

# Measurements of the highest-energy cosmic rays

XIX Vulcano Workshop  
**FRONTIER OBJECTS IN ASTROPHYSICS  
AND PARTICLE PHYSICS**

Istituto Nazionale di Fisica Nucleare (INFN) and Istituto Nazionale di Astrofisica (INAF)

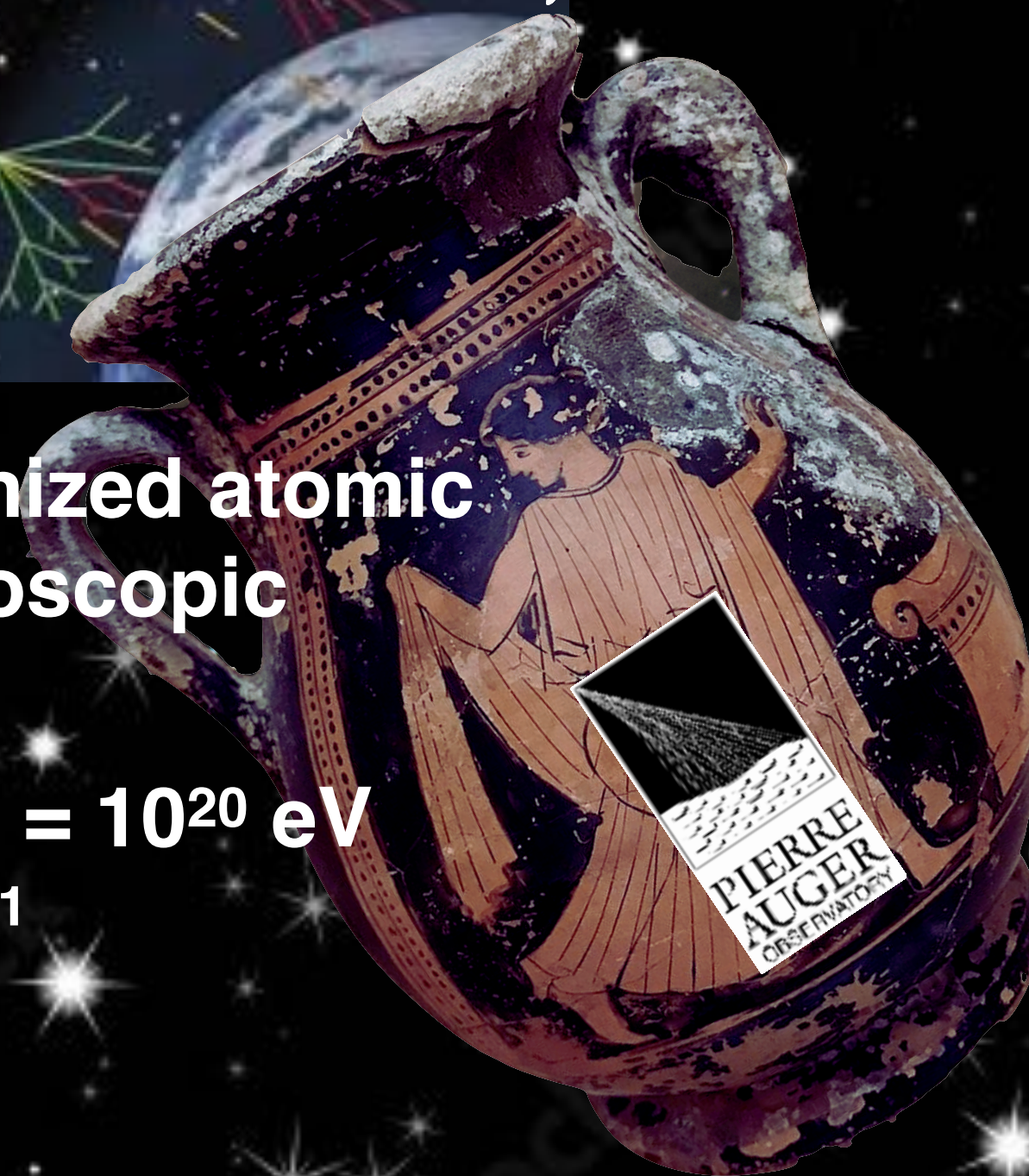
Ischia, Campania (Italy)

May 26th - June 1st, 2024



cosmic rays = ionized atomic nuclei with macroscopic energies

tennisball (50 g) at 90 km/h = 16 J =  $10^{20}$  eV  
Avogadro Number  $N_A = 6 \cdot 10^{23}$  mol<sup>-1</sup>



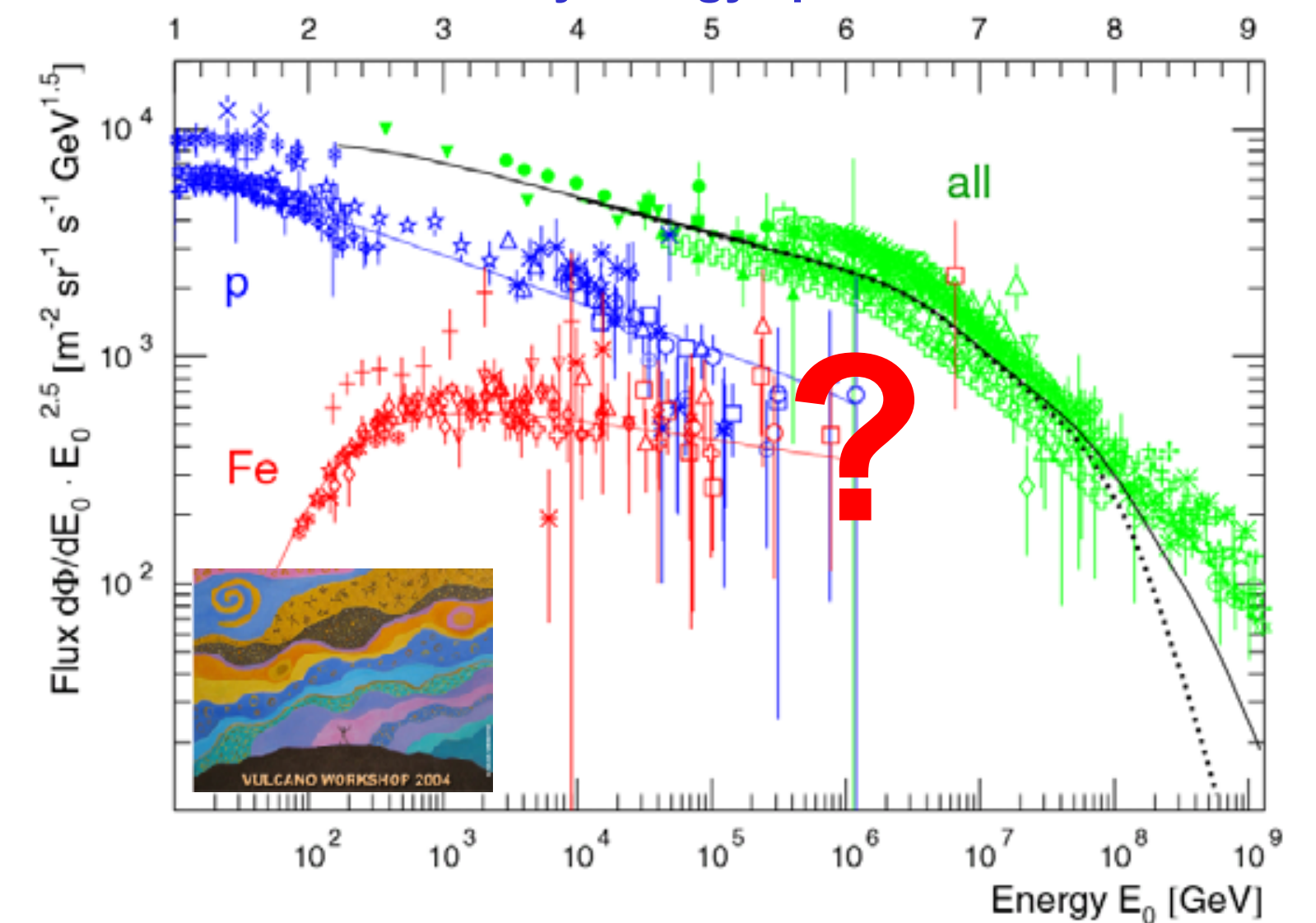
## The Composition of Cosmic Rays at the Knee

Jörg R. Hörandel

University of Karlsruhe, Germany

[www-ik.fzk.de/~joerg](http://www-ik.fzk.de/~joerg)

Cosmic-ray energy spectrum



Frontier Objects in Astrophysics and Particle Physics

Vulcano, Italy, 23-29 May 2004

Jörg R. Hörandel

Radboud University, Nijmegen - Vrije Universiteit Brussel - <http://particle.astro.ru.nl>

# Measurements of the highest-energy cosmic rays

XIX Vulcano Workshop  
FRONTIER OBJECTS IN ASTROPHYSICS  
AND PARTICLE PHYSICS

Istituto Nazionale di Fisica Nucleare (INFN) and Istituto Nazionale di Astrofisica (INAF)

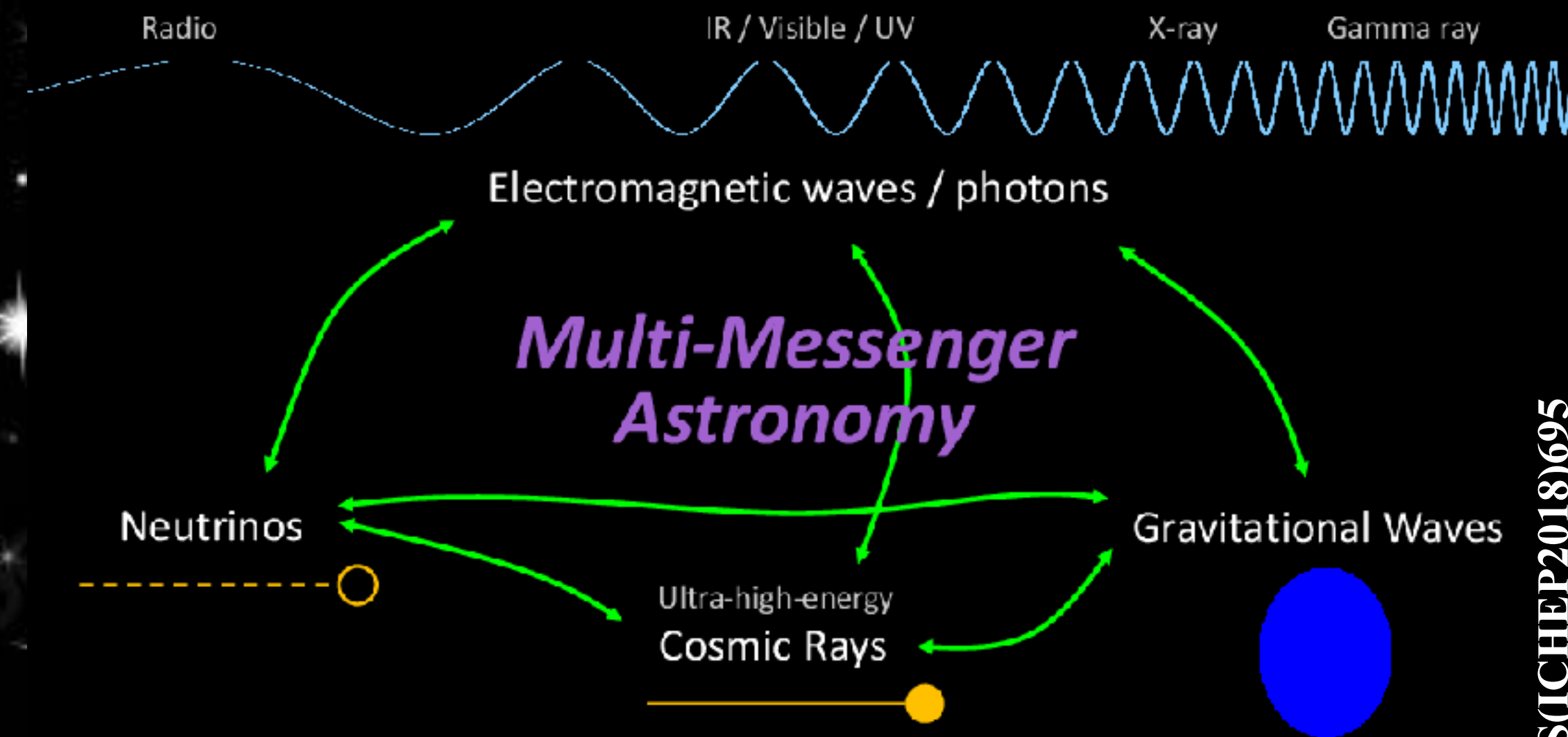
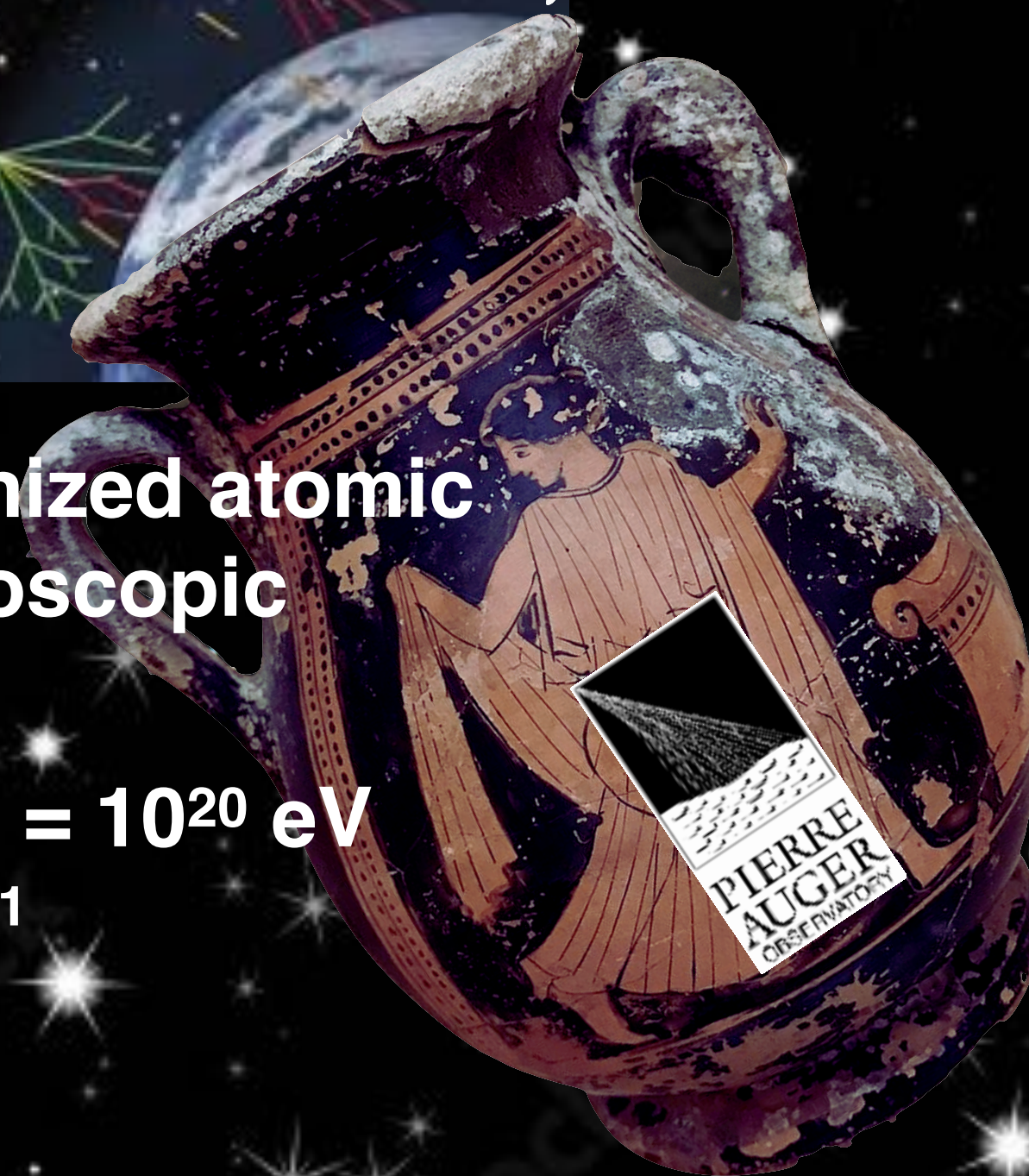
Ischia, Campania (Italy)

May 26th - June 1st, 2024



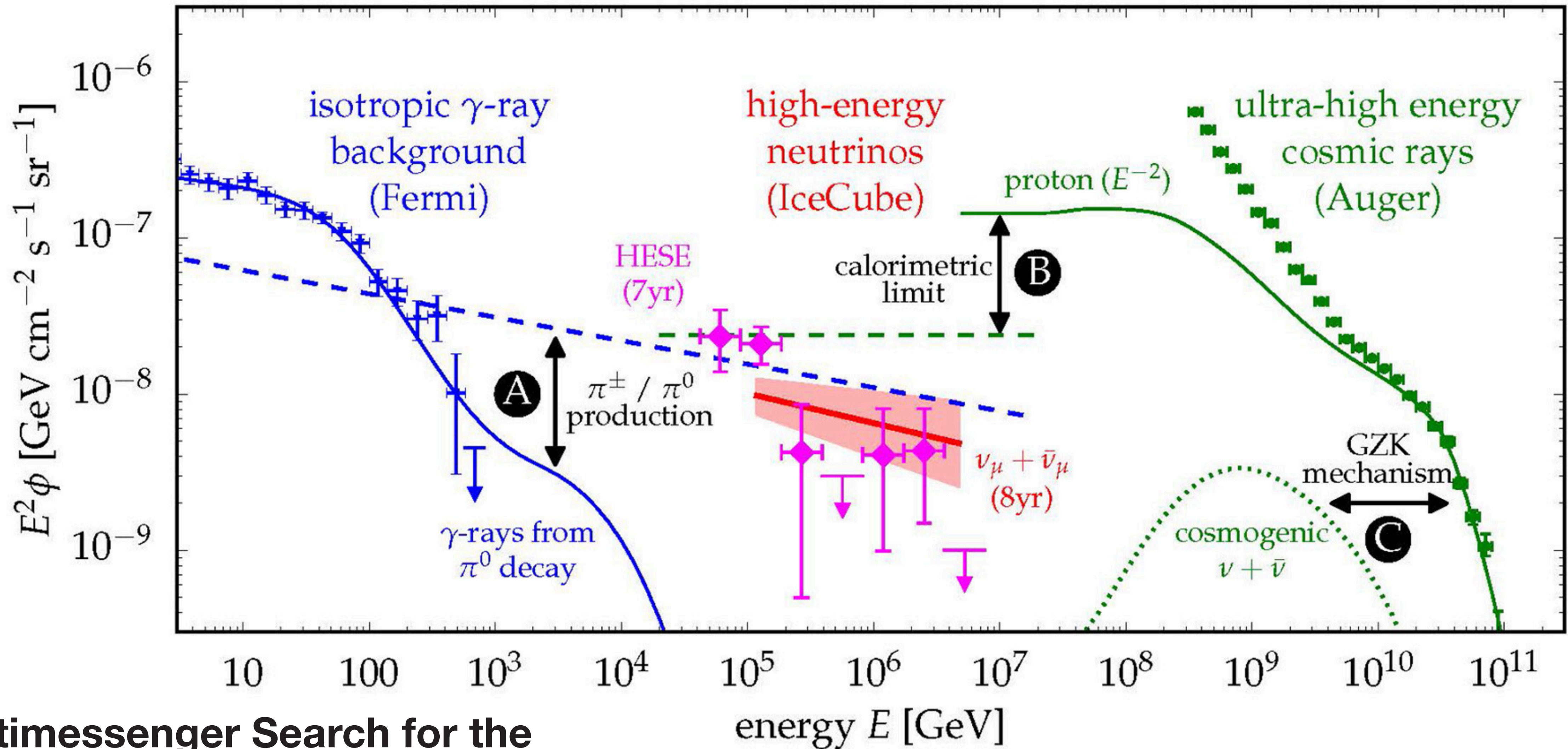
cosmic rays = ionized atomic nuclei with macroscopic energies

tennisball (50 g) at 90 km/h = 16 J =  $10^{20}$  eV  
Avogadro Number  $N_A = 6 \cdot 10^{23} \text{ mol}^{-1}$



Jörg R. Hörandel  
Radboud University, Nijmegen - Vrije Universiteit Brussel - <http://particle.astro.ru.nl>

# Observing the ultra-high-energy Universe



## Multimessenger Search for the Sources of Cosmic Rays Using Cosmic Neutrinos

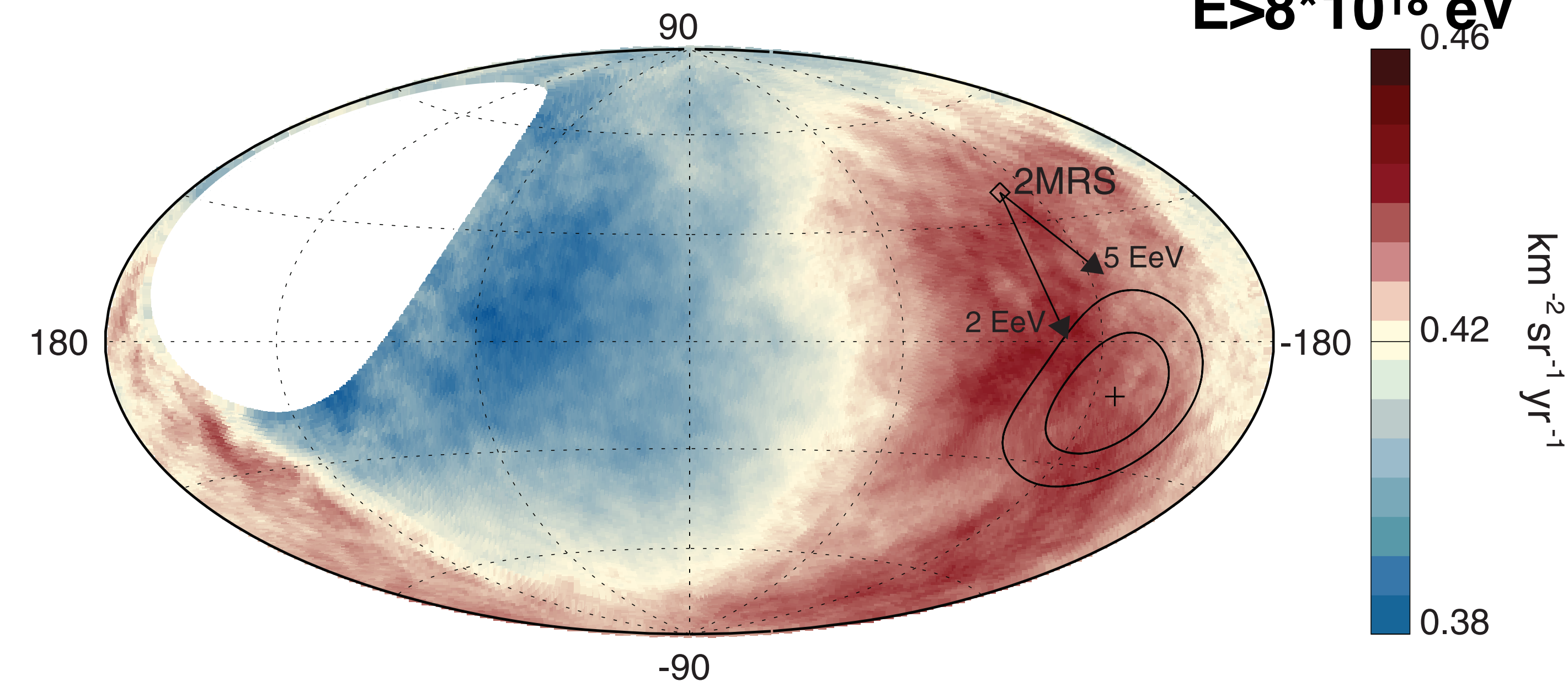
# Observing the ultra-high-energy Universe

## sky map of cosmic rays

Anisotropy detected at  $>5.2$  sigma  
dipole amplitude 6.5%

$3 \cdot 10^4$  CRs

$E > 8 \cdot 10^{18}$  eV



Longitude  $l = 233^\circ$ , Latitude  $b = -13^\circ$

## matter from other galaxies

The existence of such particles imposes immediate, yet to be answered questions:

- What are the **physics processes** involved to produce these particles?
- Are they decay or annihilation products of **Dark Matter**? If they are accelerated in violent astrophysical environments:

- How is Nature being able to **accelerate particles to such energies**?

