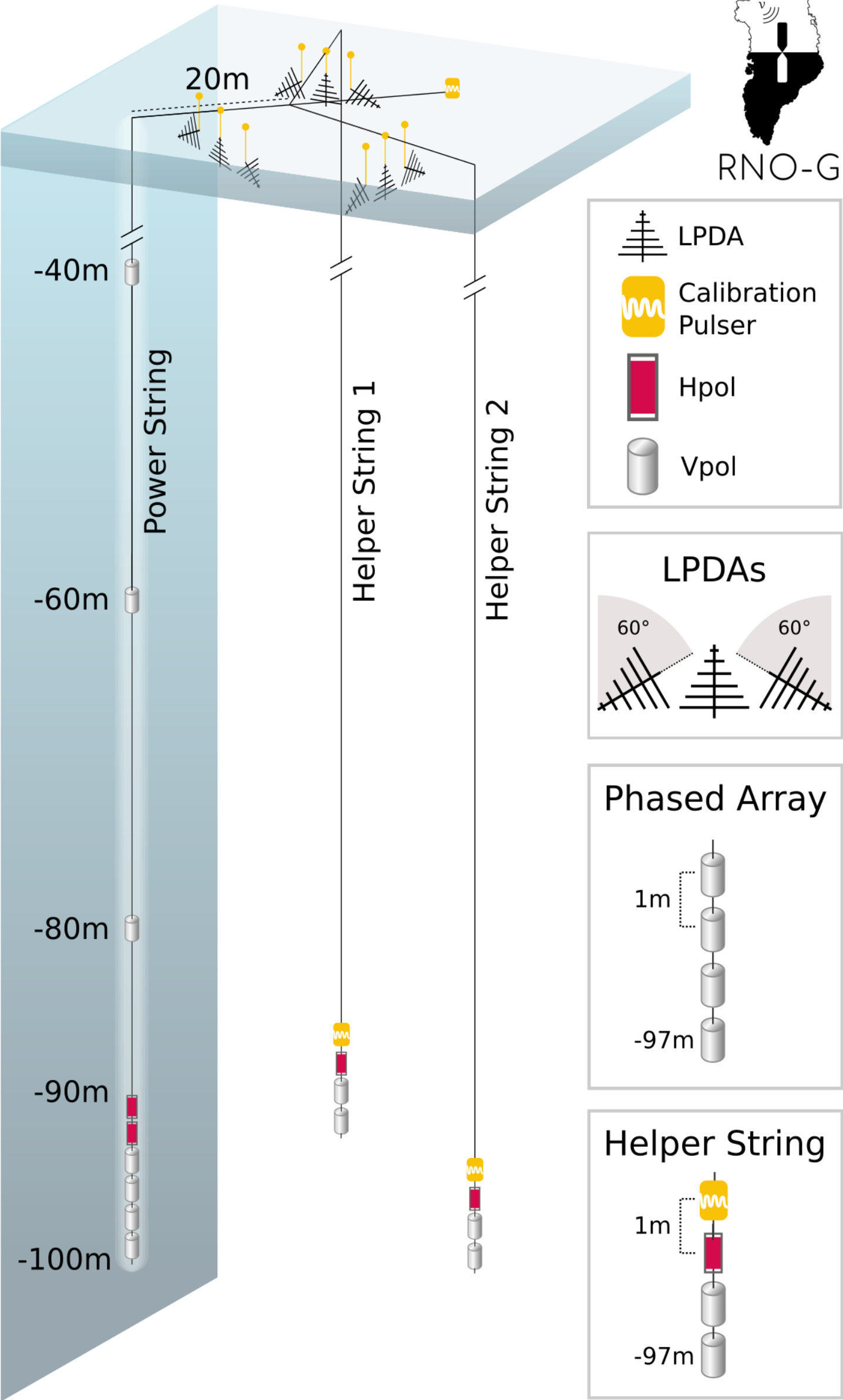