- What are the **sources** of the particles? Do we understand the **physics of the sources**?

- Is the **origin** of those particles connected to the recently observed mergers of compact objects – the **gravitational wave sources**?

The highly-relativistic particles also provide the unique possibility to study (particle) physics at its extremes:

- Is **Lorentz invariance** (still) valid under such conditions? How do these particles interact?
- Are their **interactions** described by the **Standard Model** of particle physics?

When the energetic particles interact with the atmosphere of the Earth, hadronic interactions can be studied:

- What is the **proton interaction cross section** at such energies?

# Active galaxy M87

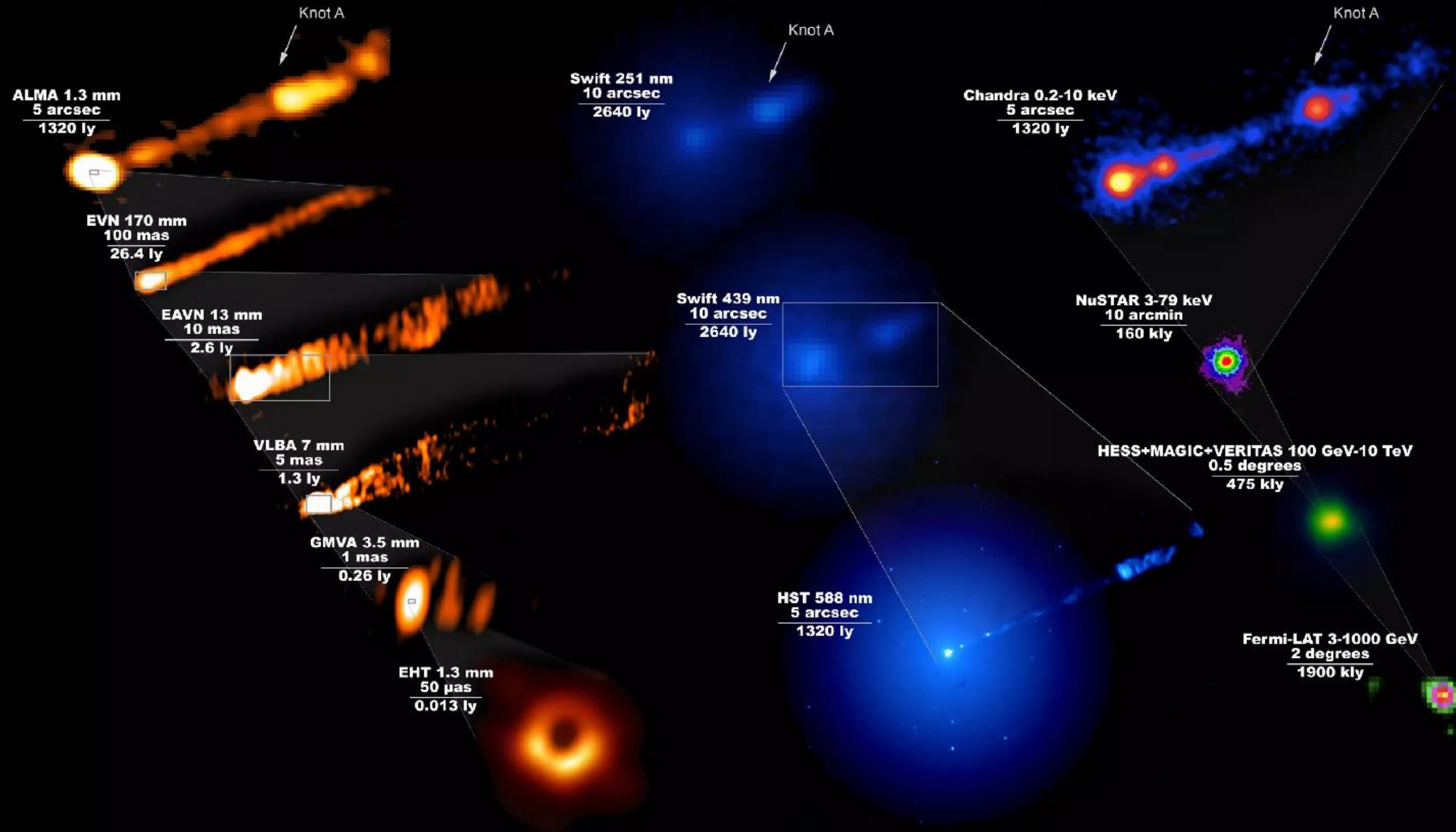


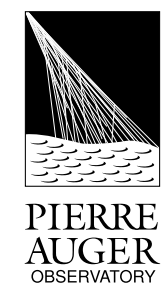
Image Credit: The EHT Multi-wavelength Science Working Group; the EHT Collaboration; ALMA (ESO/NAOJ/NRAO); the EVN; the EAVN Collaboration; VLBA (NRAO); the GMVA; the Hubble Space Telescope; the Neil Gehrels Swift Observatory; the Chandra X-ray Observatory; the Nuclear Spectroscopic Telescope Array; the Fermi-LAT Collaboration; the H.E.S.S collaboration; the MAGIC collaboration; the VERITAS collaboration; NASA and ESA. Composition by J. C. Algaba

# Constraining cosmic-ray sources



Journal of **C**osmology and **A**stroparticle **P**hysics  
An IOP and SISSA journal

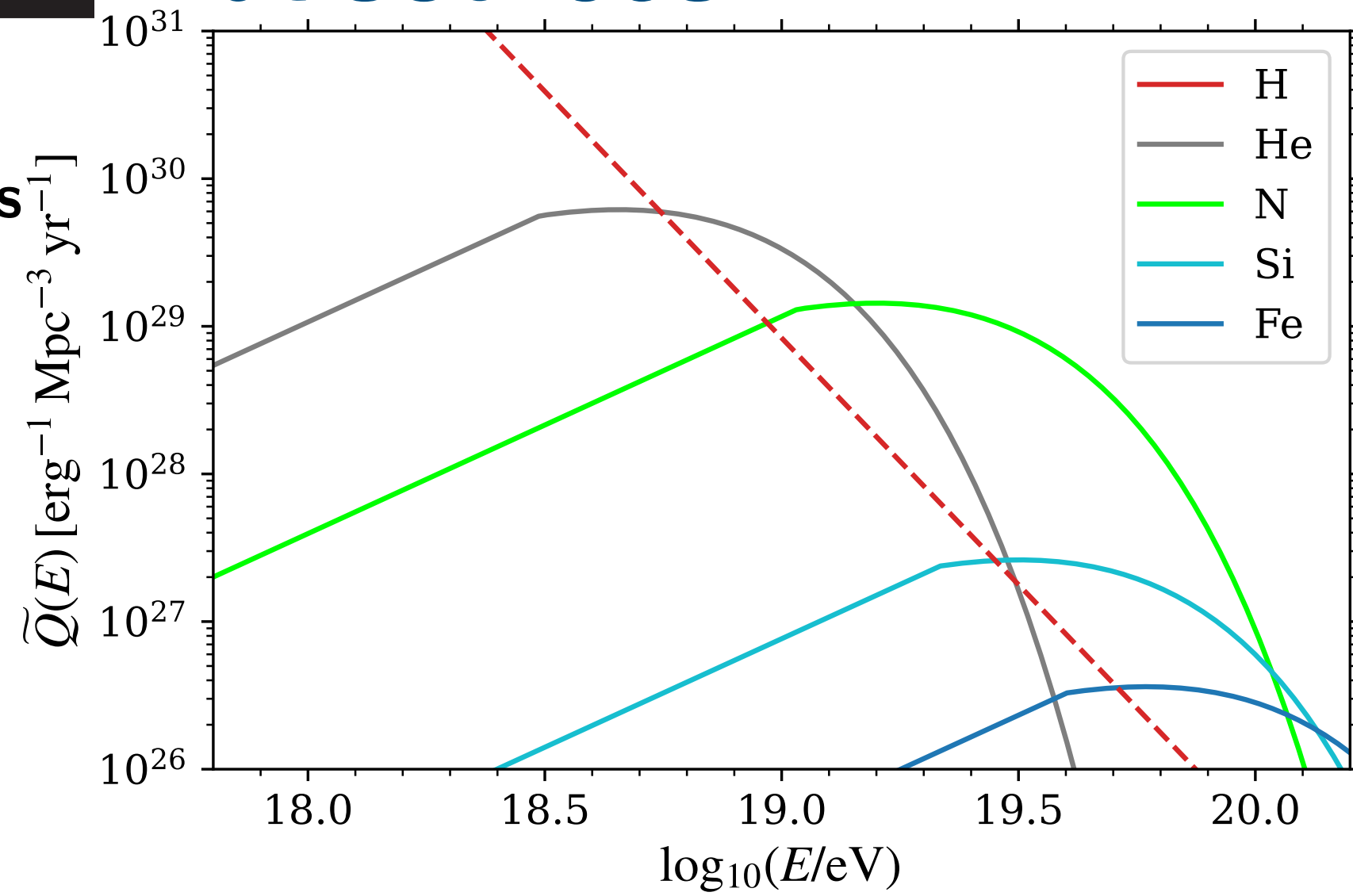
Constraining the sources of ultra-high-energy cosmic rays across and above the ankle with the spectrum and composition data measured at the Pierre Auger Observatory



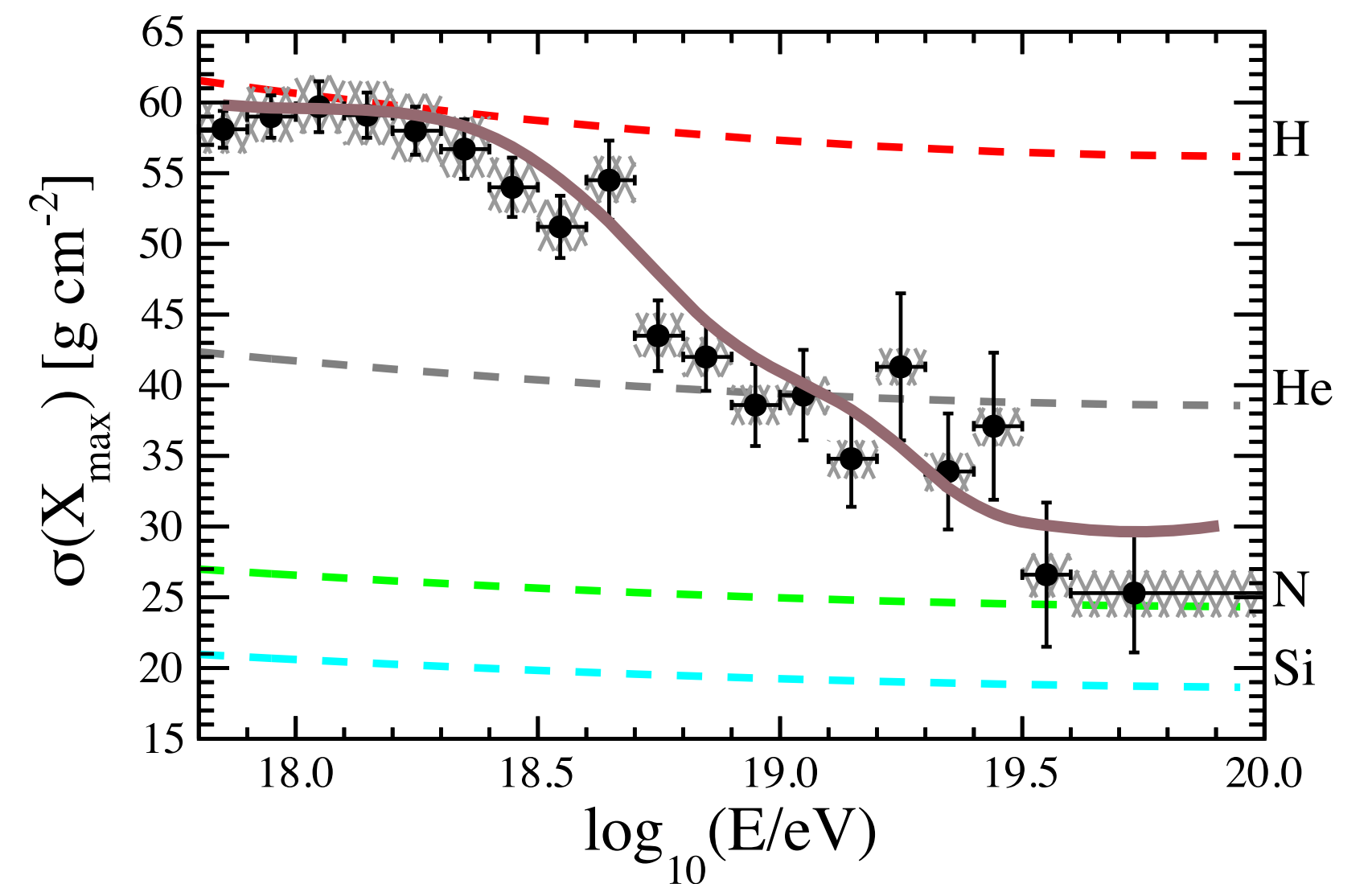
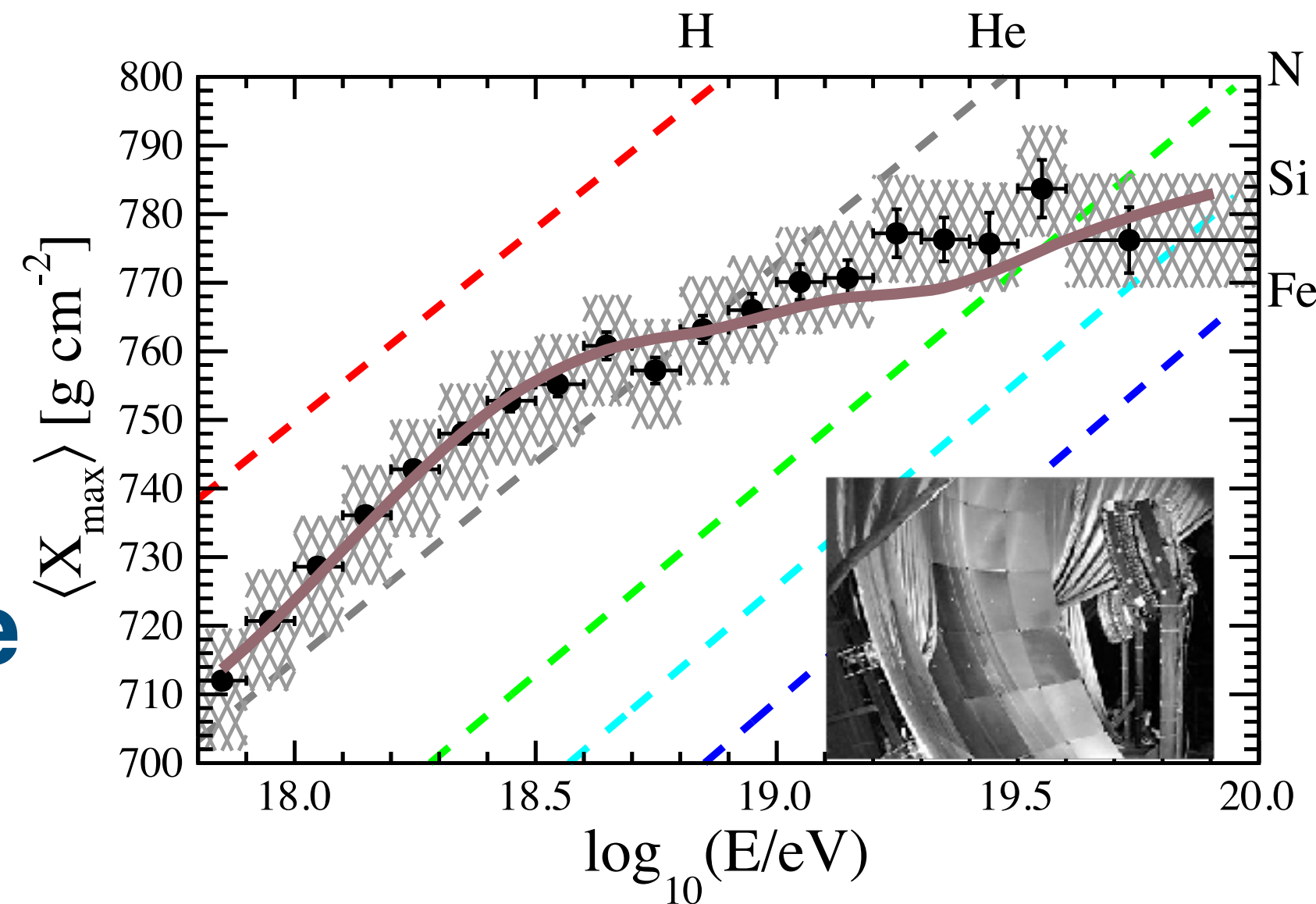
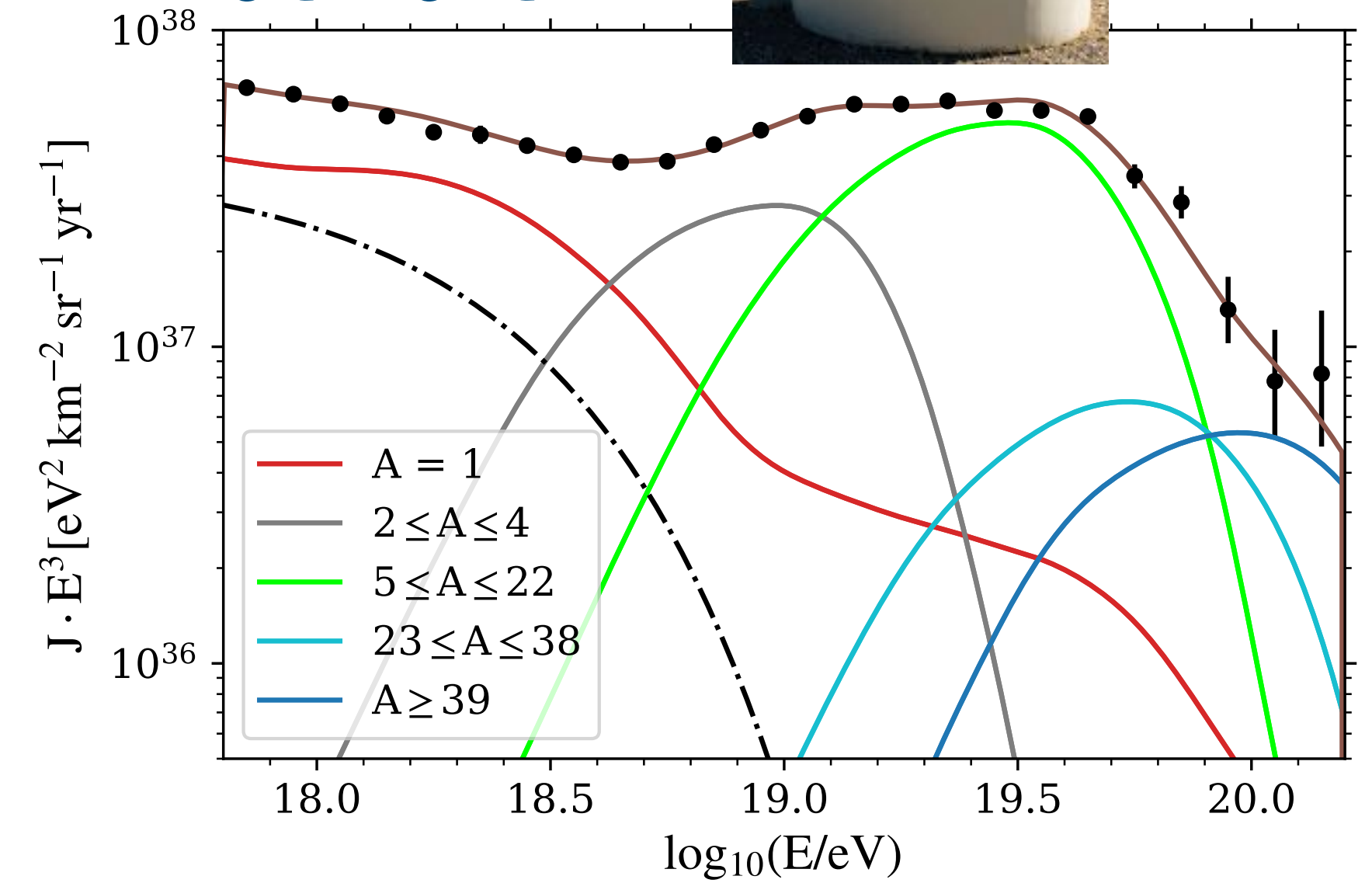
PIERRE AUGER OBSERVATORY

combining  
spectrum & mass  
composition  
information  
fluorescence  
detector & surface  
detector

at sources



at Earth

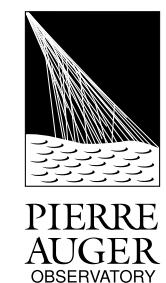


# Constraining cosmic-ray sources



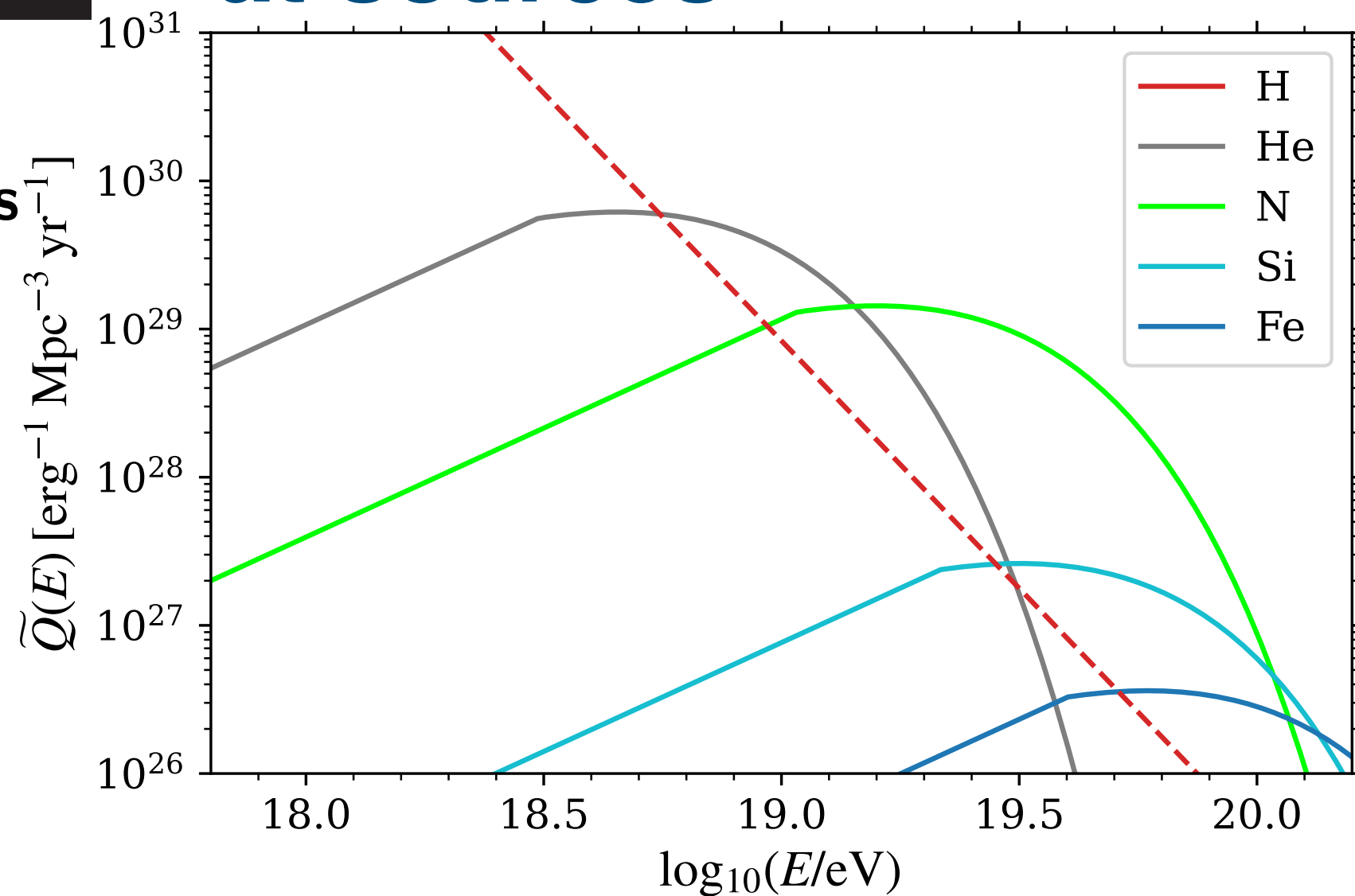
Journal of **Cosmology and Astroparticle Physics**  
An IOP and SISSA journal

Constraining the sources of ultra-high-energy cosmic rays across and above the ankle with the spectrum and composition data measured at the Pierre Auger Observatory

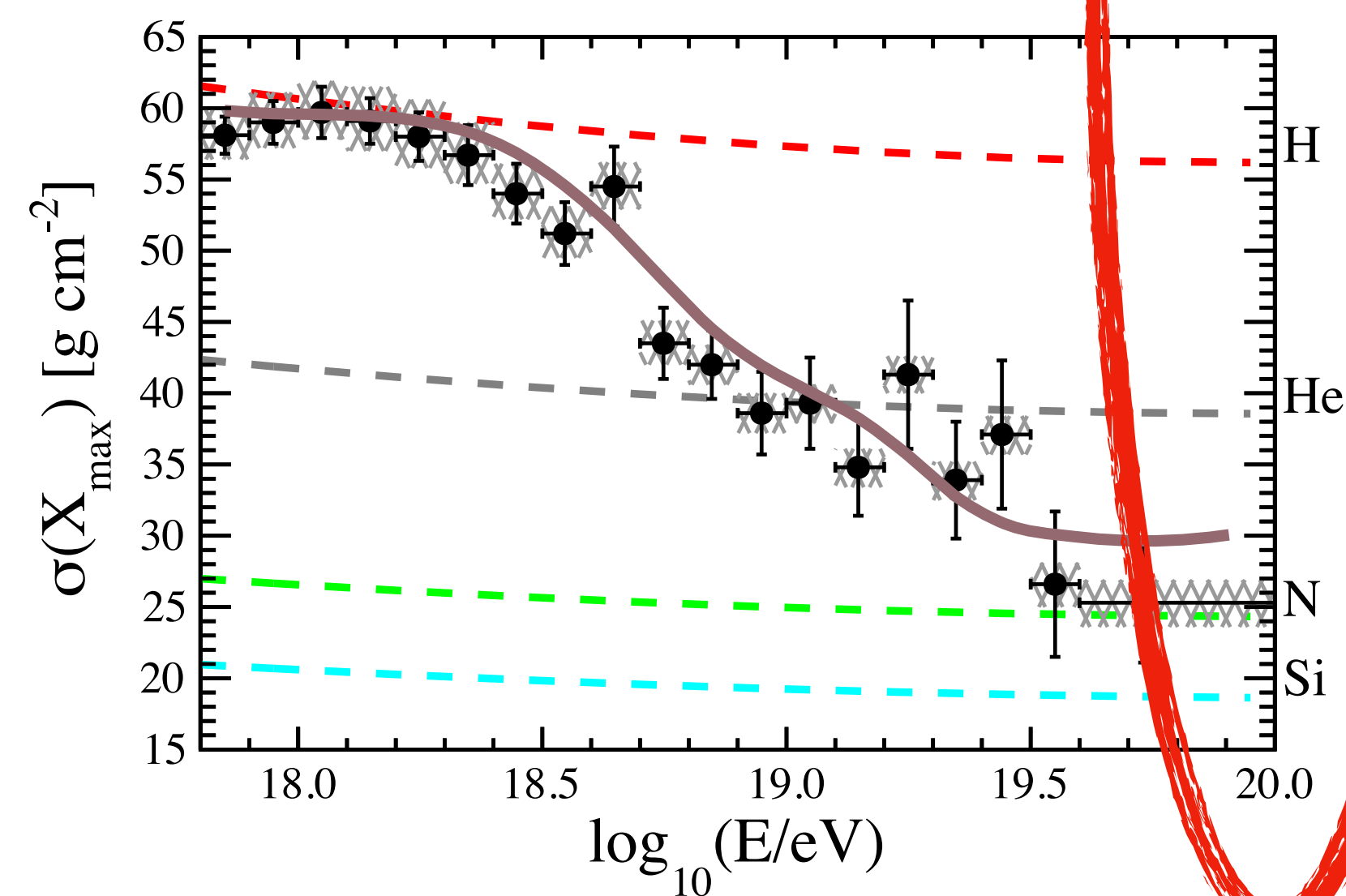
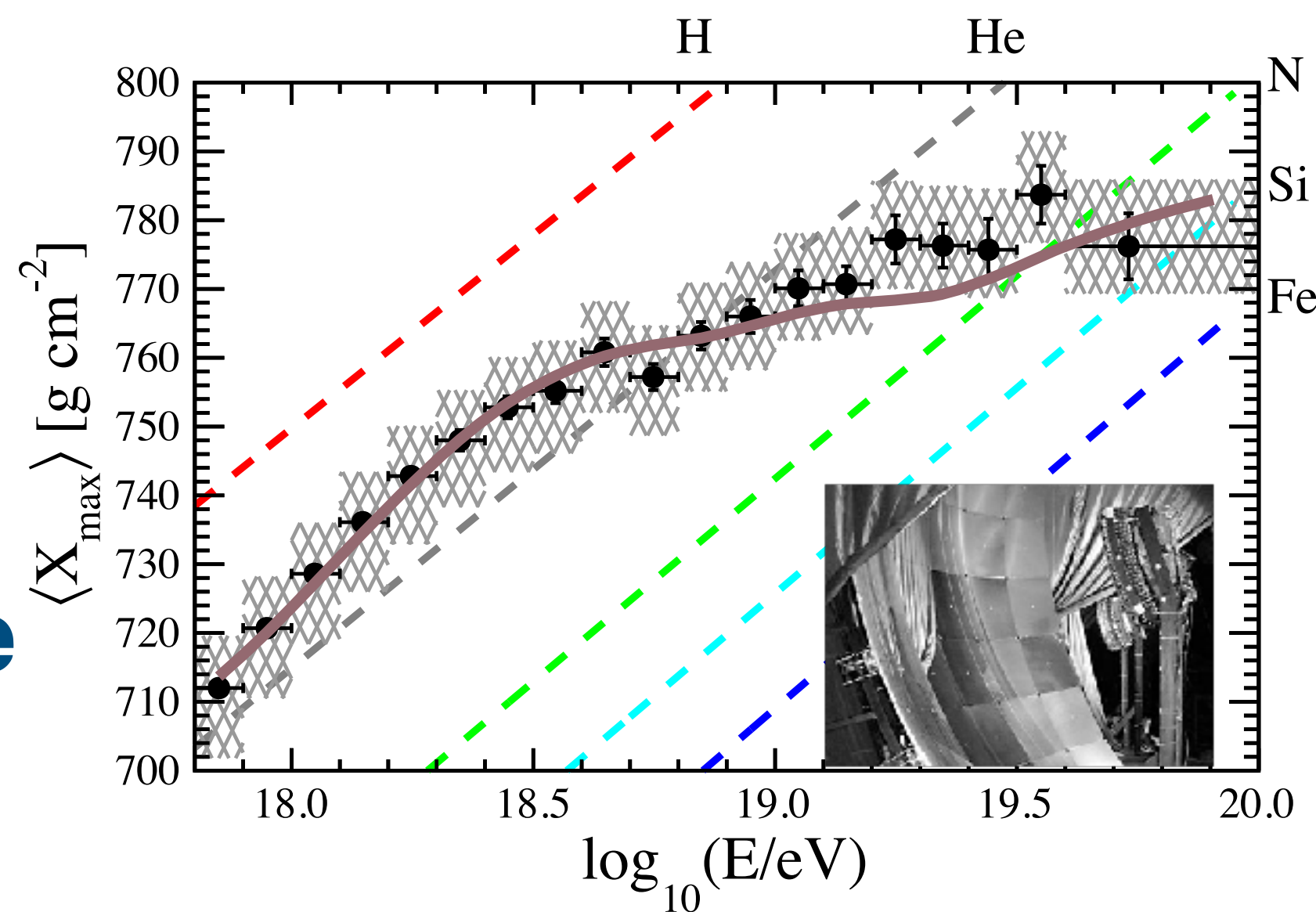
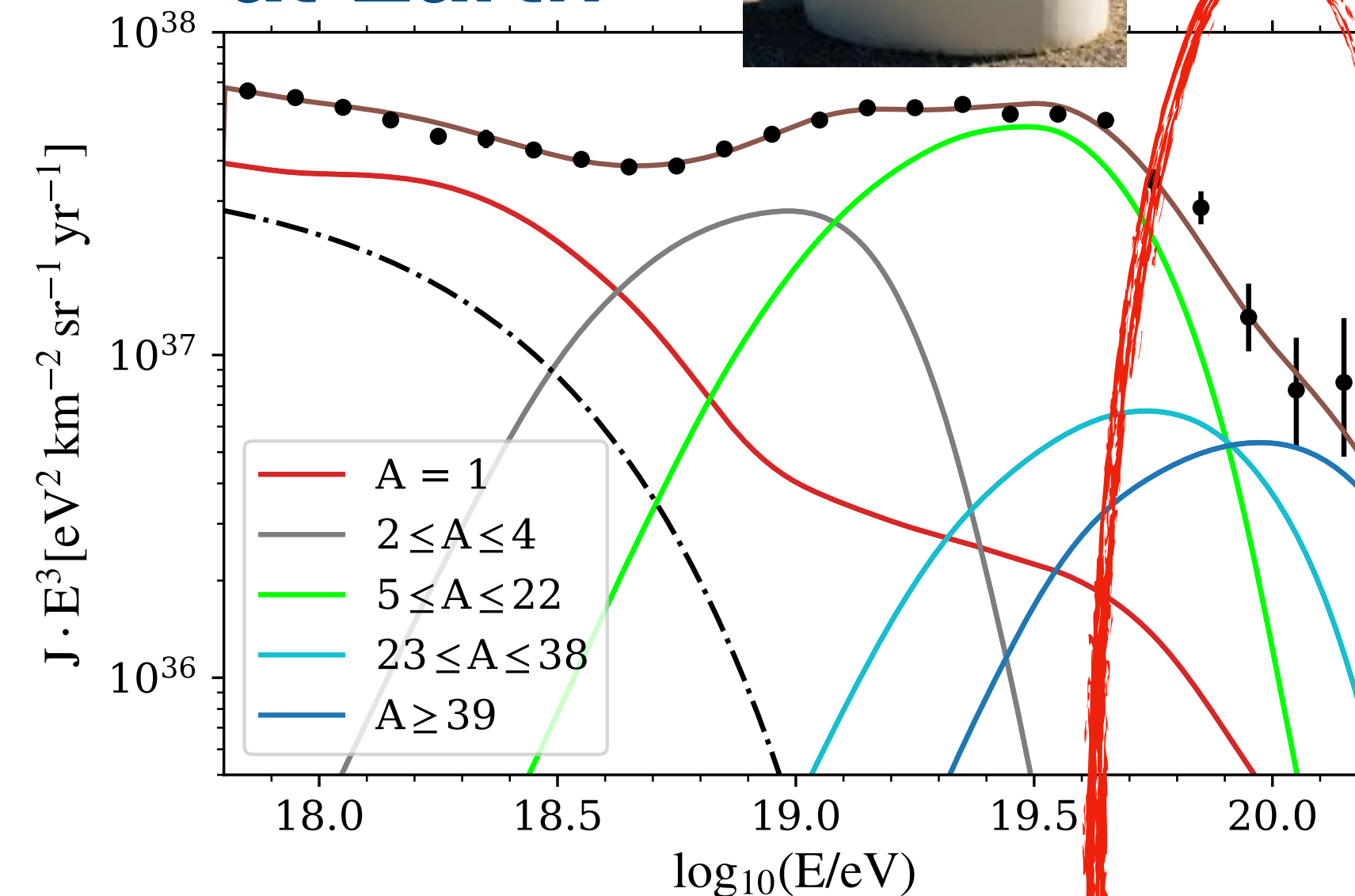


combining  
spectrum & mass  
composition  
information  
fluorescence  
detector & surface  
detector

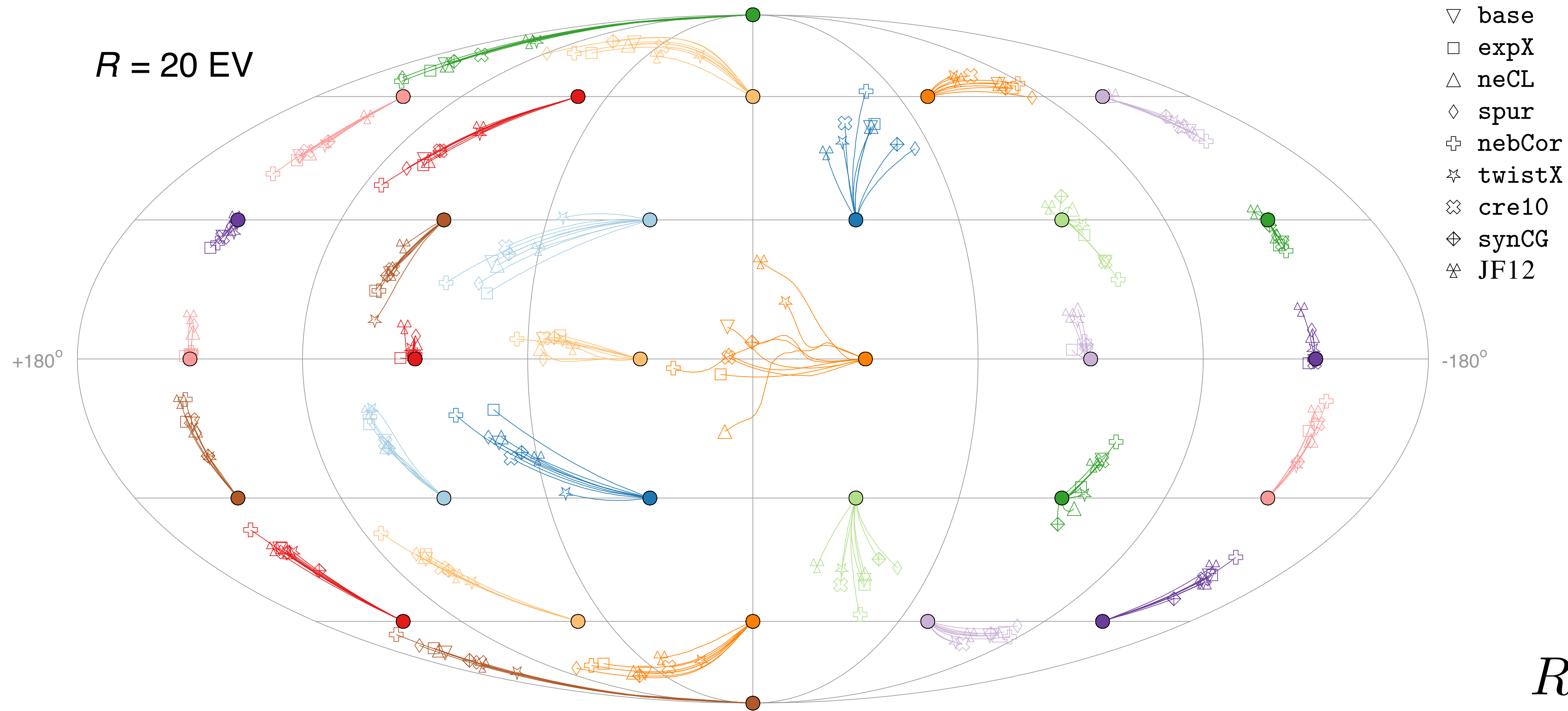
at sources



at Earth



# 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 ( $2 \times 10^{19}$  V). Filled circles denote a grid of arrival directions and the open symbols are the back-tracked directions at the edge of the Galaxy.

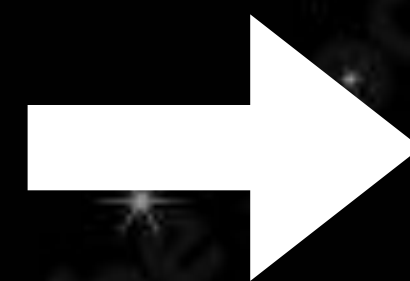
**The Coherent Magnetic Field of the Milky Way**