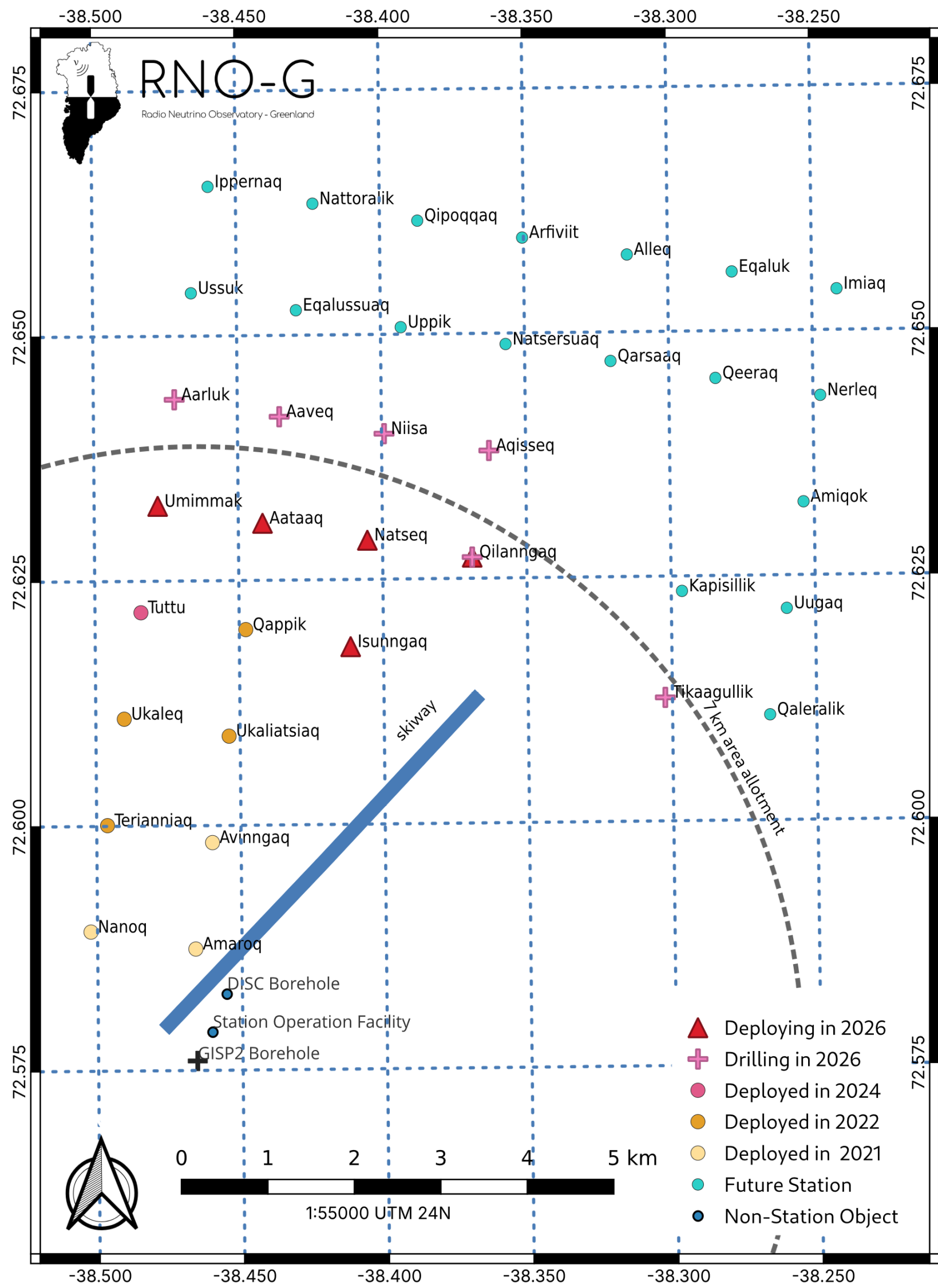