MICHAEL UNGER <sup>1,2</sup> AND GLENNYS R. FARRAR <sup>3</sup>

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



# The Upgrade of the Pierre Auger Observatory



provide **good mass sensitivity** up to the highest energies

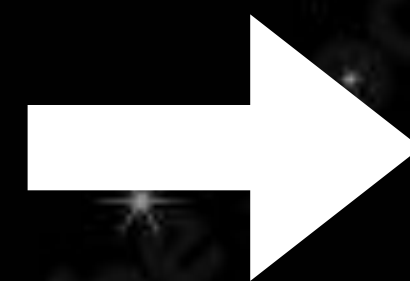
1999 start Pierre Auger observatory

2008 installation completed

2024 upgrade completed



# The Upgrade of the Pierre Auger Observatory



provide **good mass sensitivity** up to the highest energies

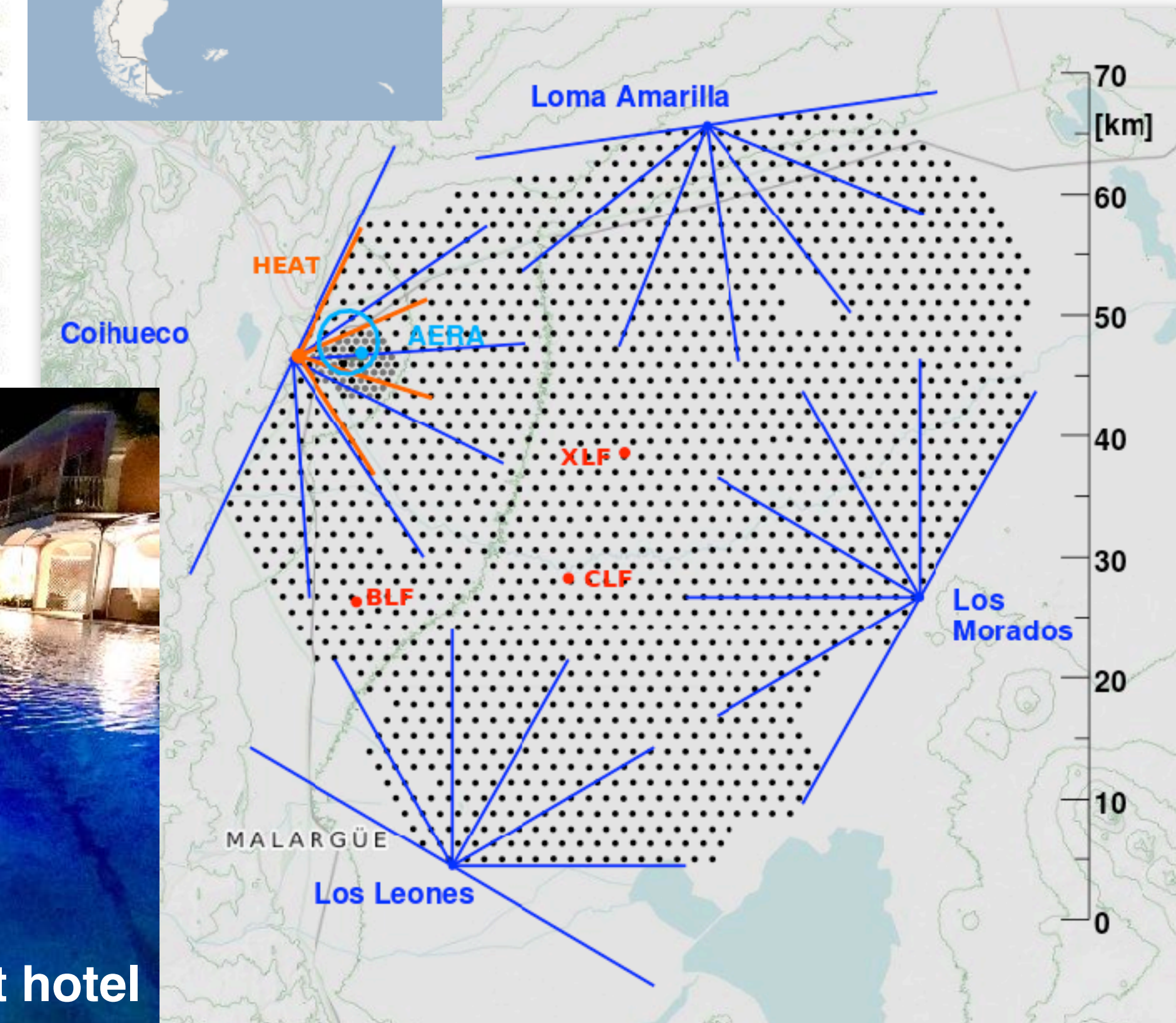
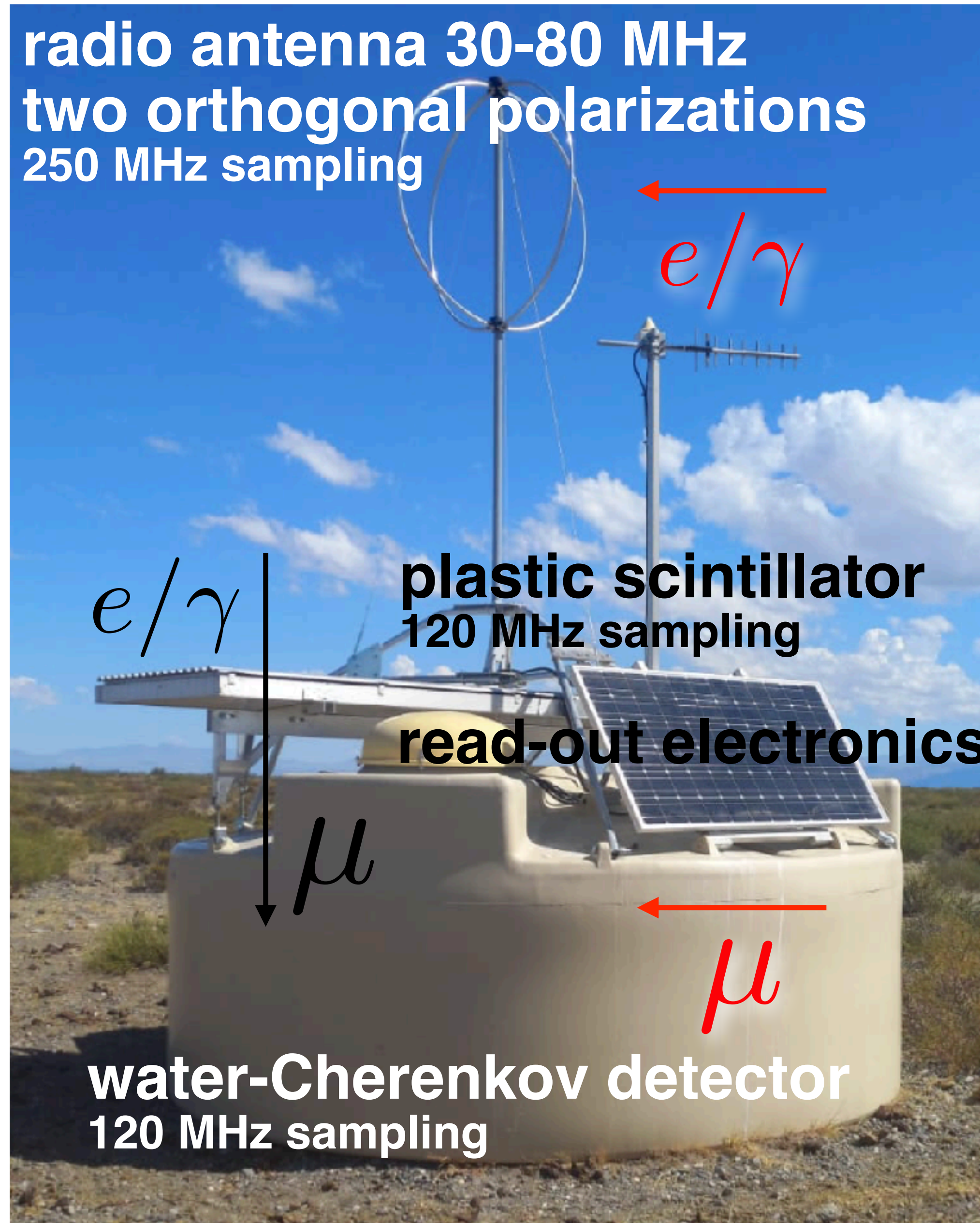


1999 start Pierre Auger observatory

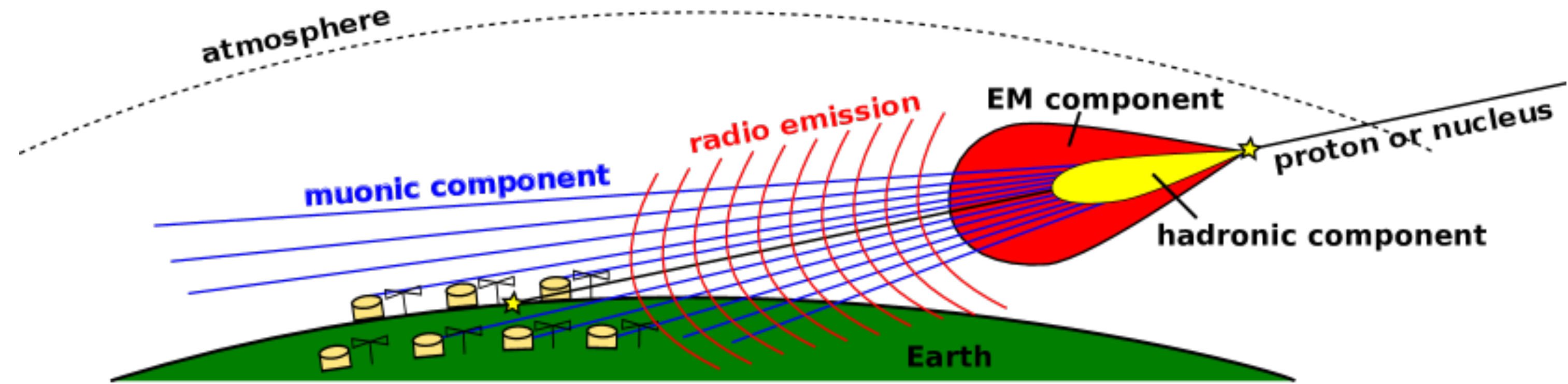
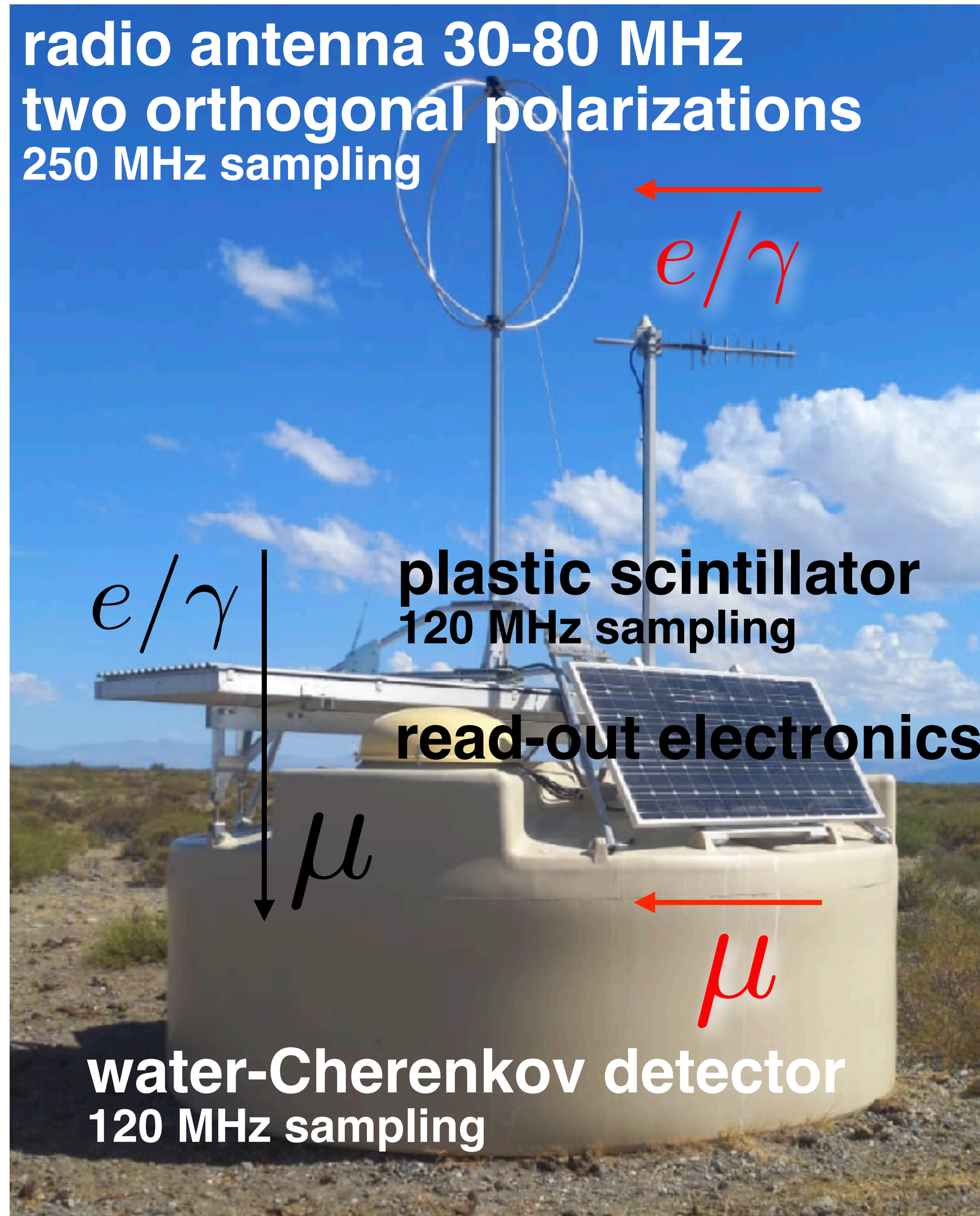
2008 installation completed

2024 upgrade completed

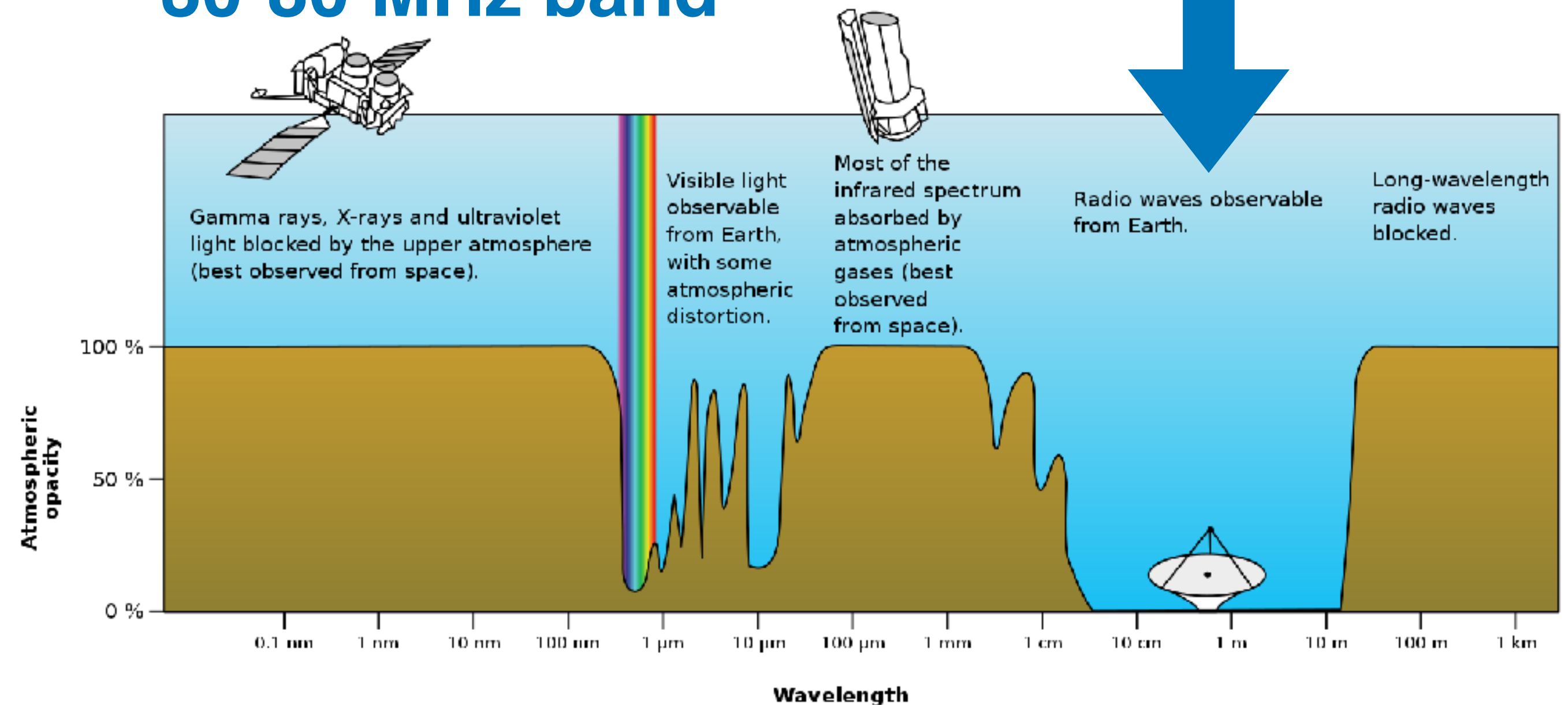
# Upgraded Surface Detector of Auger Observatory



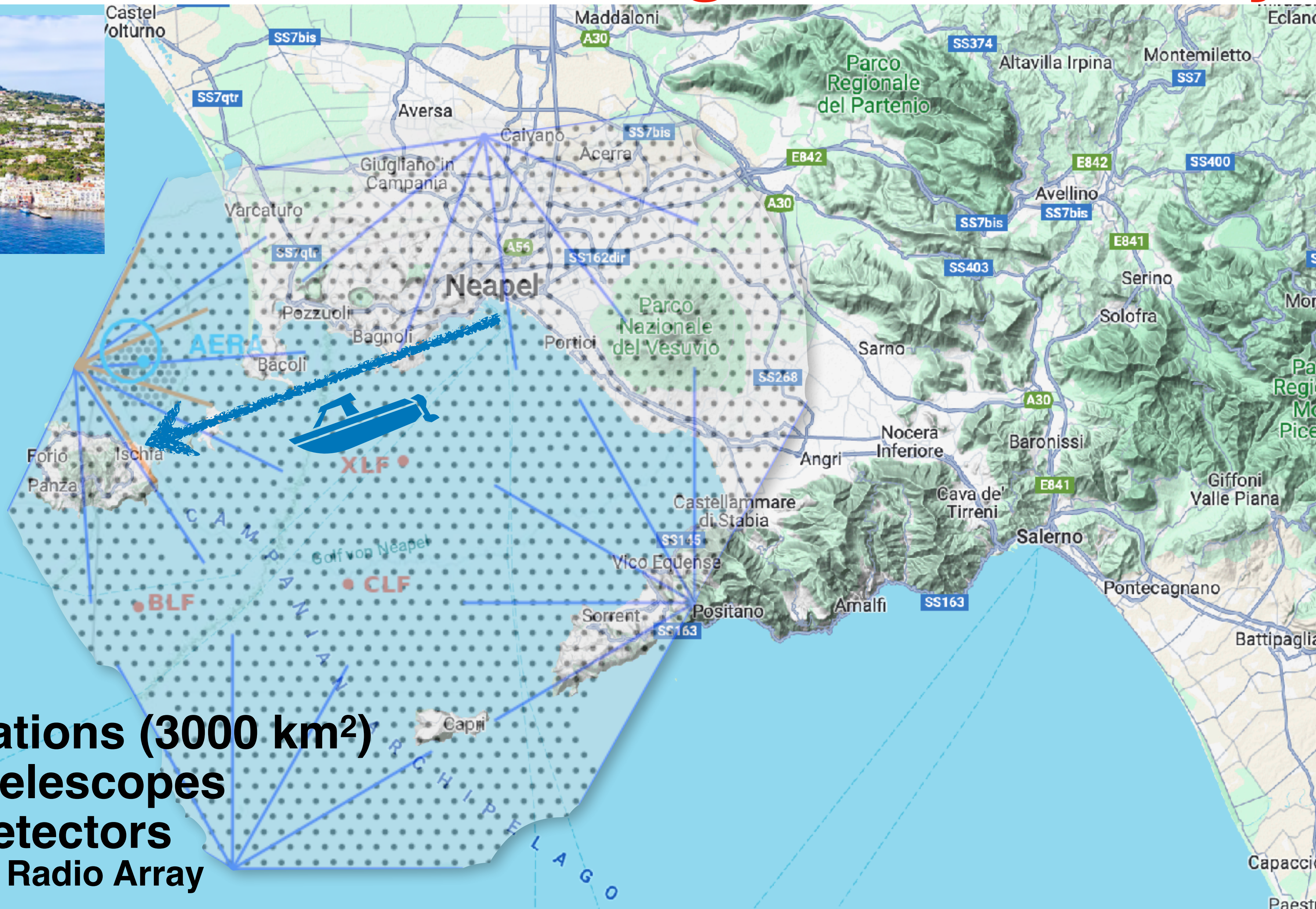
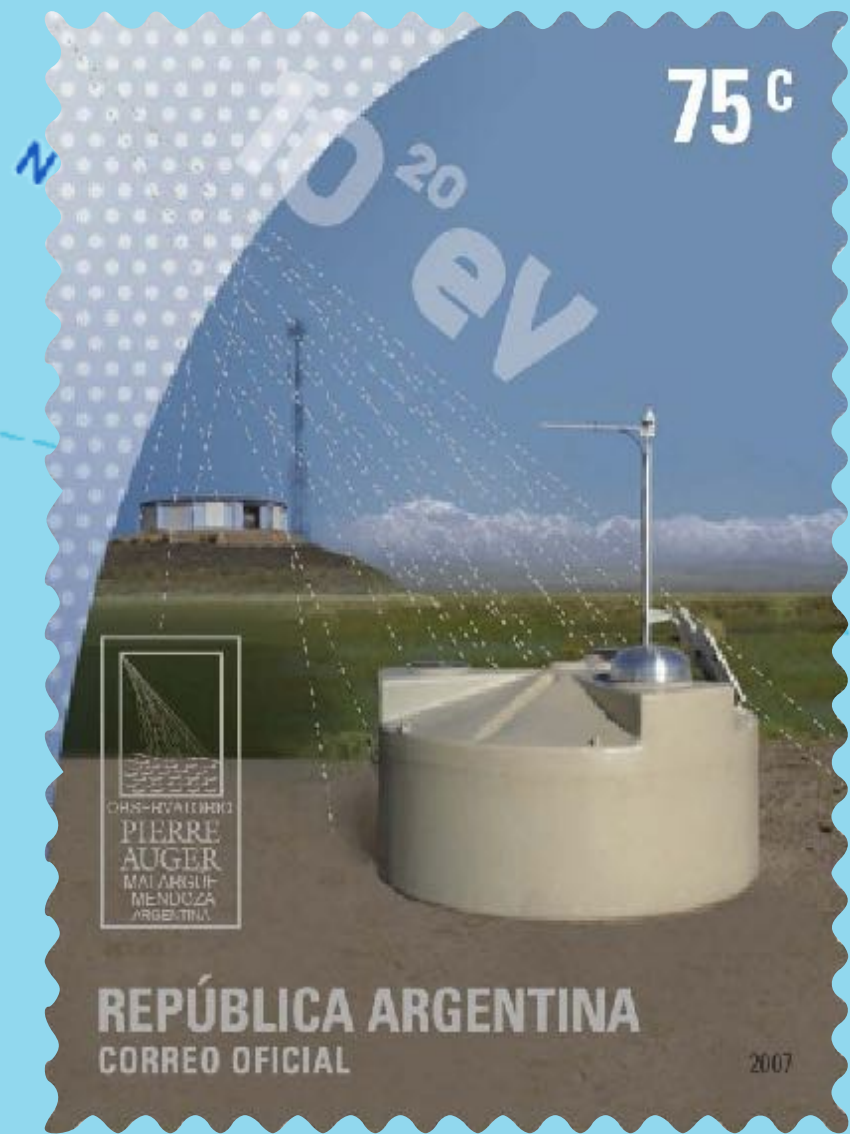
# Upgraded Surface Detector of Auger Observatory



atmosphere of Earth is transparent in 30-80 MHz band



# Upgraded Surface Detector of Auger Observatory



- 1660 surface detector stations (3000 km<sup>2</sup>)
- 24+4 fluorescence light telescopes
- 60 underground muon detectors
- 150 antennas Auger Engineering Radio Array

# Radio Emission in Air Showers

 **Mainly: Charge separation in geomagnetic field**

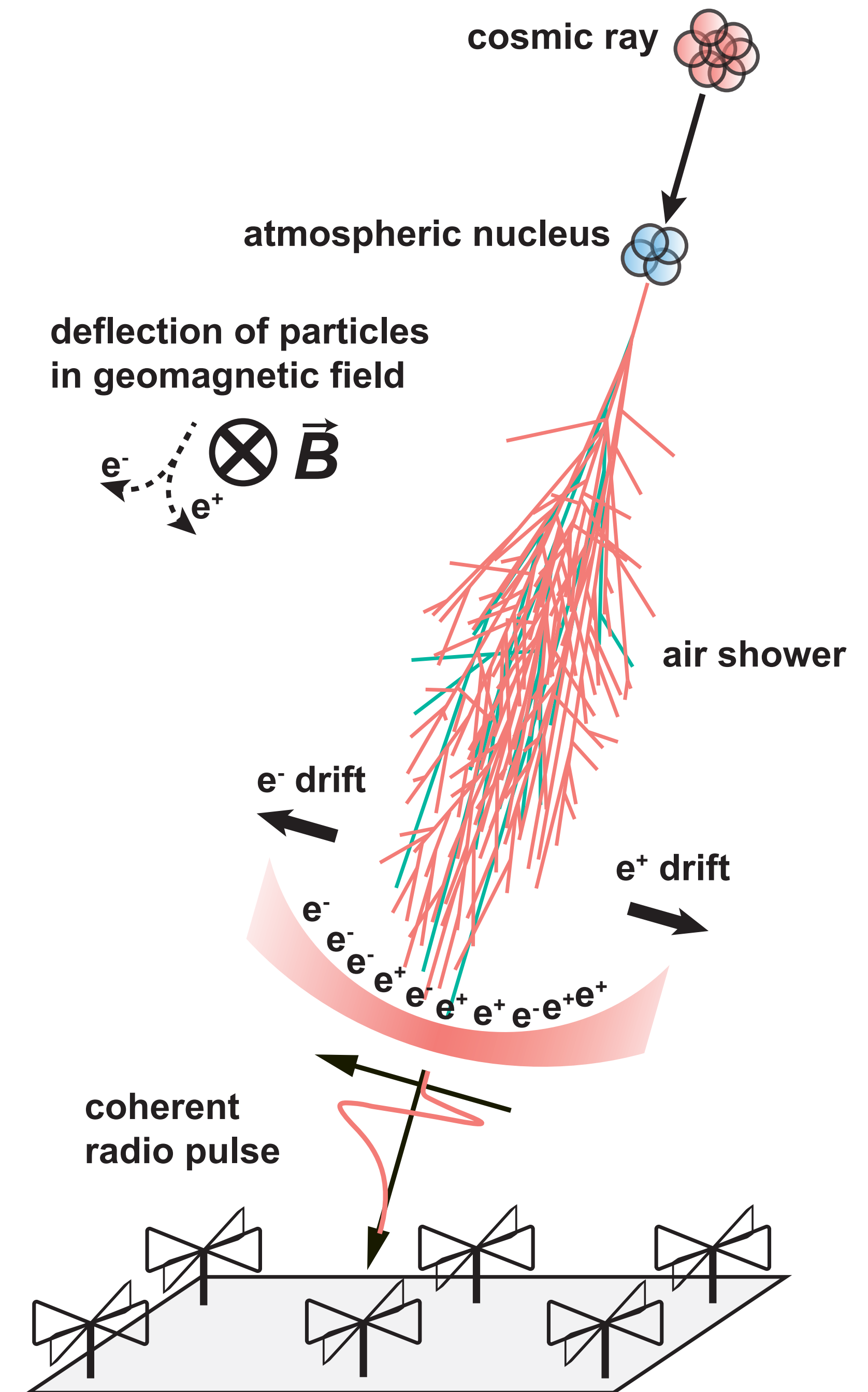
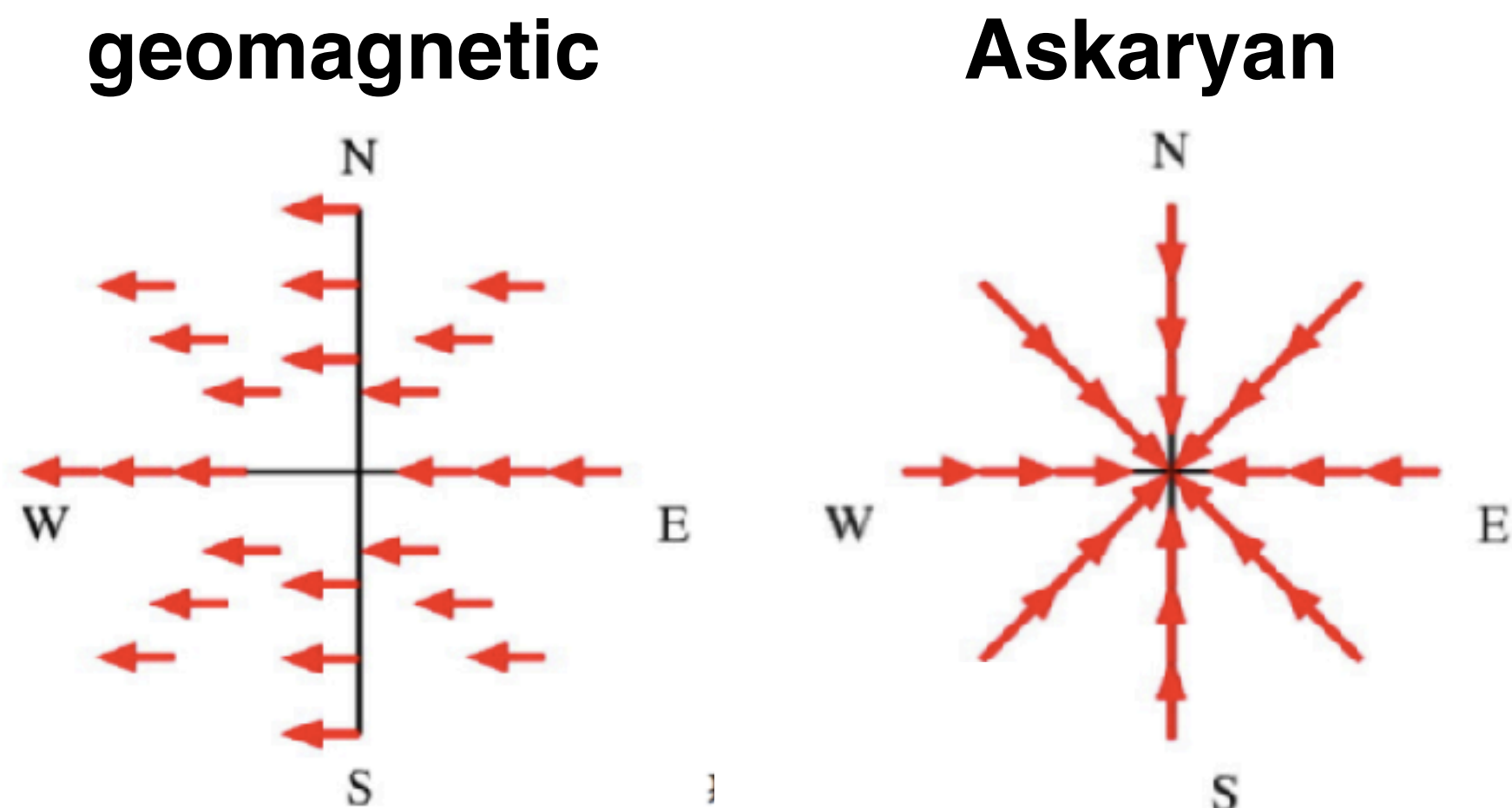
$$\vec{E} \propto \vec{v} \times \vec{B}$$

**Theory predicts additional mechanisms:**

 **excess of electrons in shower: charge excess**

 **superposition of emission due to Cherenkov effects in atmosphere**

**polarization of radio signal**



# Radio Emission in Air Showers

Mainly: Charge separation in geomagnetic field

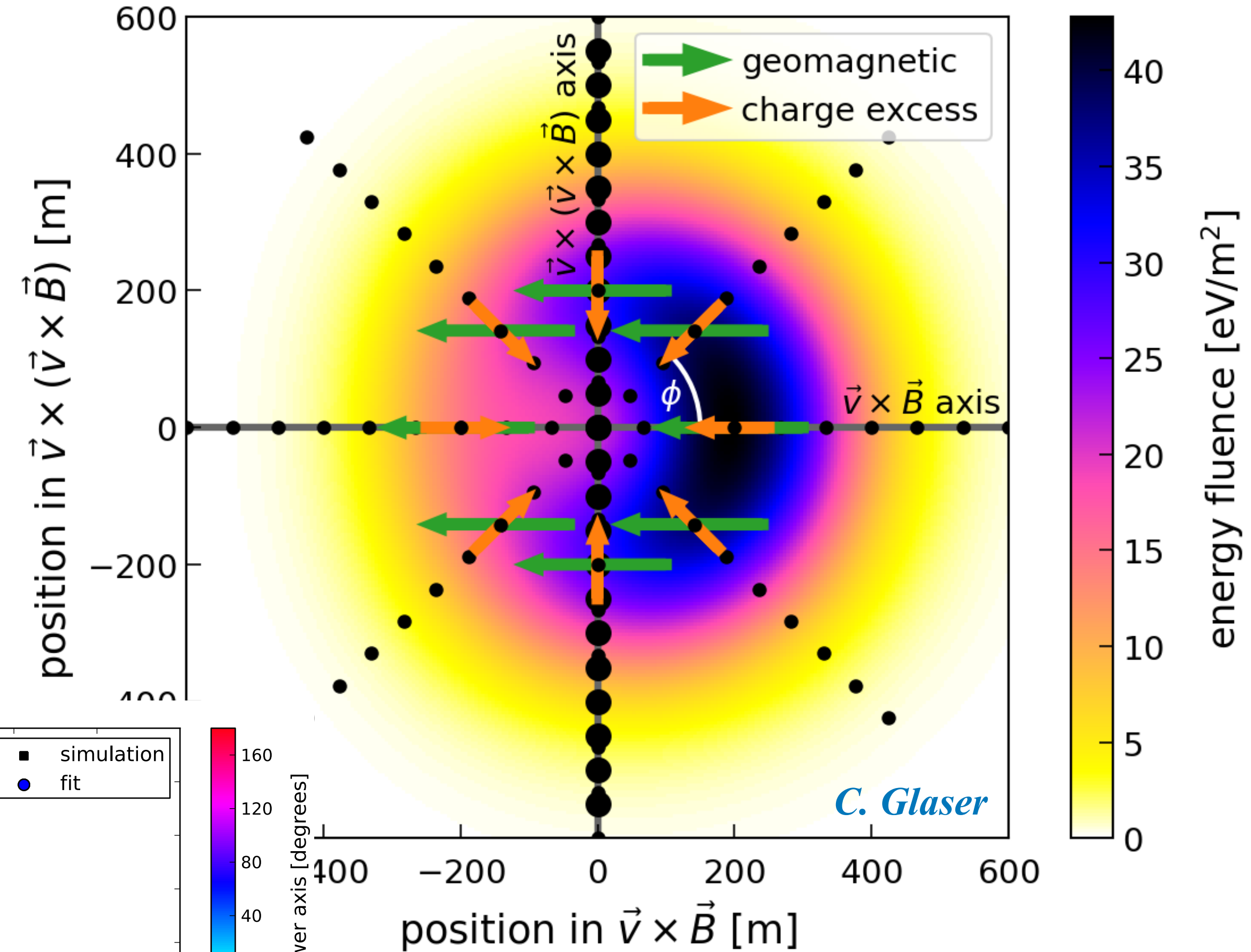
$$\vec{E} \propto \vec{v} \times \vec{B}$$

Theory predicts additional mechanisms:

excess of electrons in shower: charge excess

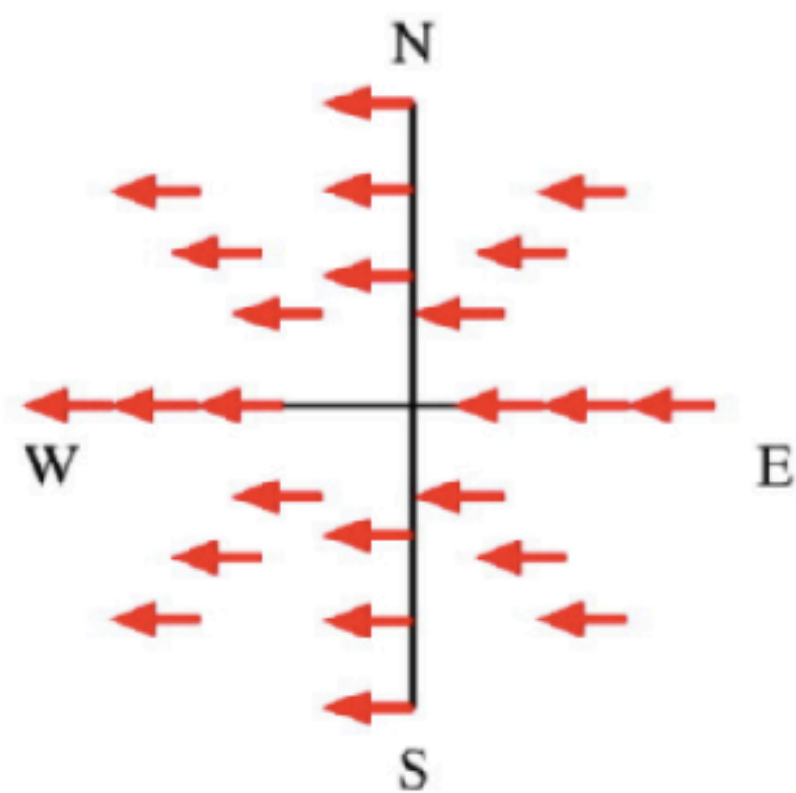
superposition of emission due to Cherenkov effects in atmosphere

footprint of shower on the ground

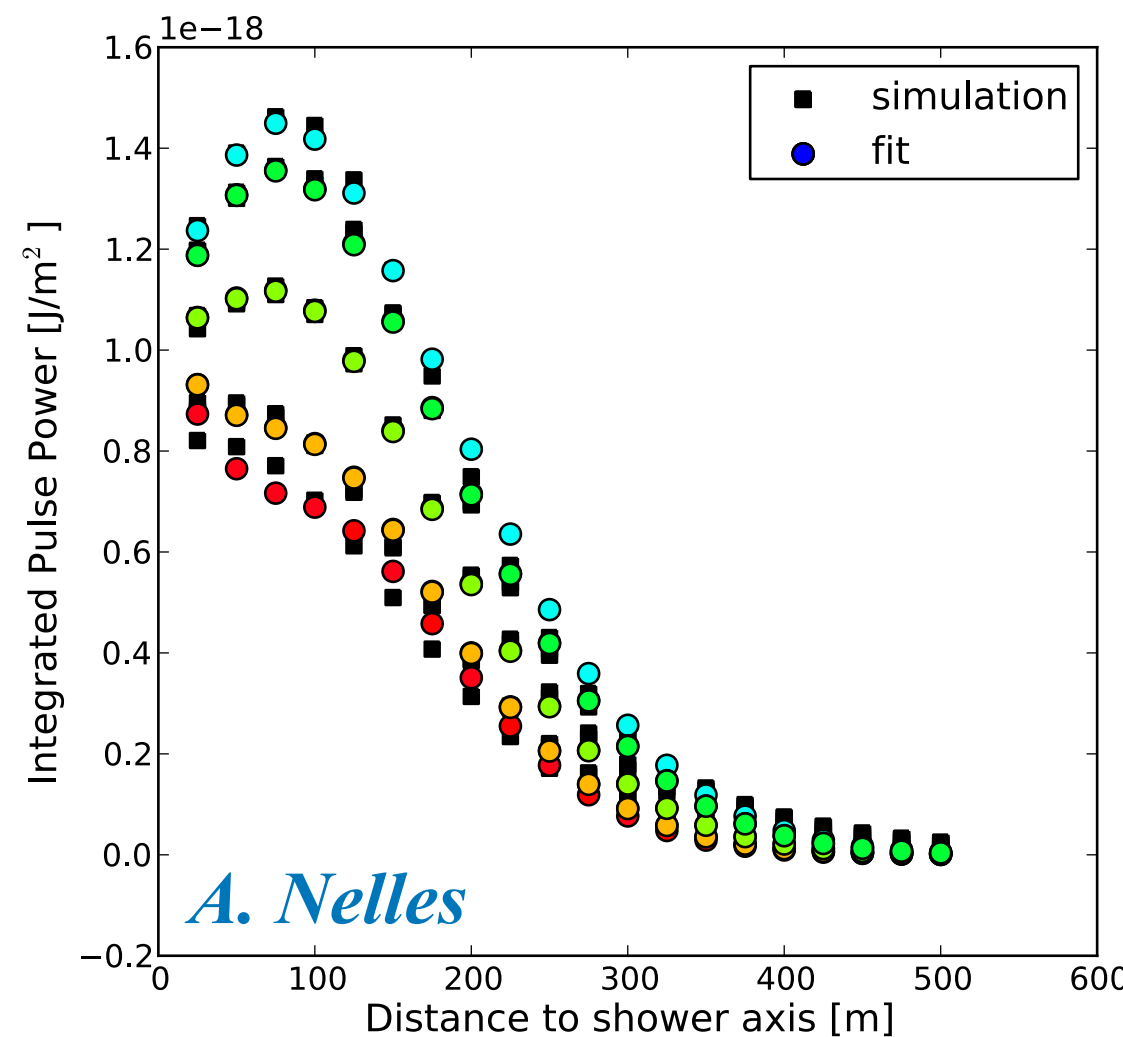
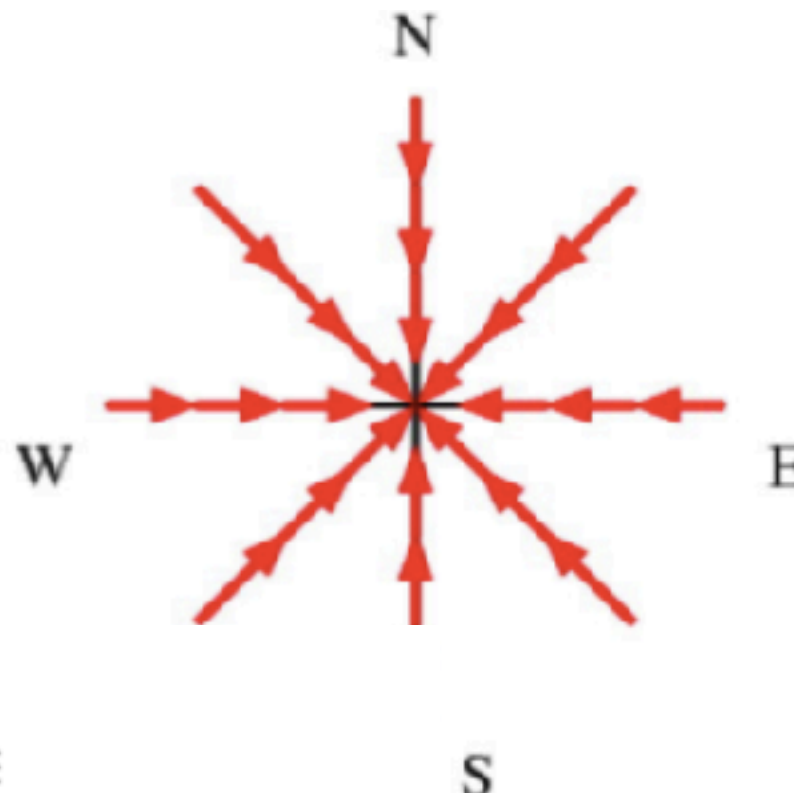


polarization of radio signal

geomagnetic



Askaryan



# Radio Detector of the Pierre Auger Observatory

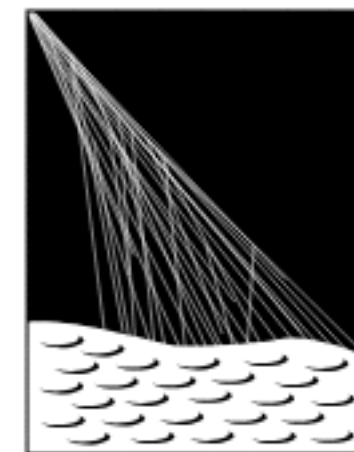
extend mass sensitivity to inclined showers  $\theta > 60^\circ$



European Research Council  
Established by the European Commission



- increasing measurements of  $e/m$  and  $\mu$  components for inclined showers by an order of magnitude
- close to ideal p-Fe separation
- increase sky coverage and overlap with TA
- RD/WCD has different systematic effects as compared to SSD/WCD
- clean measurement of  $e/m$  shower component  
—> independent energy scale



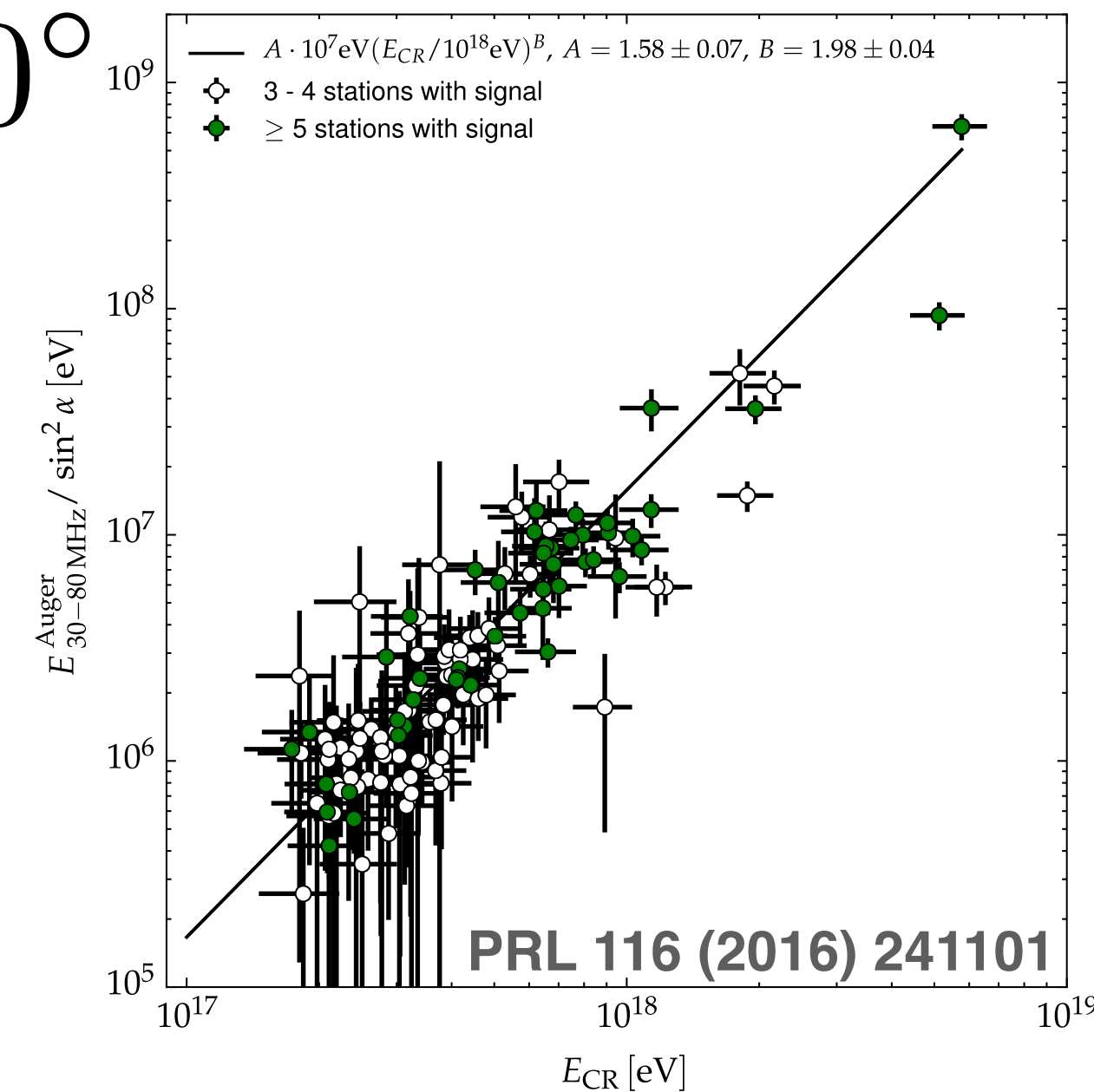
PIERRE  
AUGER  
OBSERVATORY



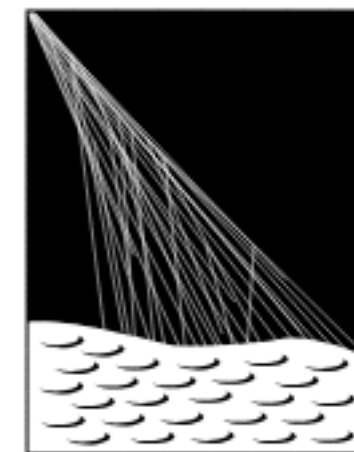
# Radio Detector of the Pierre Auger Observatory