Radio Neutrino Observatory in Greenland (RNO-G)

- RNO-G deployment progresses in Greenland
- air showers detected successfully
- pathfinder for IceCube-Gen2 with chance to provide first radio measurement of UHE neutrinos



RNO-G Coll., ARENA 2026



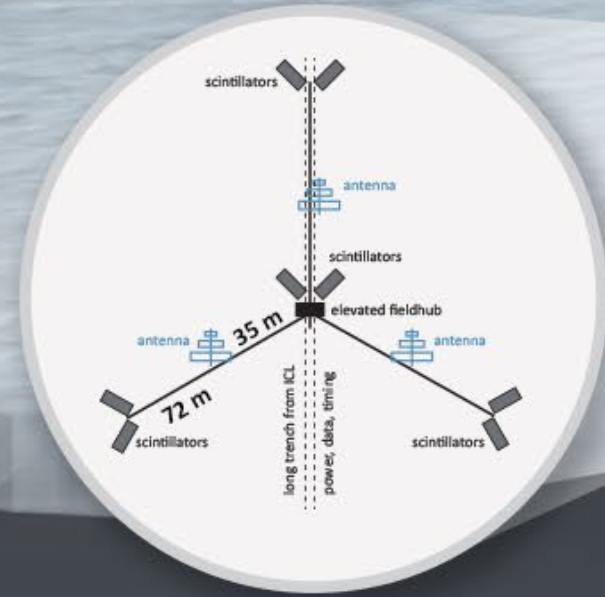


ICECUBE GEN2

DETECTORS

SURFACE • RADIO • OPTICAL

10 year construction project



Cosmic Ray Surface Array

An air shower array that sits on top of the optical array

One surface station installed above each optical string



IceCube-Gen2 Optical Module

4x the sensitivity of IceCube's modules

9,600 new optical modules in total to be deployed in the ice



50 m

1370 m

2780 m

IceCube-Gen2:
120 new strings of optical modules

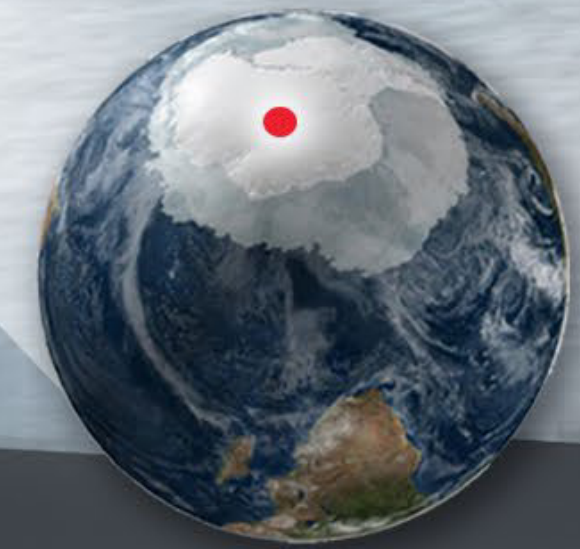
IceCube:
86 strings of optical modules

DeepCore

Antarctic bedrock

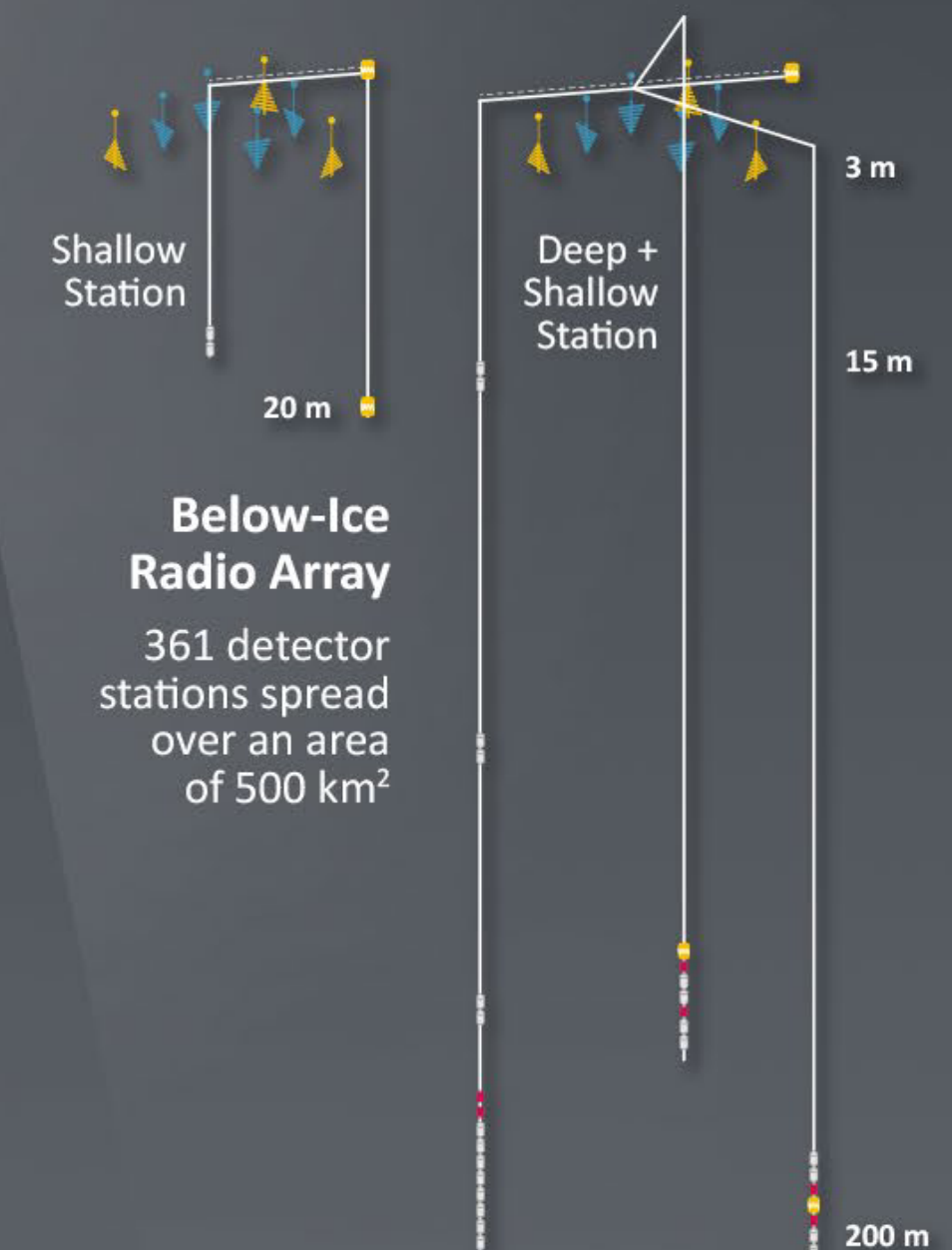
IceCube
(1 km)