extend mass sensitivity to inclined showers  $\theta > 60^\circ$

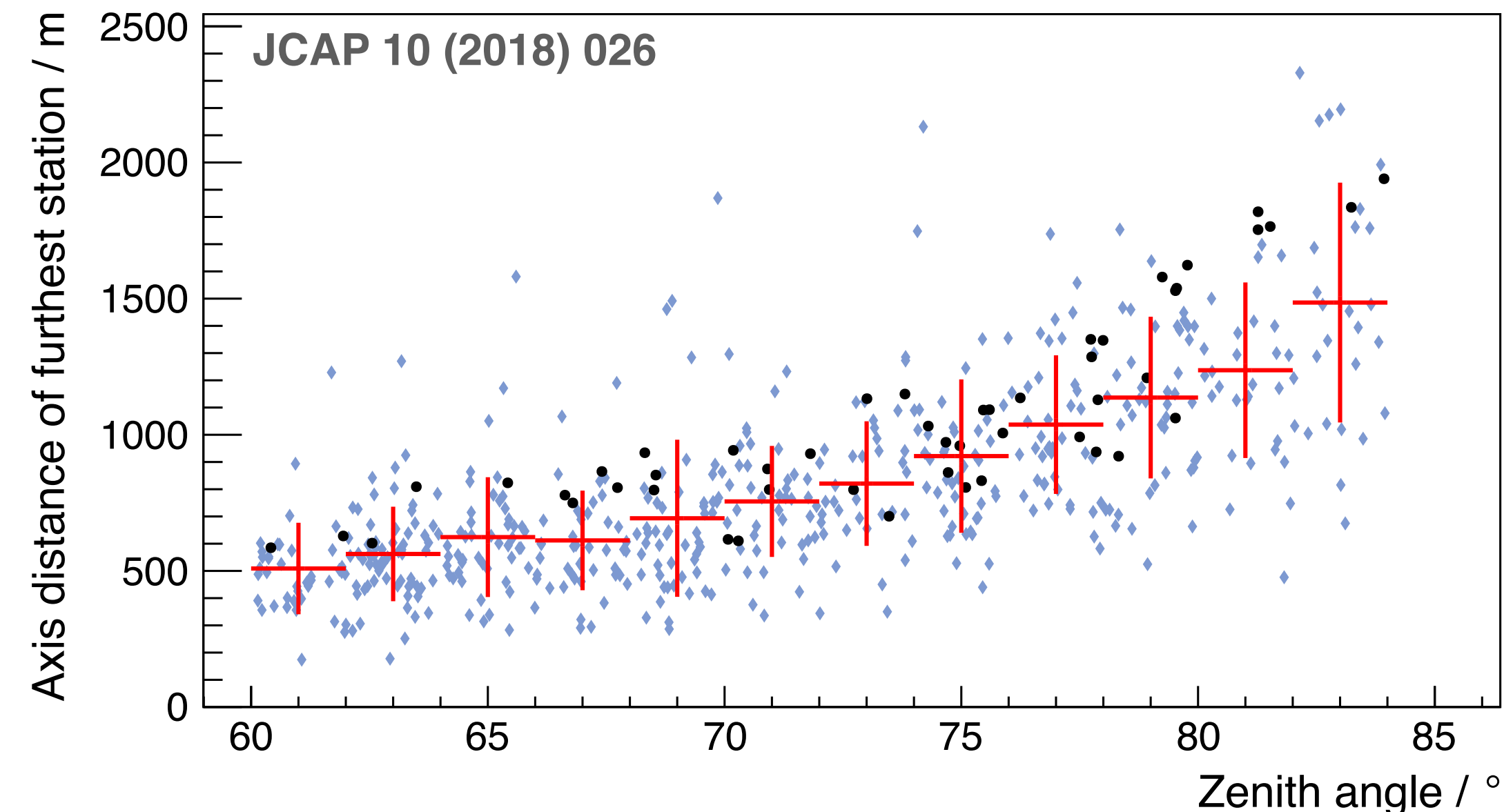
- increasing measurements of  $e/m$  and  $\mu$  components for inclined showers by an order of magnitude
- close to ideal p-Fe separation
- increase sky coverage and overlap with TA
- RD/WCD has different systematic effects as compared to SSD/WCD
- clean measurement of  $e/m$  shower component  
—> independent energy scale
- based on 15 years of experience with AERA



European Research Council  
Established by the European Commission



PIERRE  
AUGER  
OBSERVATORY



# Antenna assembly



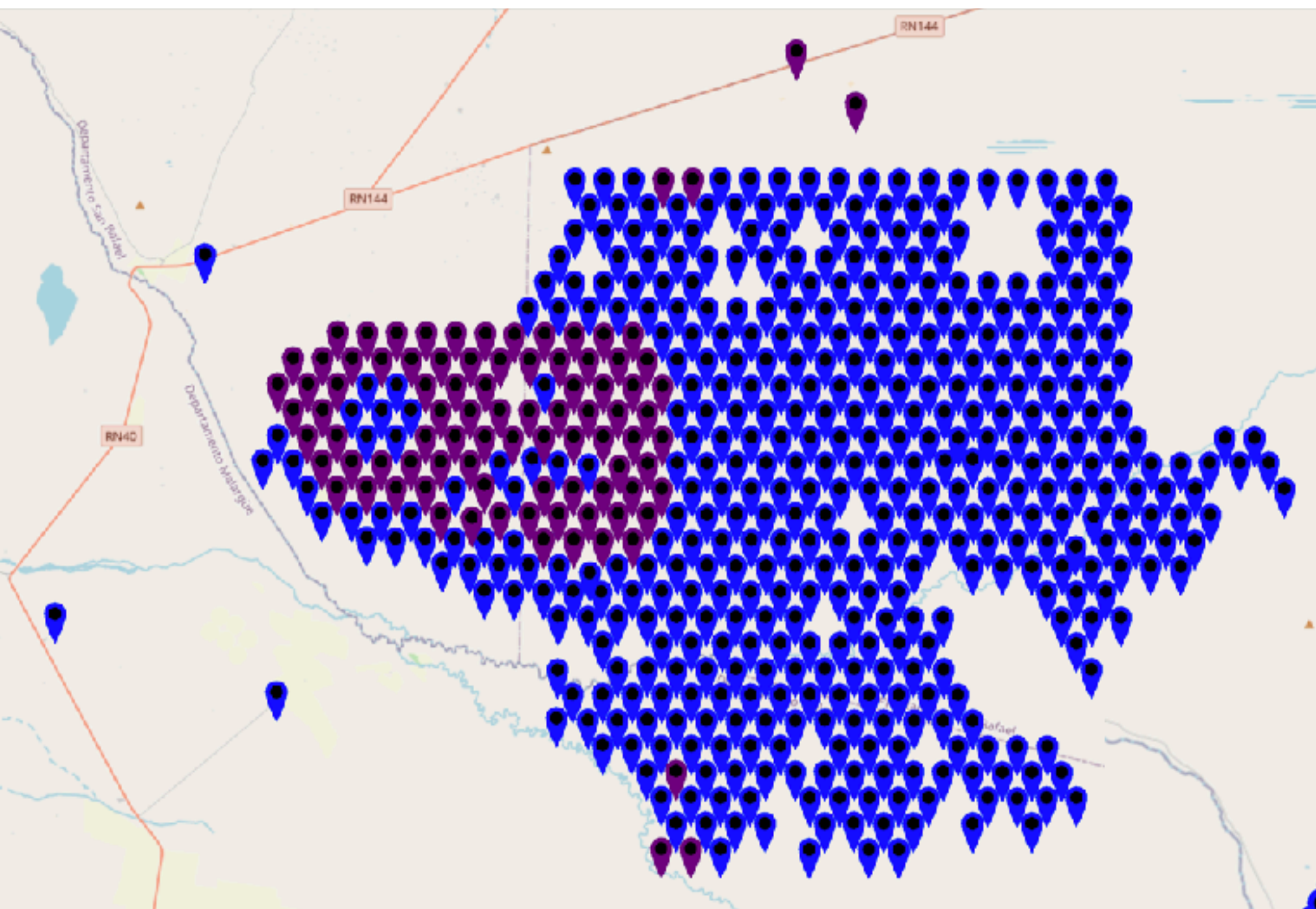
# Transport to position



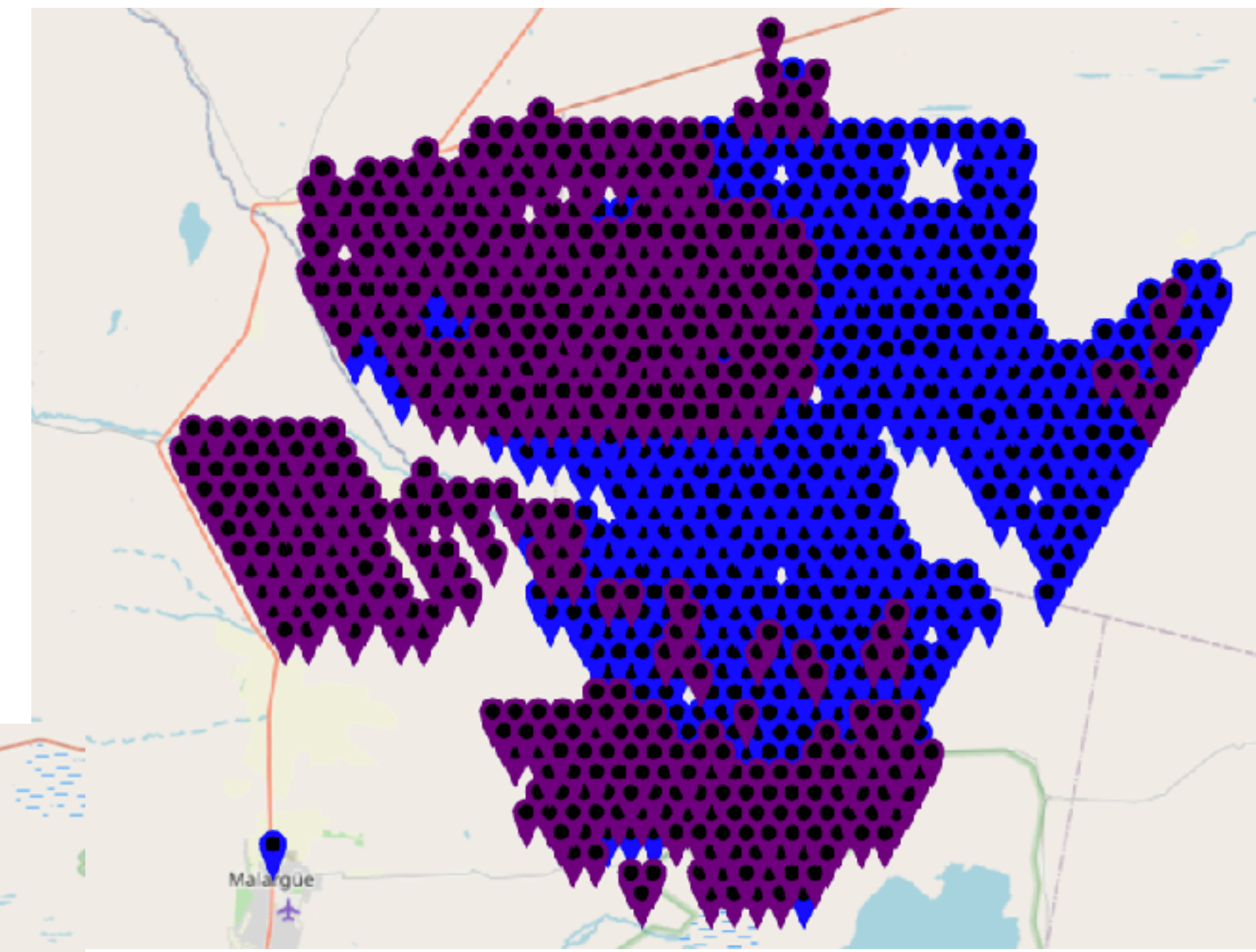
# Station assembly



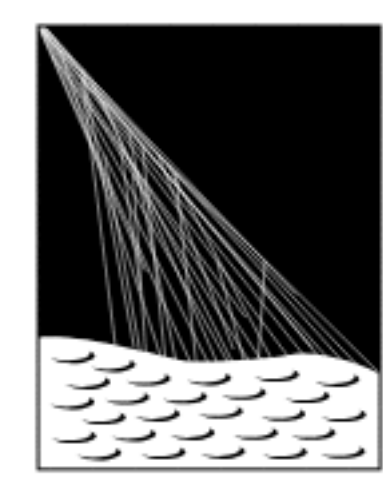
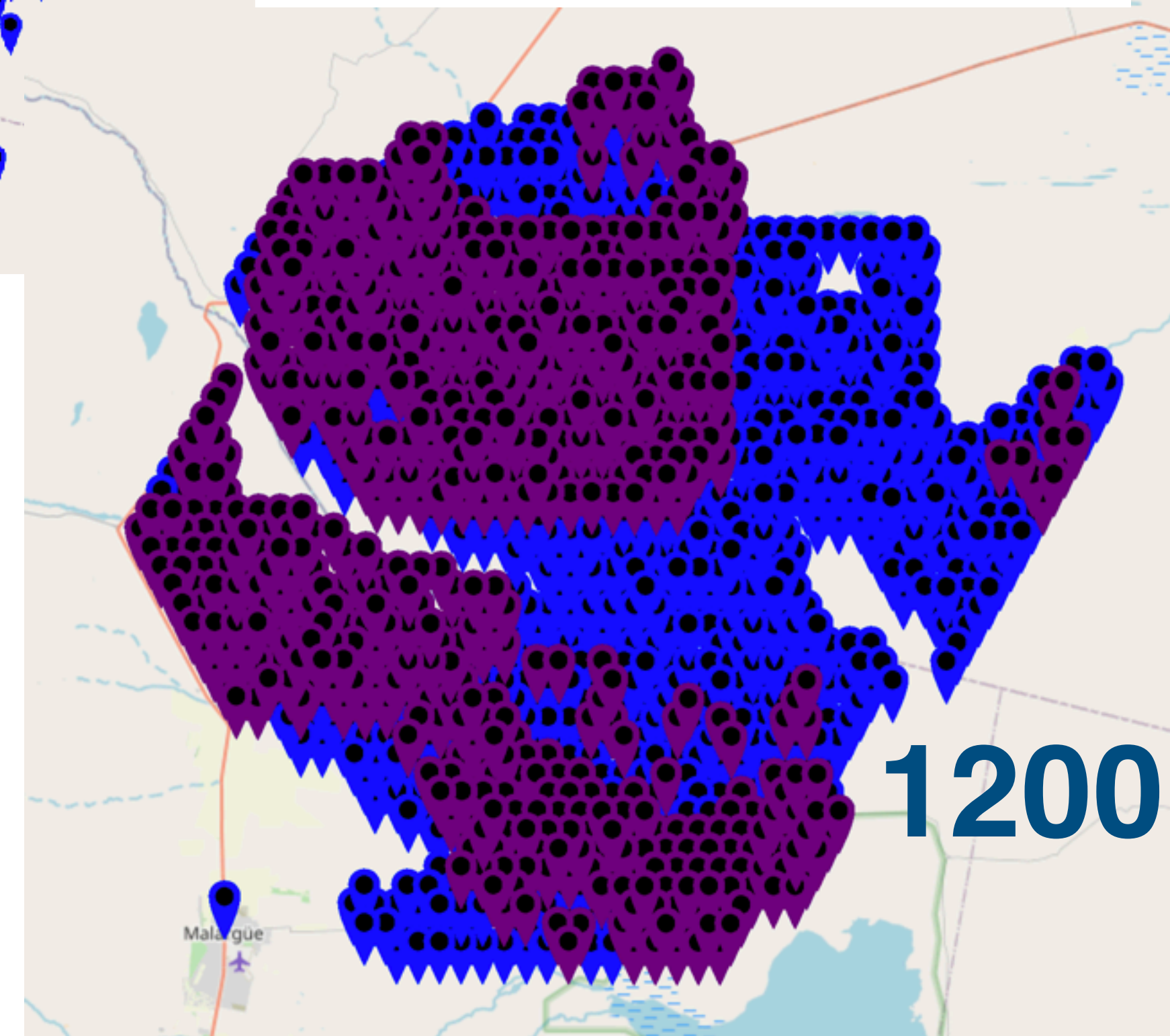
# 500 stations Nov 2023



# 1000 stations Mar 2024



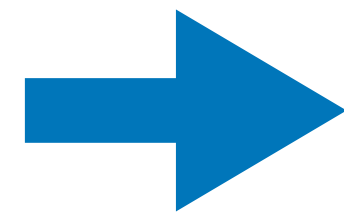
# 1200 stations May 2024



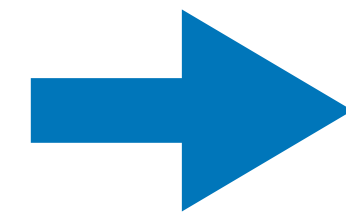
PIERRE  
AUGER  
OBSERVATORY

# RD calibration concept

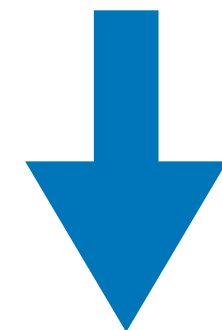
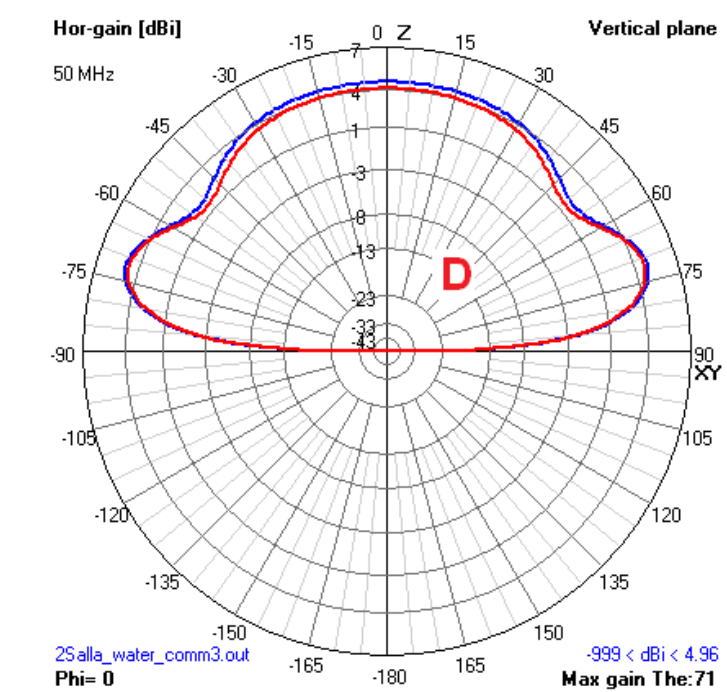
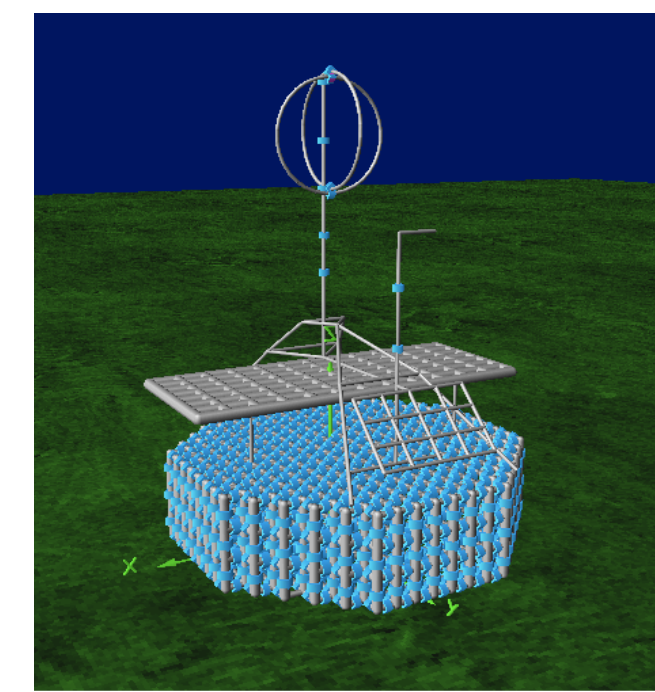
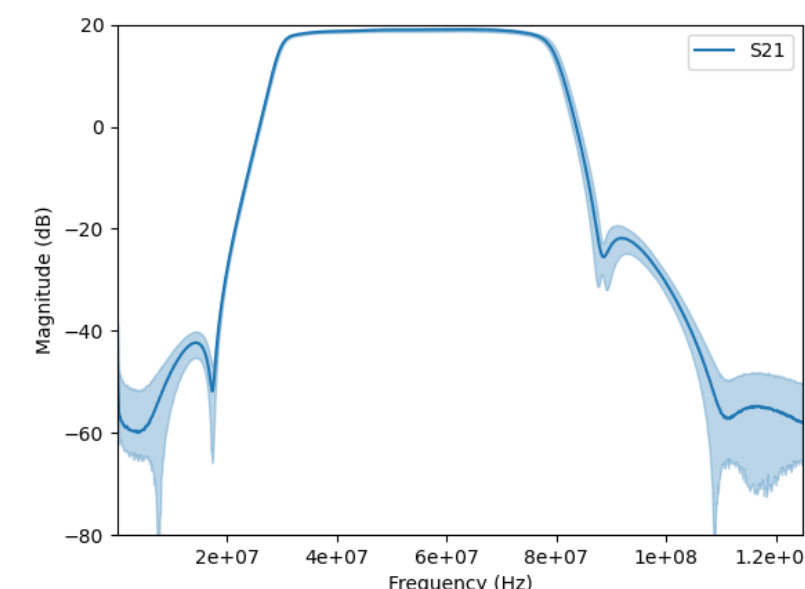
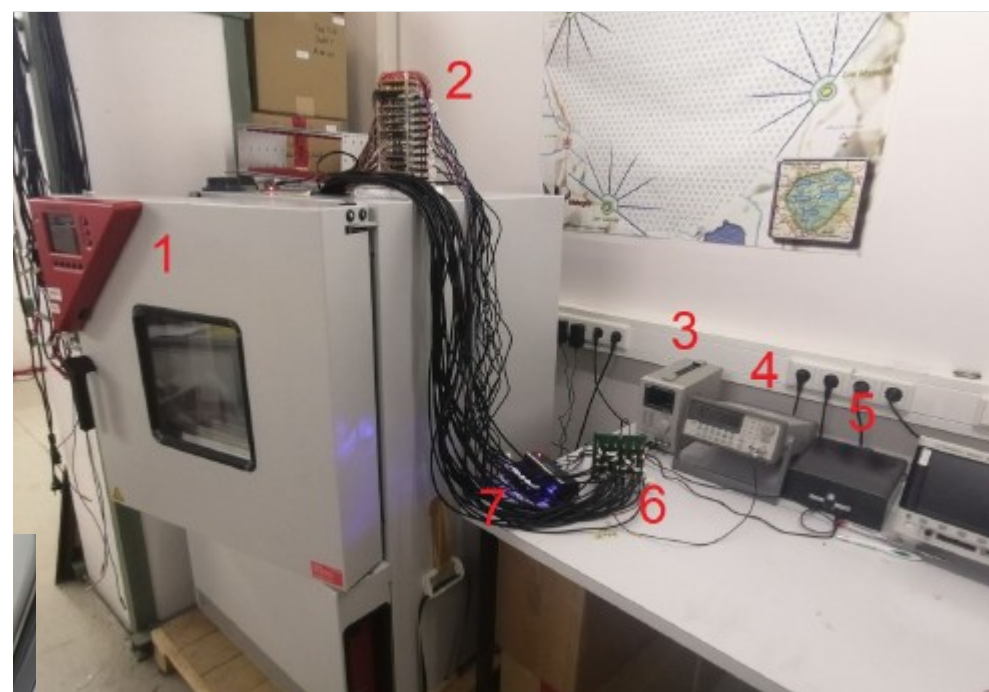
thermal cycling (aging)  
LNA & digitizer