IceCube-Gen2
(5 km)



Amundsen-Scott South Pole Station, Antarctica

A National Science Foundation-managed research facility



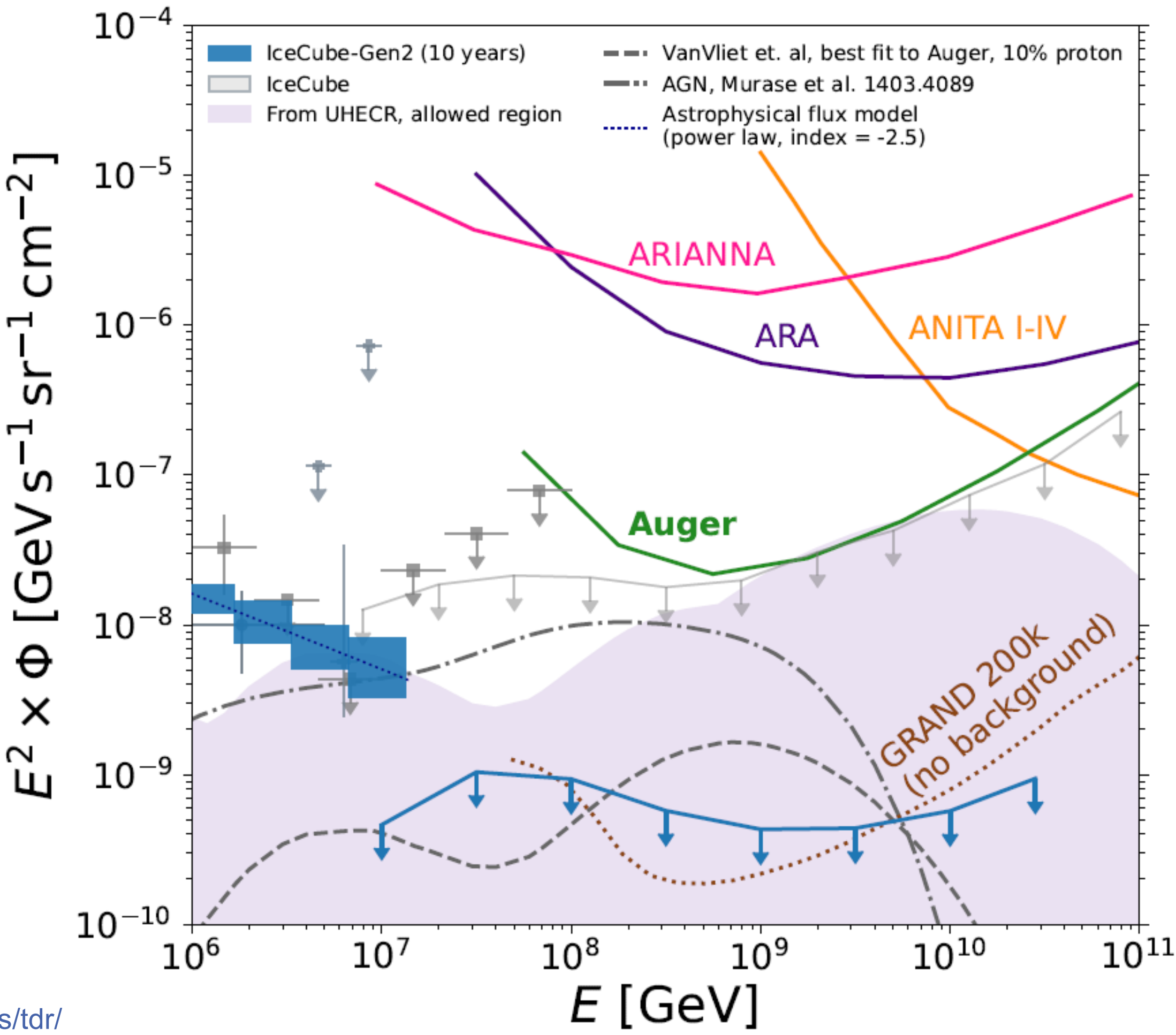
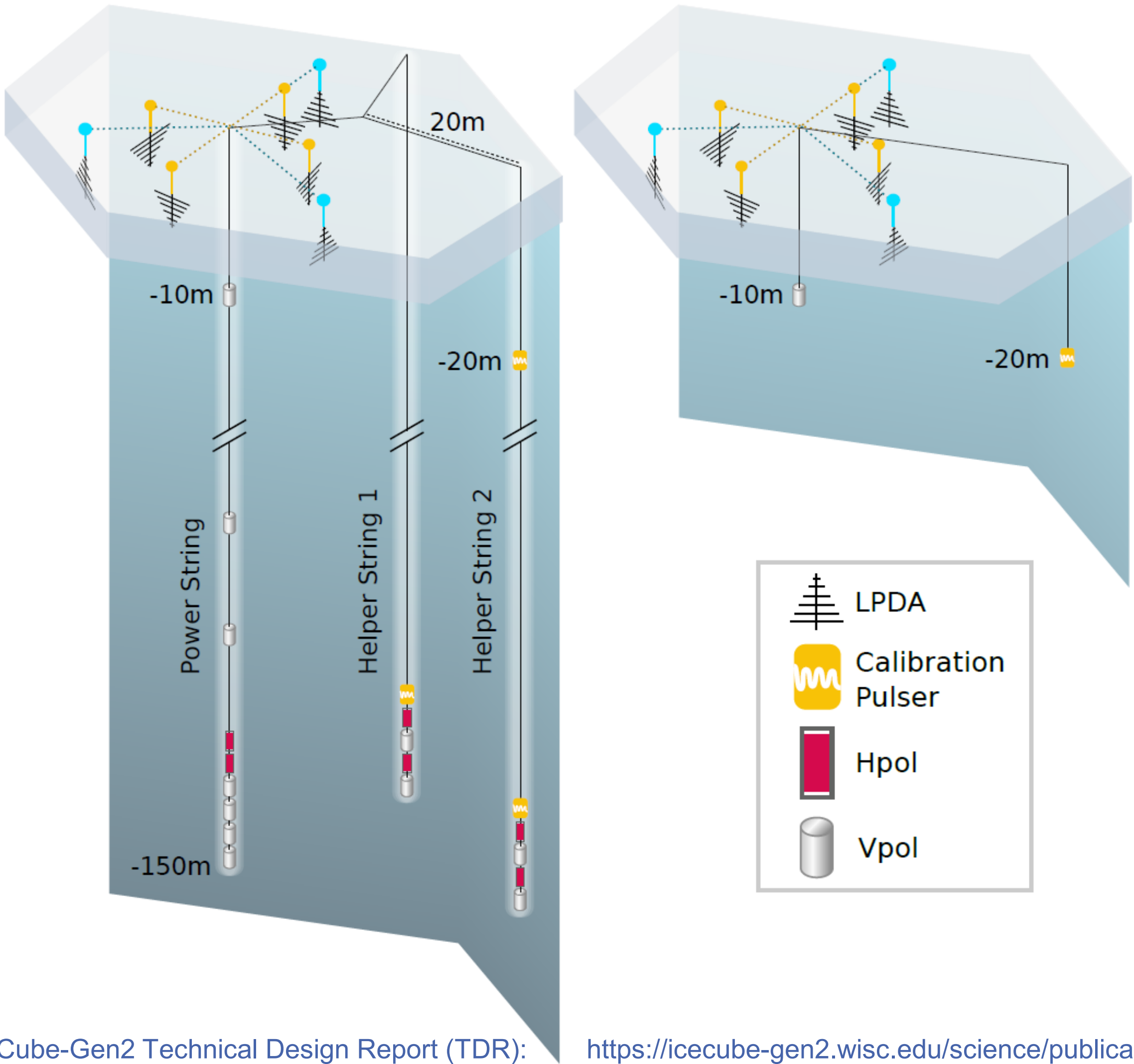
Below-Ice Radio Array

361 detector stations spread over an area of 500 km²

IceCube-Gen2 Radio Array (in-ice)



■ Shallow + deep antennas for in-ice Askaryan emission to detect UHE neutrinos

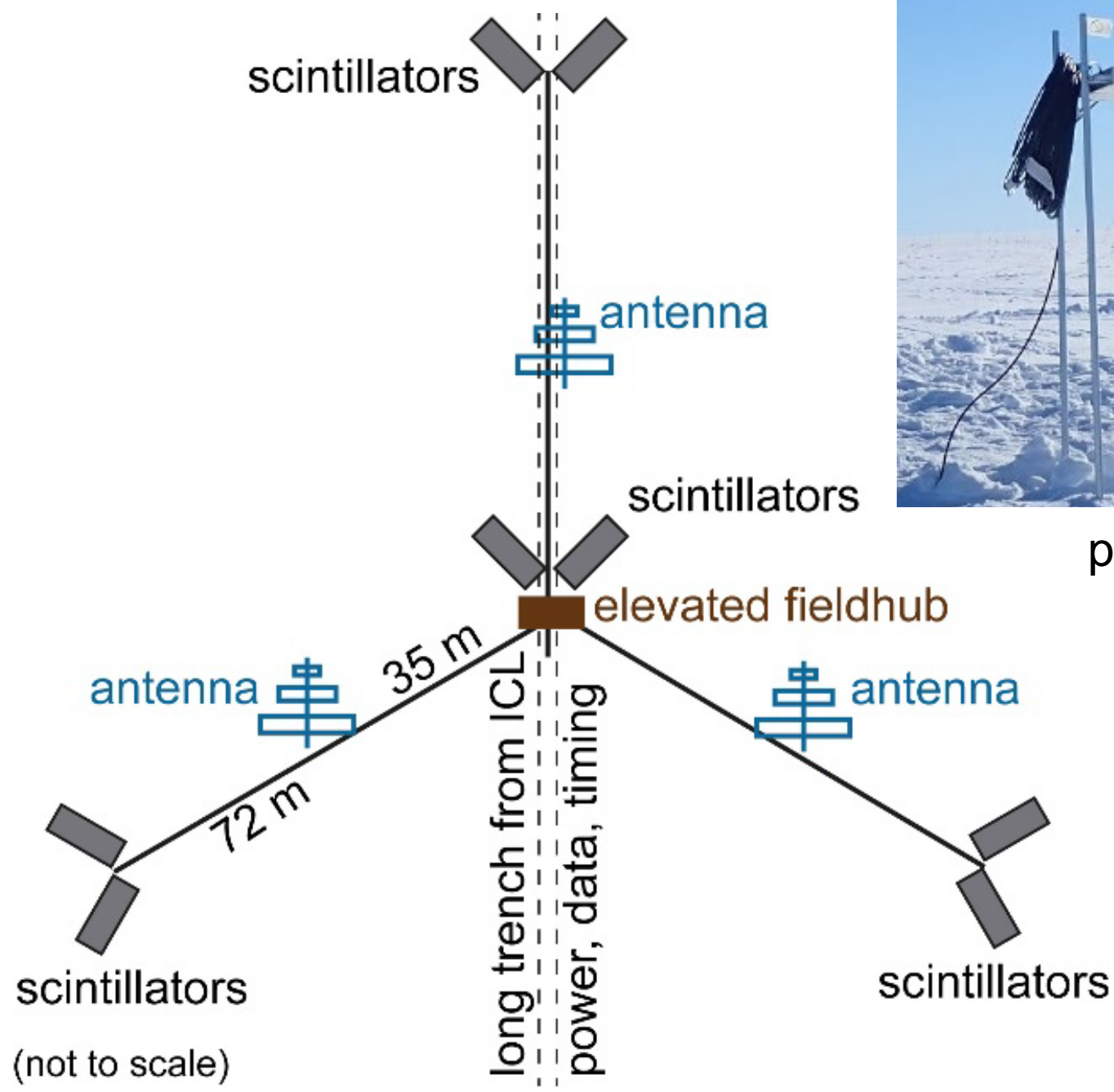
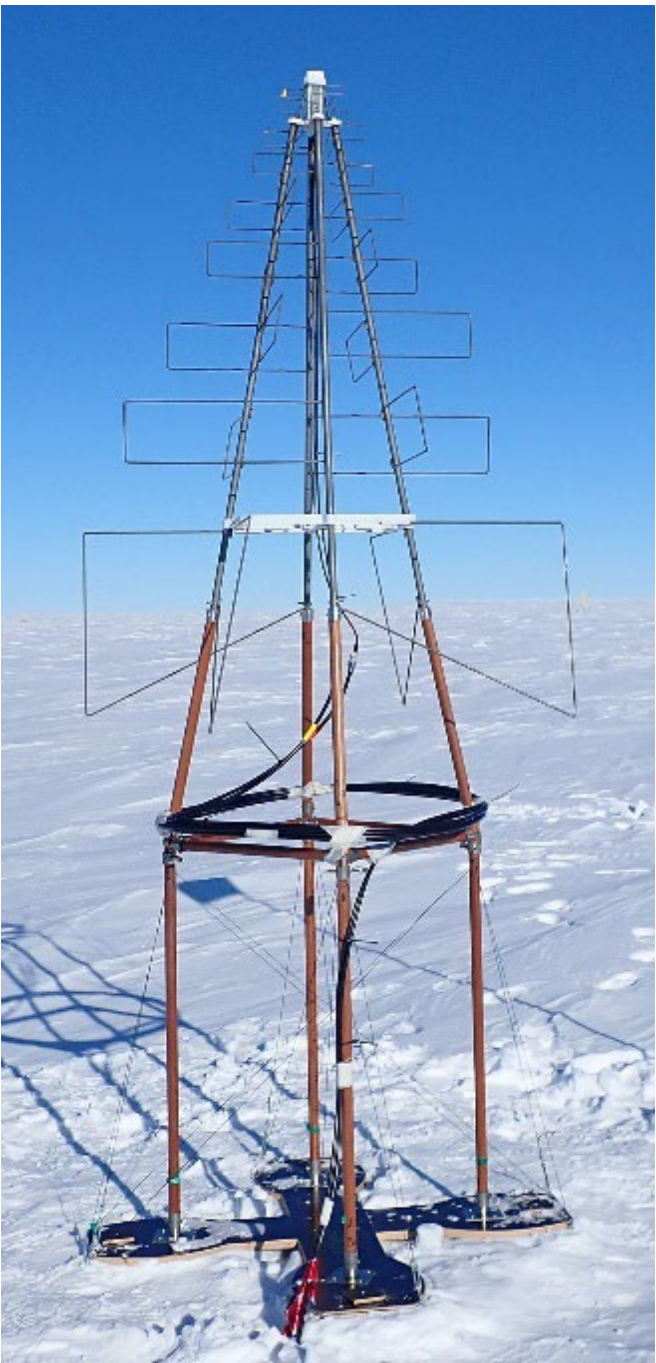


IceCube-Gen2 Surface Array

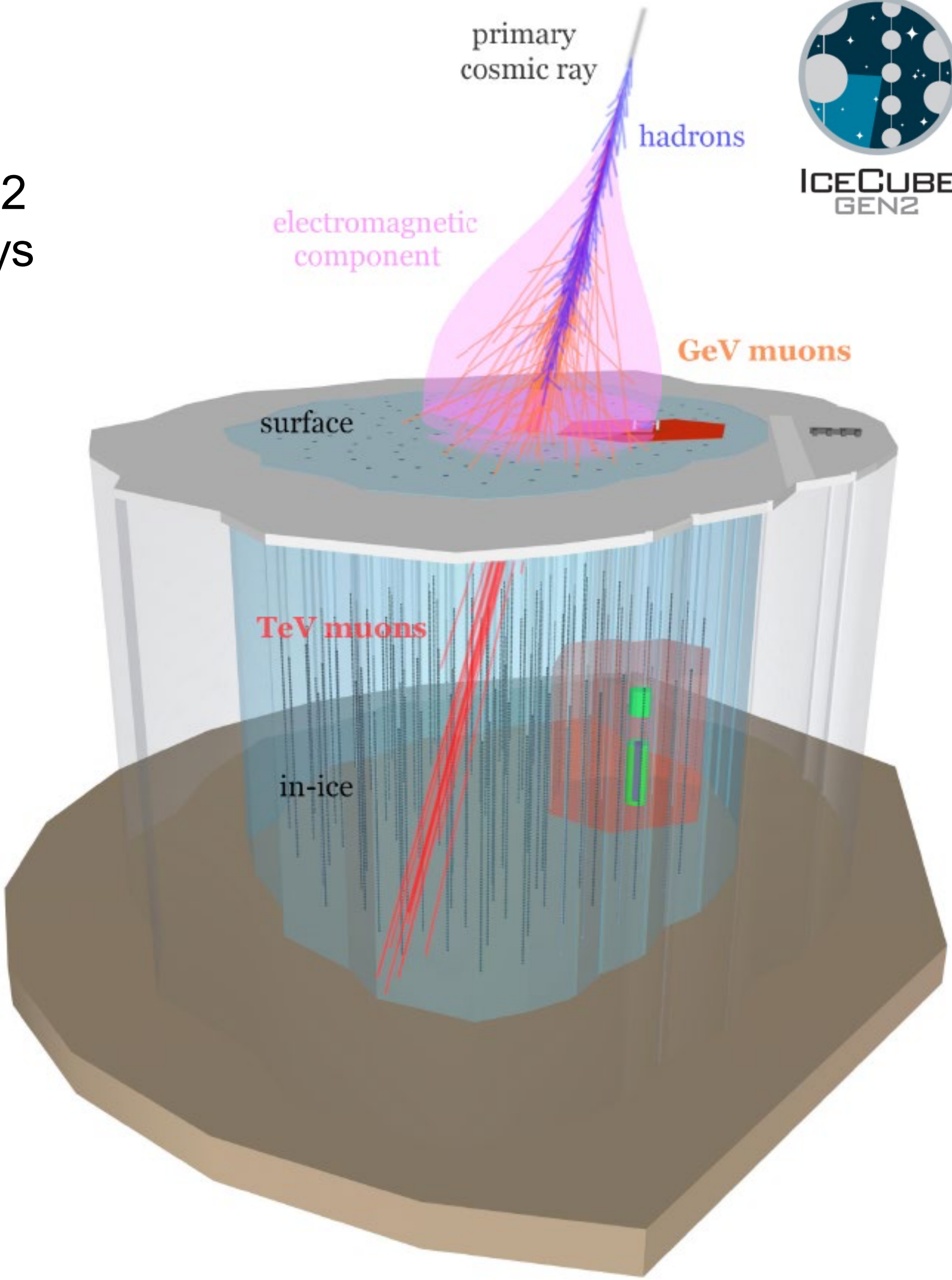
- Combination of deep and surface detector will make IceCube-Gen2 a unique laboratory for air-shower physics and Galactic cosmic rays
- 8x larger area, 30x larger aperture for in-ice coincidences

Surface Array of approx. 150 stations:

4 pairs of scintillators + 3 antennas

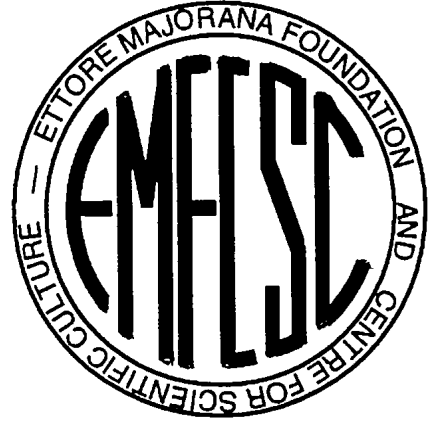


photos: prototype station at South Pole



Radio detection of extensive air showers

Precision measurements of the properties of cosmic rays



Pushing the Frontiers in Radio Detection

- **Cosmic Rays**
 - Large scale arrays and dense arrays are entering a *precision era* for radio
- **Neutrinos: *Scaling Up***
 - Several ideas (Earth-skimming tau, in-ice radio, balloons)
 - First results from prototypes (GRANDProto300, BEACON, ARA, RNO-G)
 - Efforts to move from prototypes to science scale instruments



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