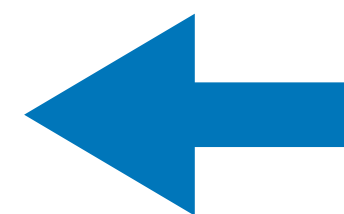
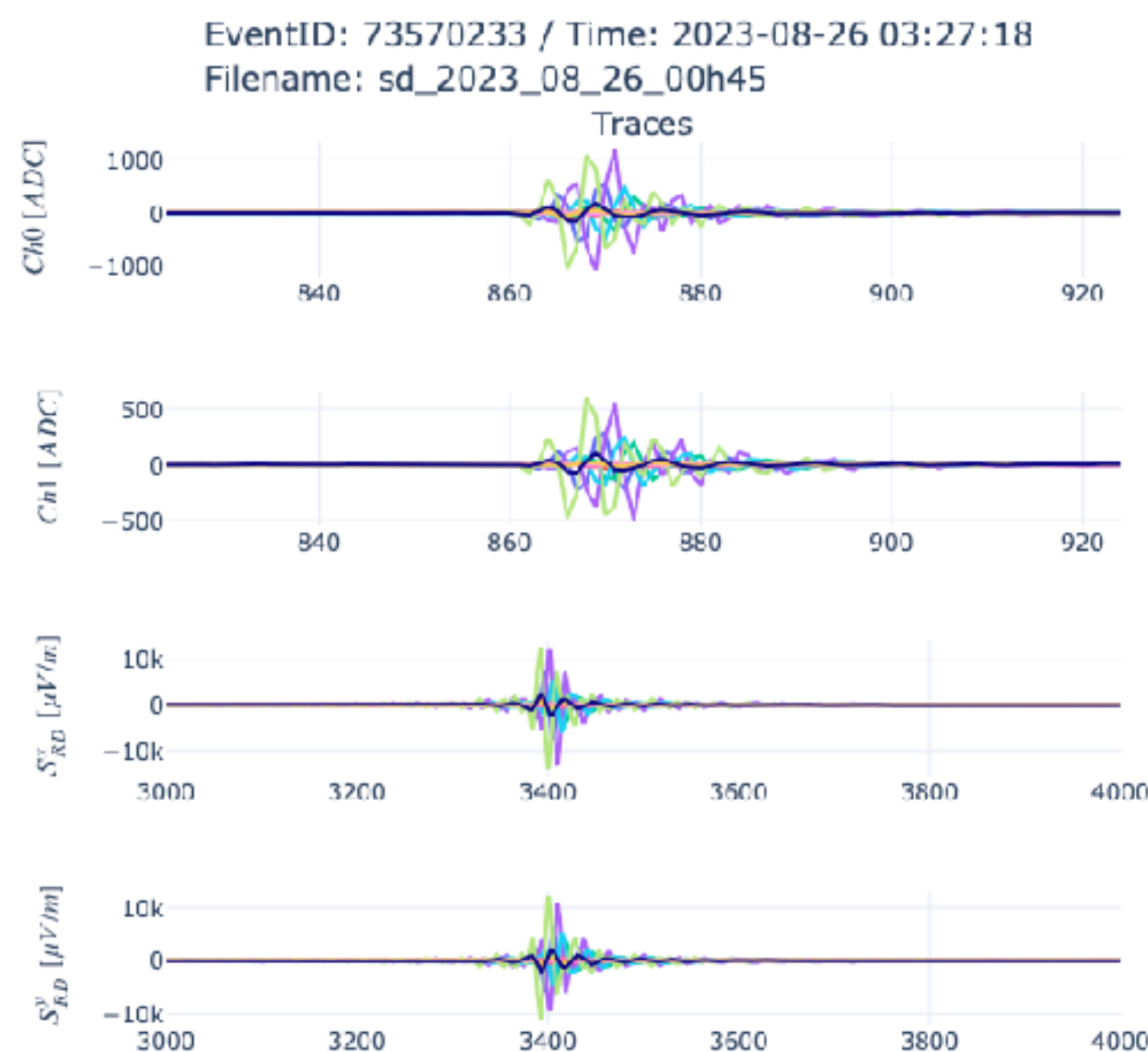
end-to-end calibration in lab  
LNA & digitizer



simulation of antenna pattern  
NEC

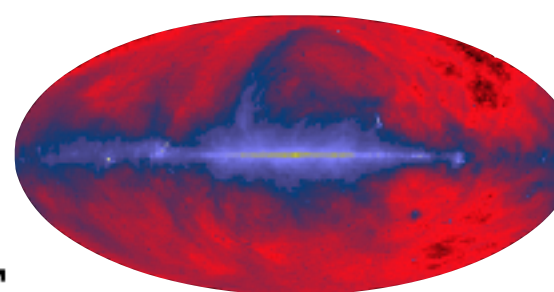
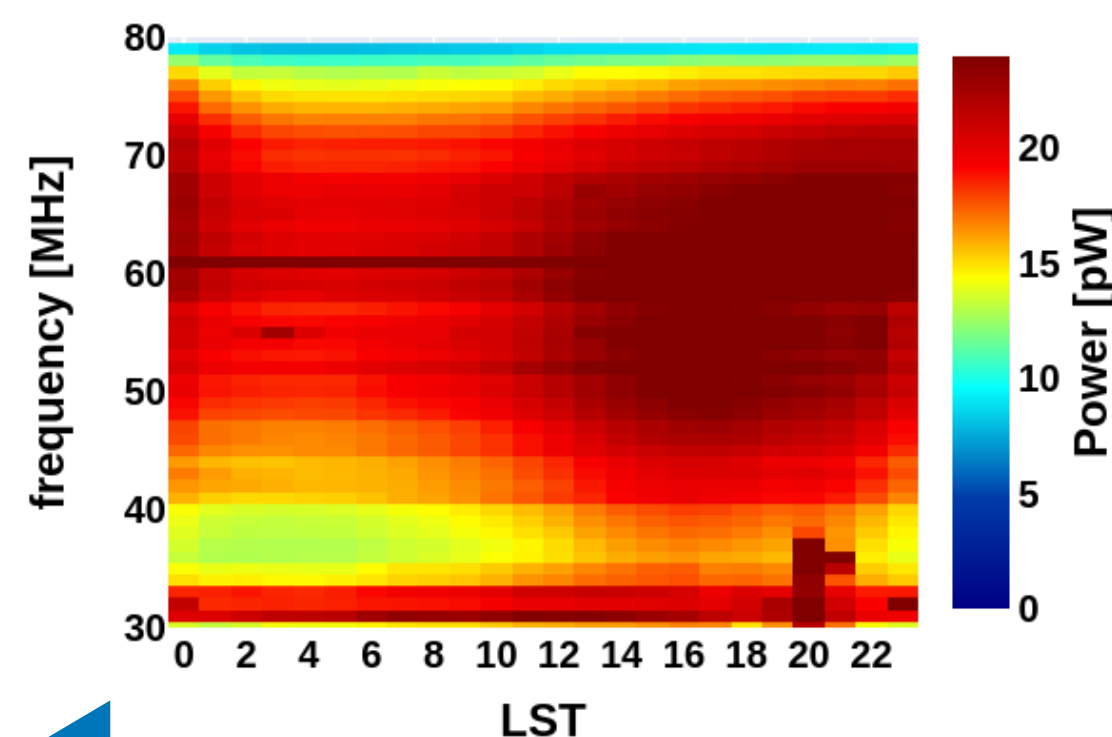


absolutely calibrated signals

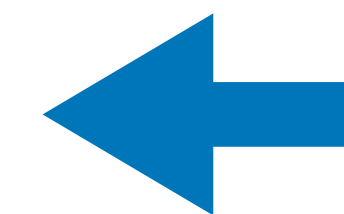


Galactic emission

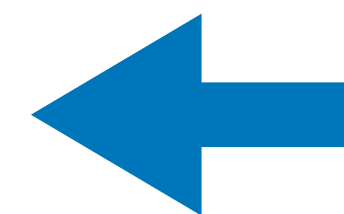
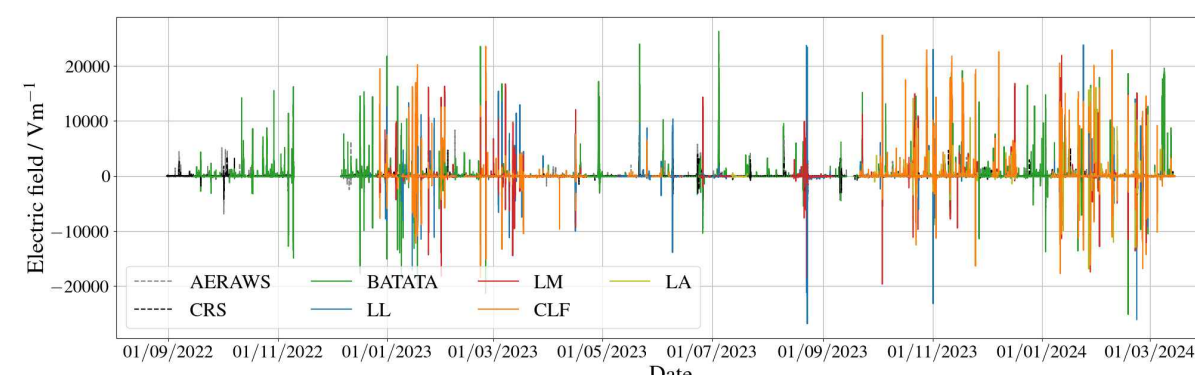
Measured power dataset:



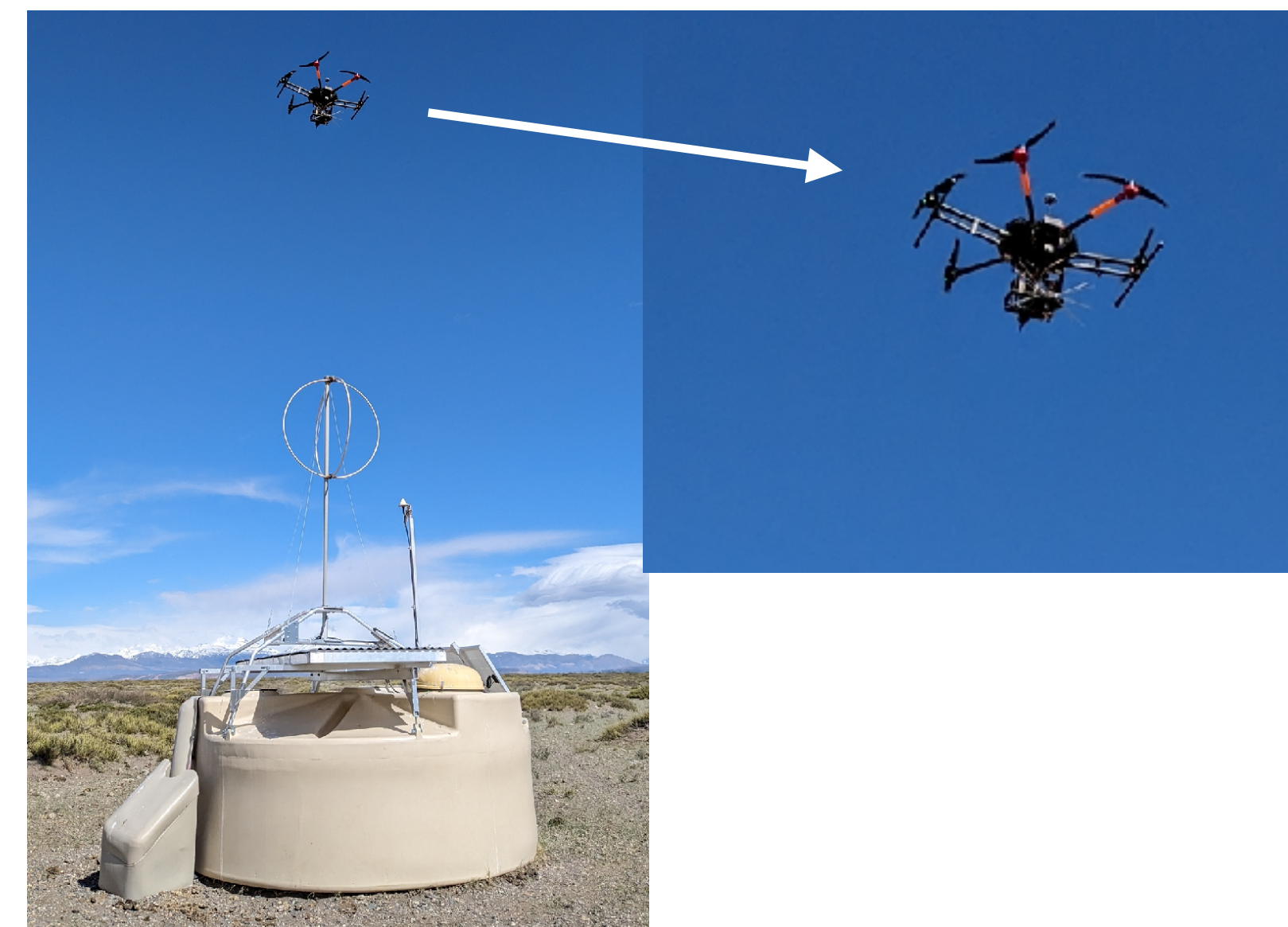
the „muon peak“ for radio



atmospheric electric field

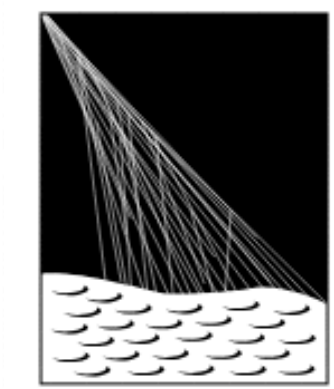


in-situ calibration with reference antenna

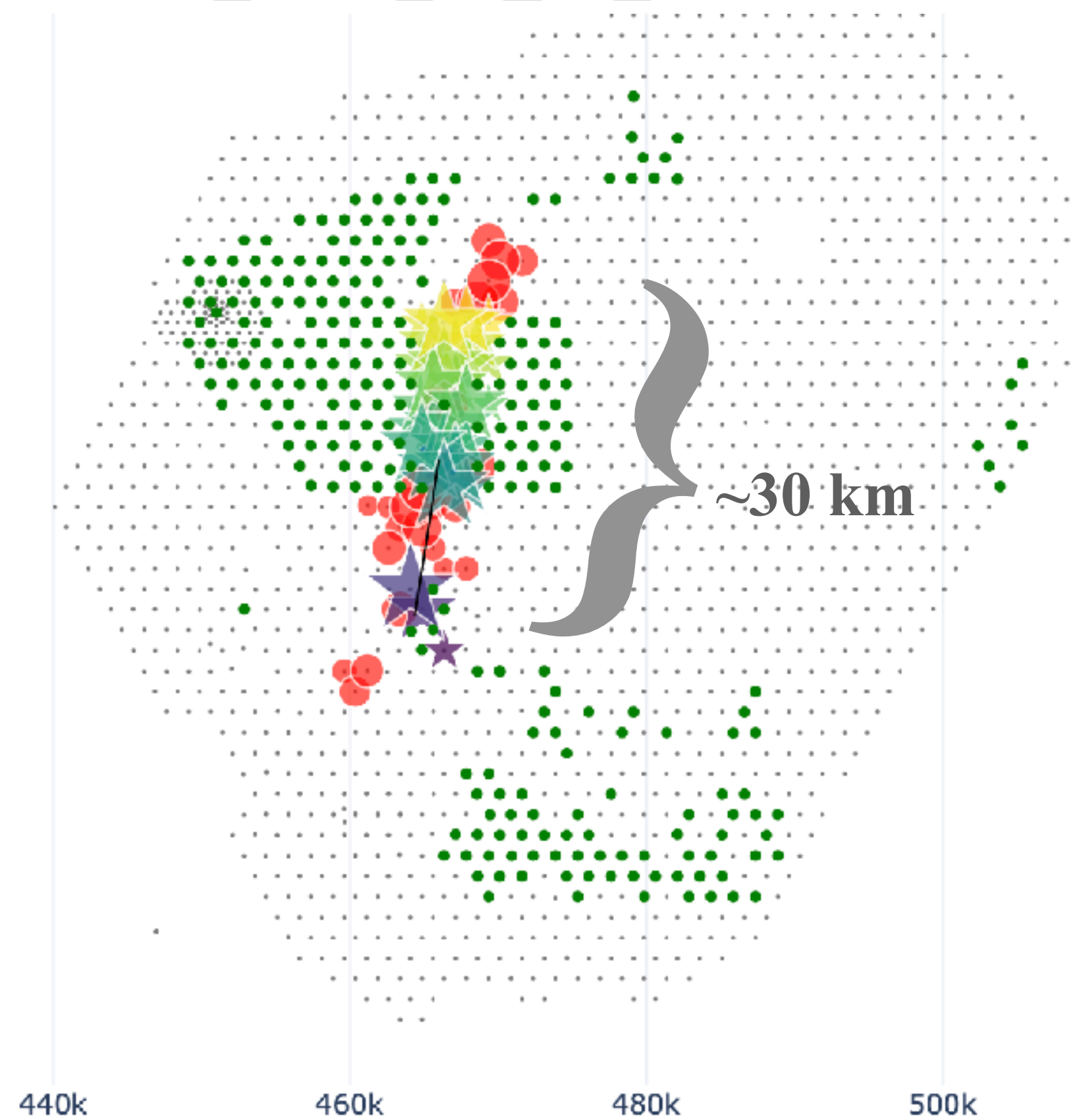


EventID: 74870325 / Time: 2024-02-06 13:39:16

Filename: sd\_2024\_02\_06\_13h13



PIERRE AUGER OBSERVATORY



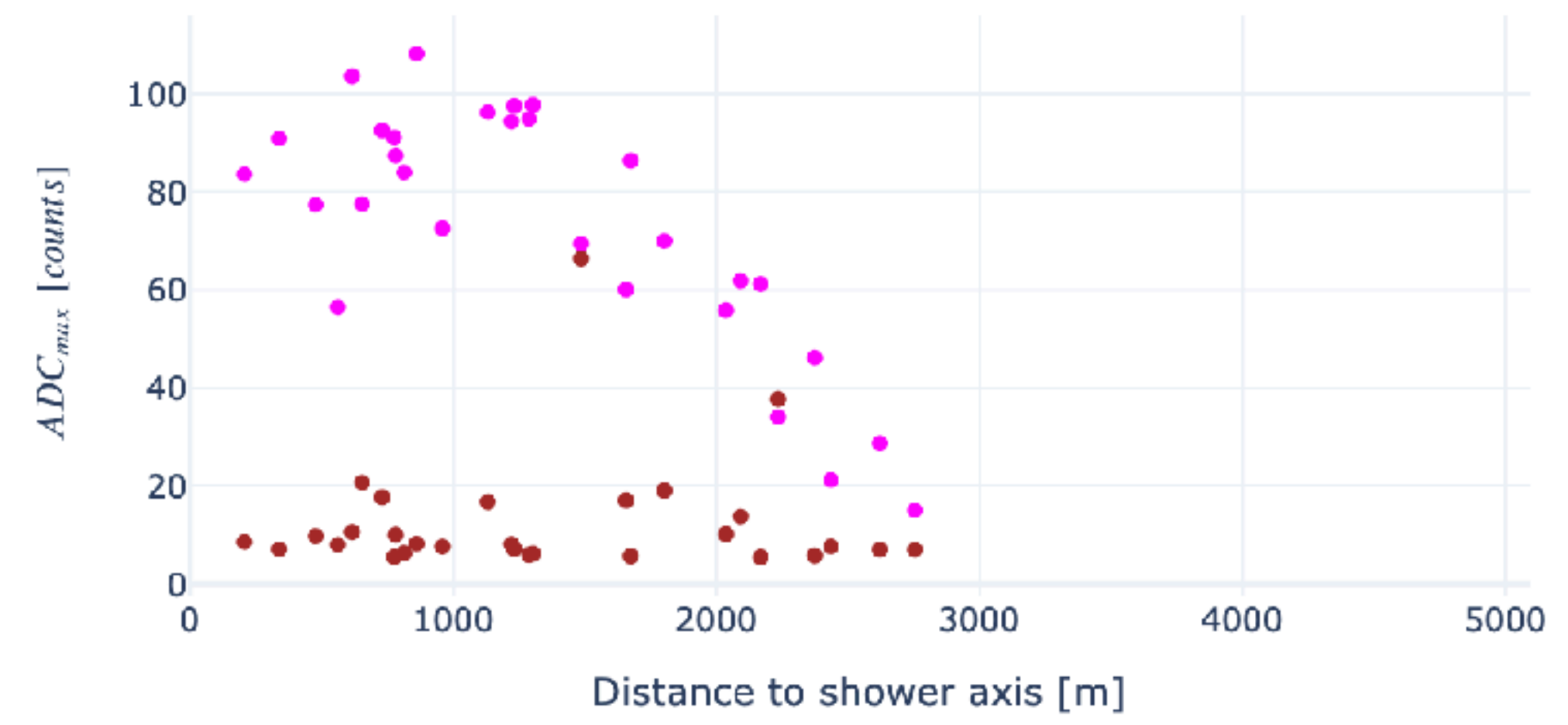
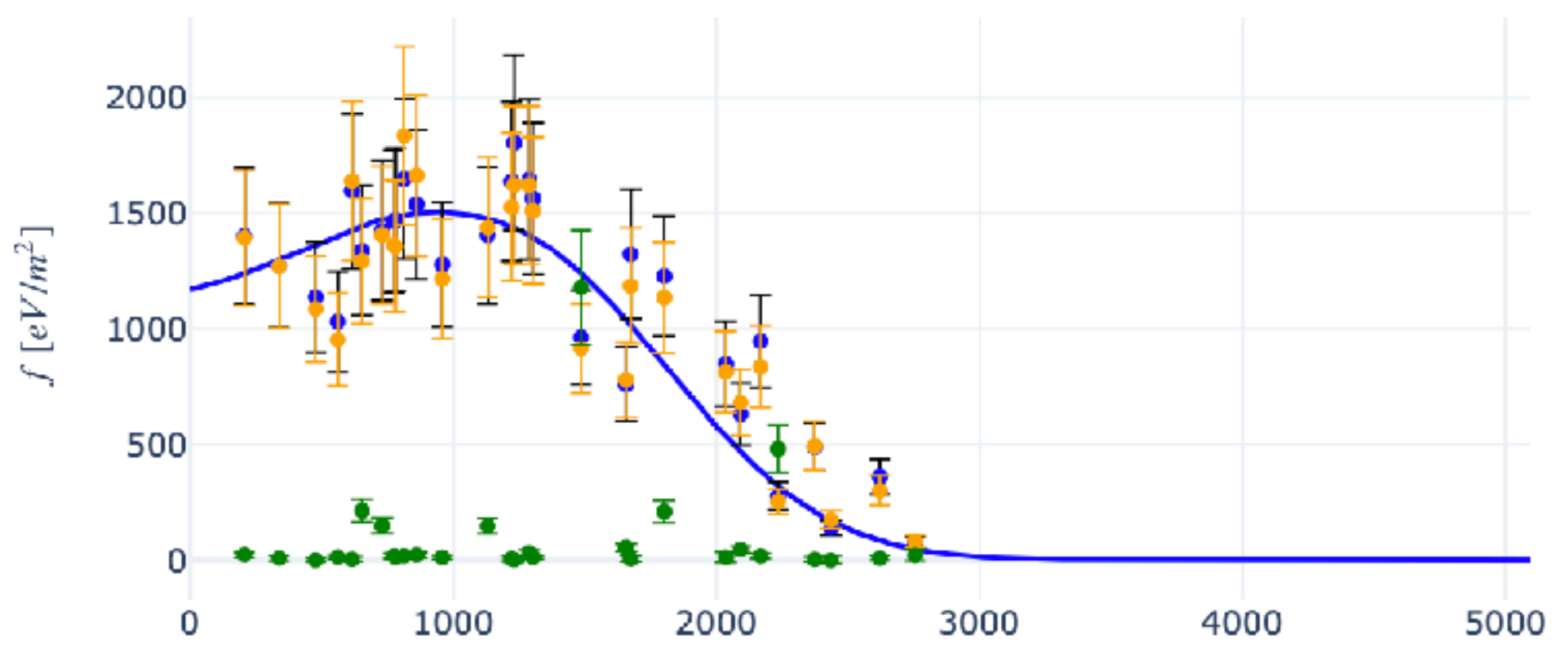
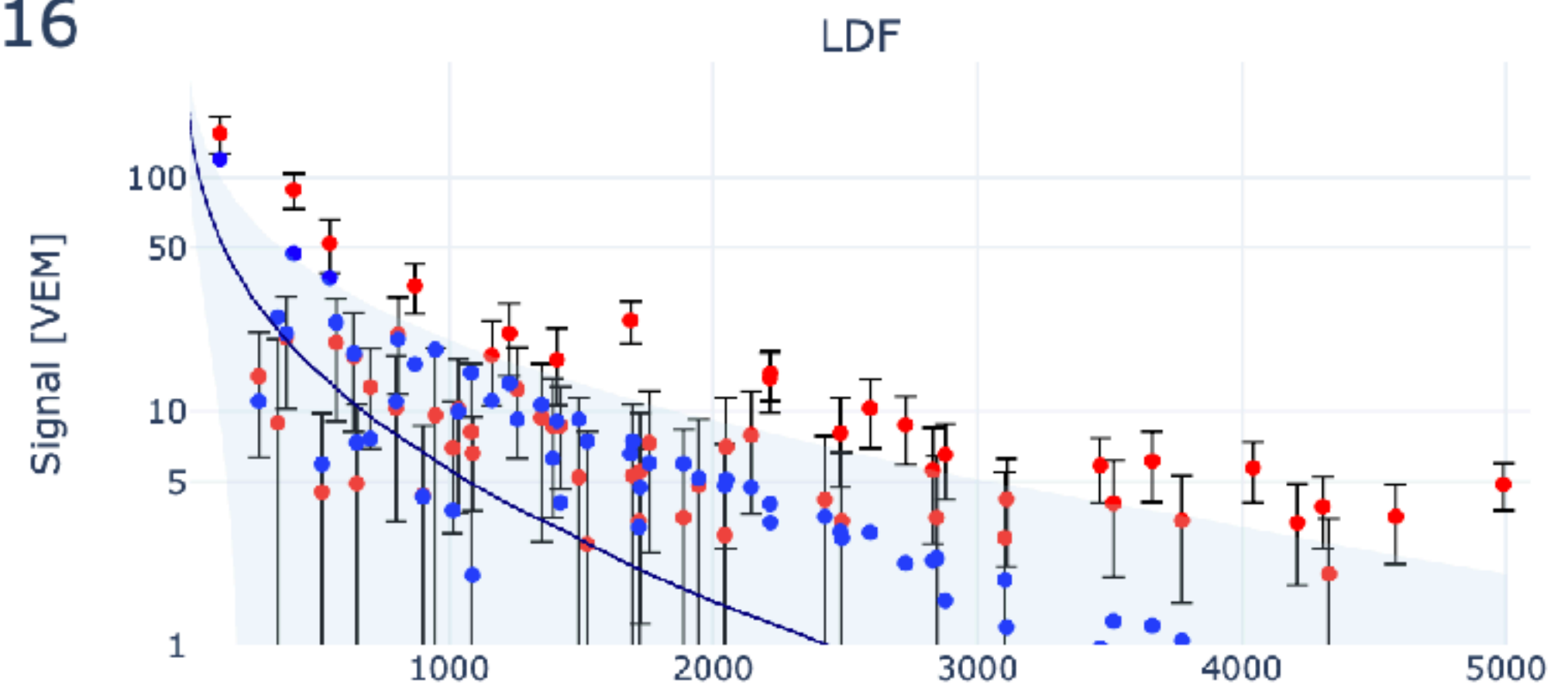
**WCD Reconstruction (61 stations)**

$E_{SD} = 21.13 \pm 1.7 EeV$   
 $\theta_{SD} = 85.8 \pm 0.1 deg$   
 $\phi_{SD} = 260.6 \pm 0.0 deg$   
 $N_{19} = 3.6 \pm 0.3$

**RD Reconstruction (29 stations)**

$E_{RD} = 28.35 \pm 3.3 EeV$   
 $\theta_{RD} = 85.8 \pm 0.0 deg$   
 $\phi_{RD} = 260.6 \pm 0.0 deg$   
 $TSFlag = 0,0,0,0$

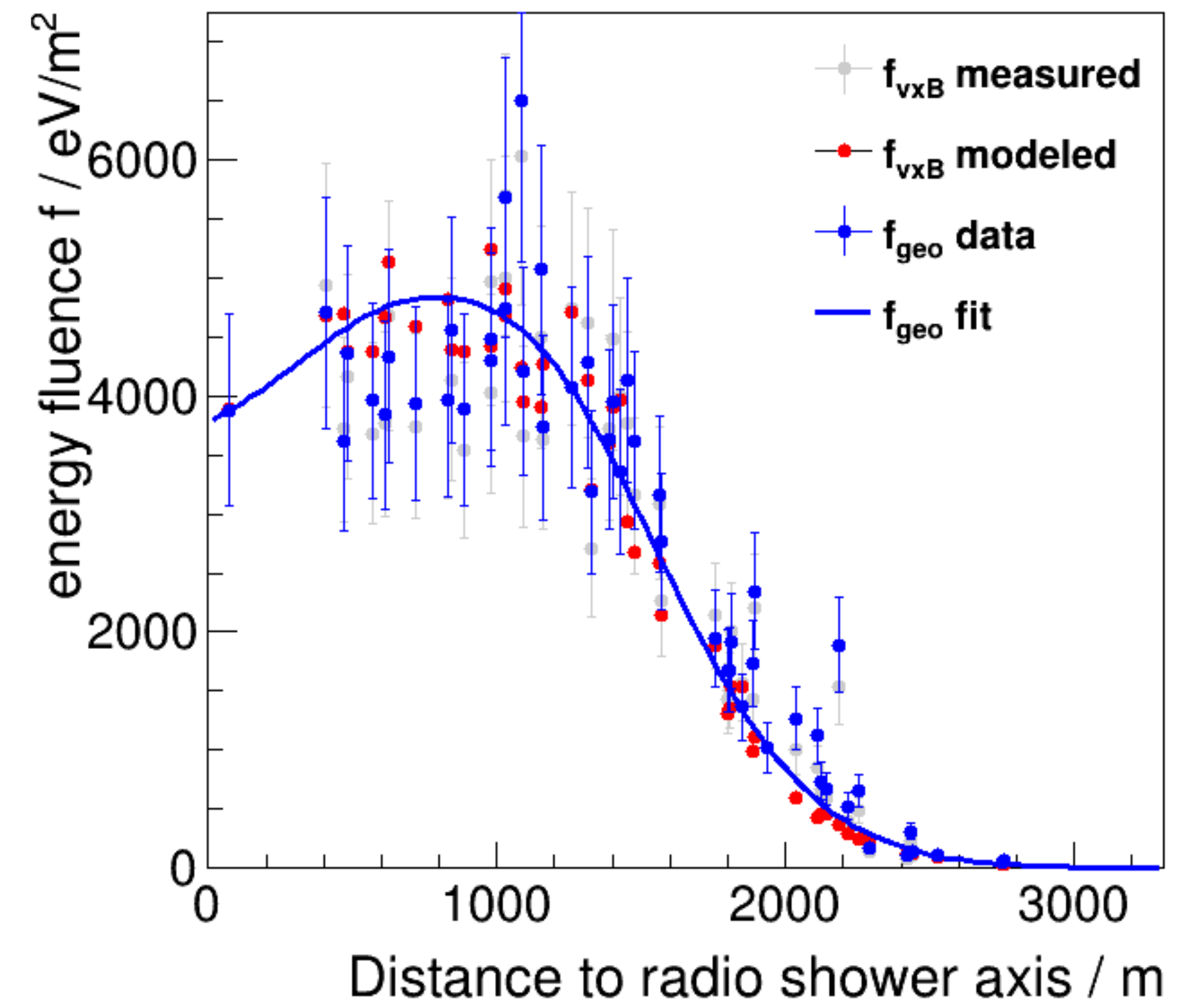
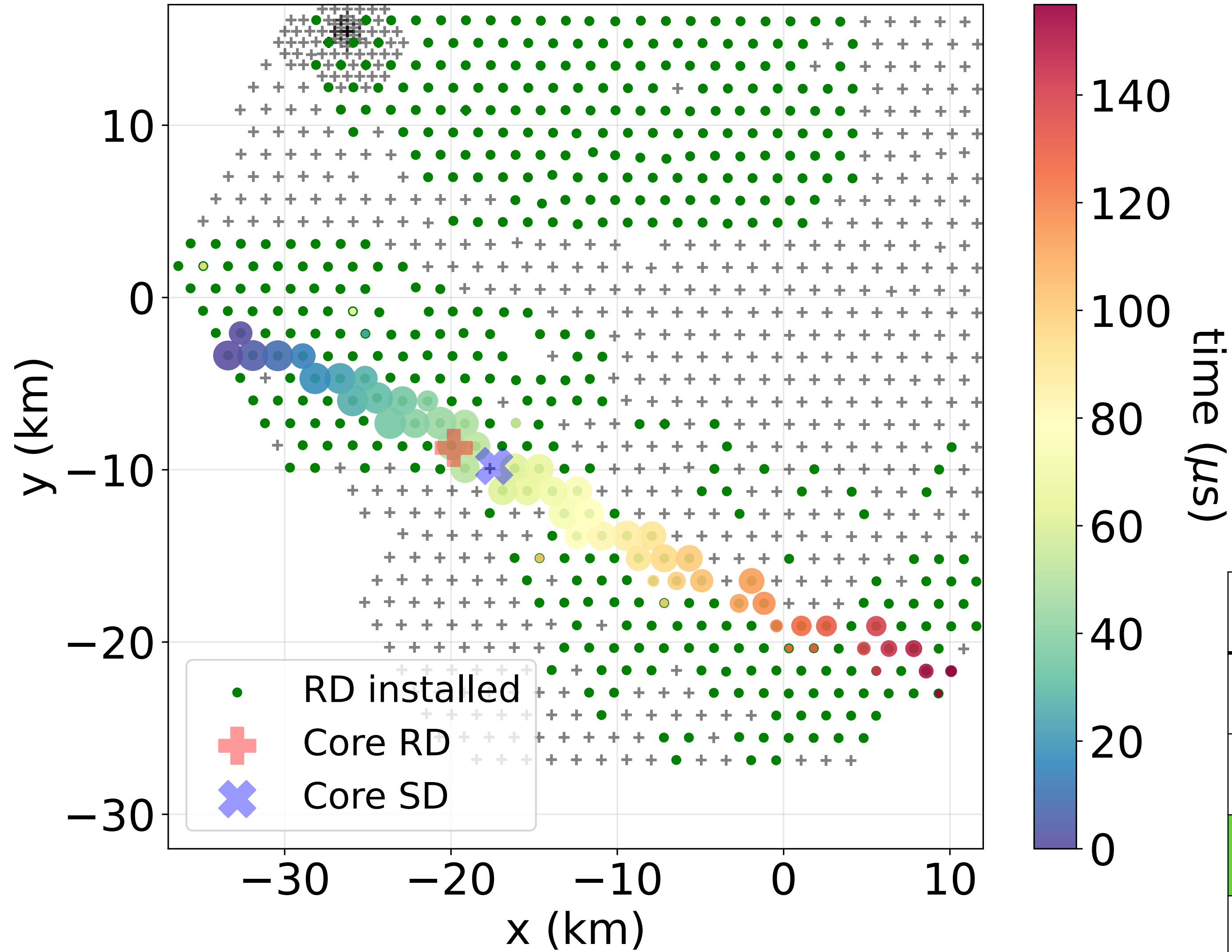
**21 EeV 86° zenith angle**



RD stations participated in reconstruction

- Amil
- Antartida Arg.
- Catalina
- Christiane
- D. Bello
- El Gualicho
- Eleuterio
- Eulogio
- Facundo
- Garrafon
- Guillemina
- Hector Refsgaard
- Hormiguita
- Huali Jr
- Isabeau
- Issacco Jr.
- Jambroni Jr.
- Kabu
- Marchaterre
- Marcio
- Olaia Jr.
- Oppio

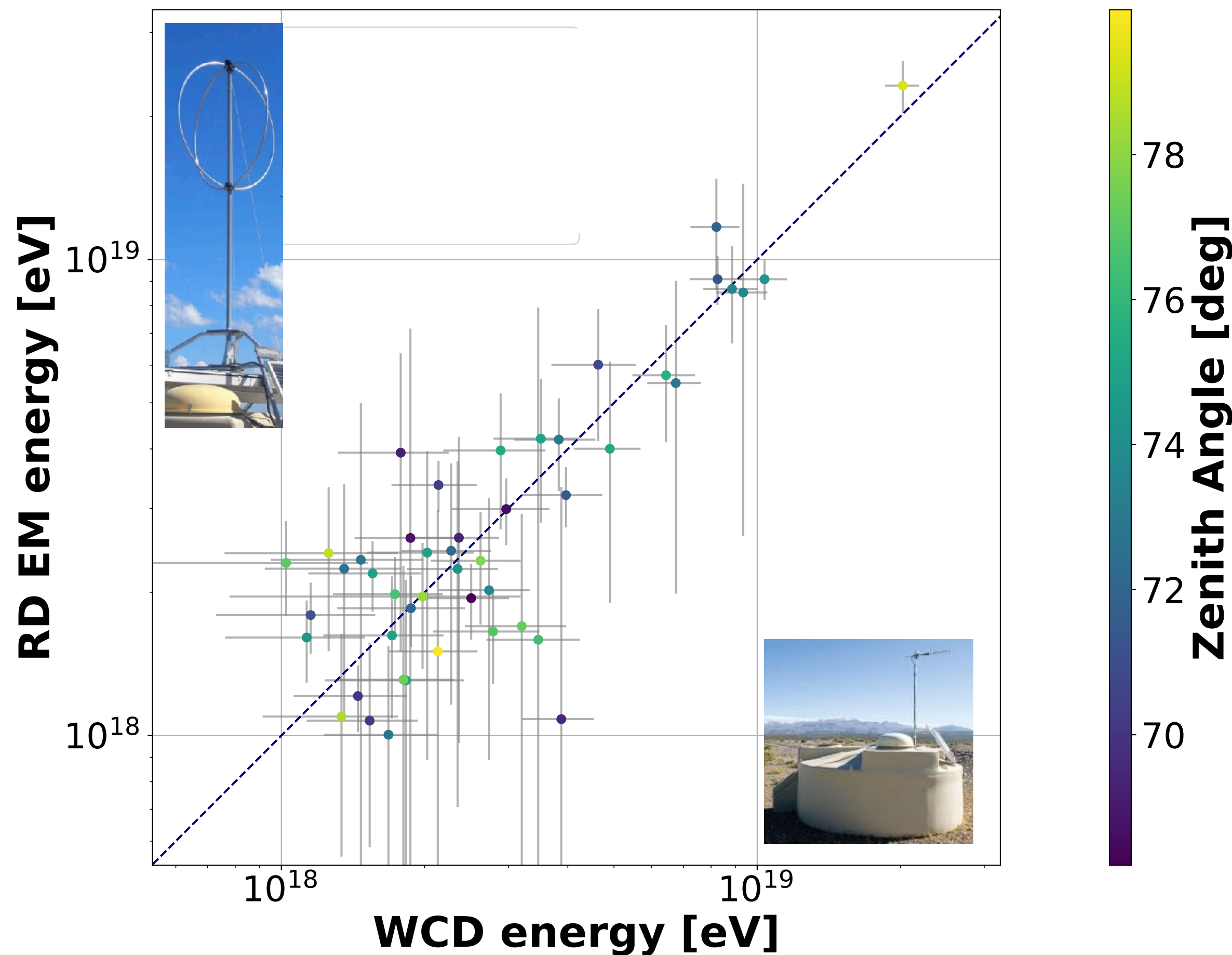
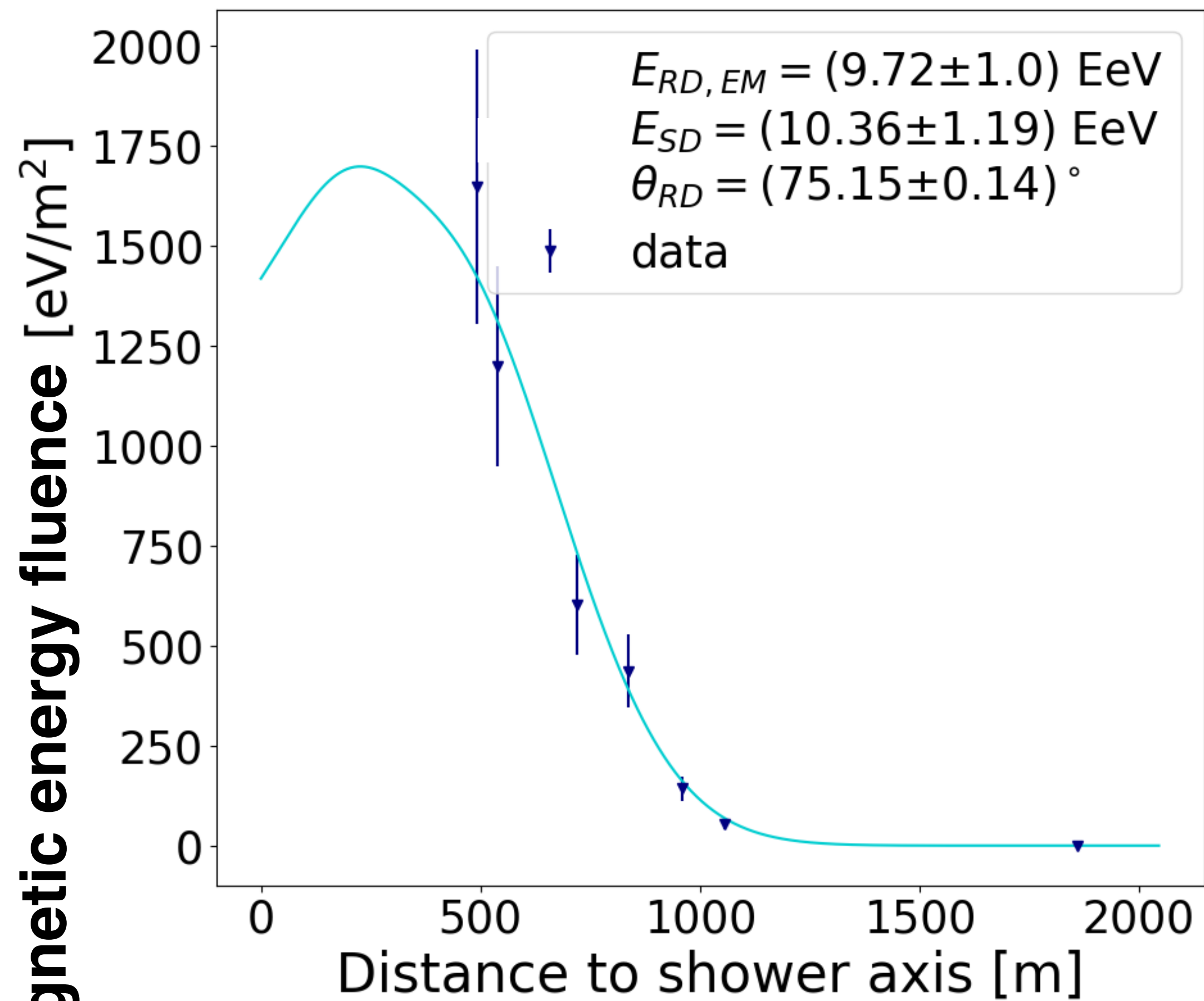
# A measured cosmic ray



	RD	SD
<b>Azimuth (deg)</b>	$156.99 \pm 0.01$	$157 \pm 0.1$
<b>Zenith (deg)</b>	$84.7 \pm 0.01$	$84.7 \pm 0.1$
<b>Energy (EeV)</b>	$36.23 \pm 3.34$	$38.55 \pm 2.92$
<b>Core X (km)</b>	-19.8	$-17.40 \pm 0.88$
<b>Core Y (km)</b>	-8.73	$-9.78 \pm 0.45$



# Hybrid measurements RD-WCD

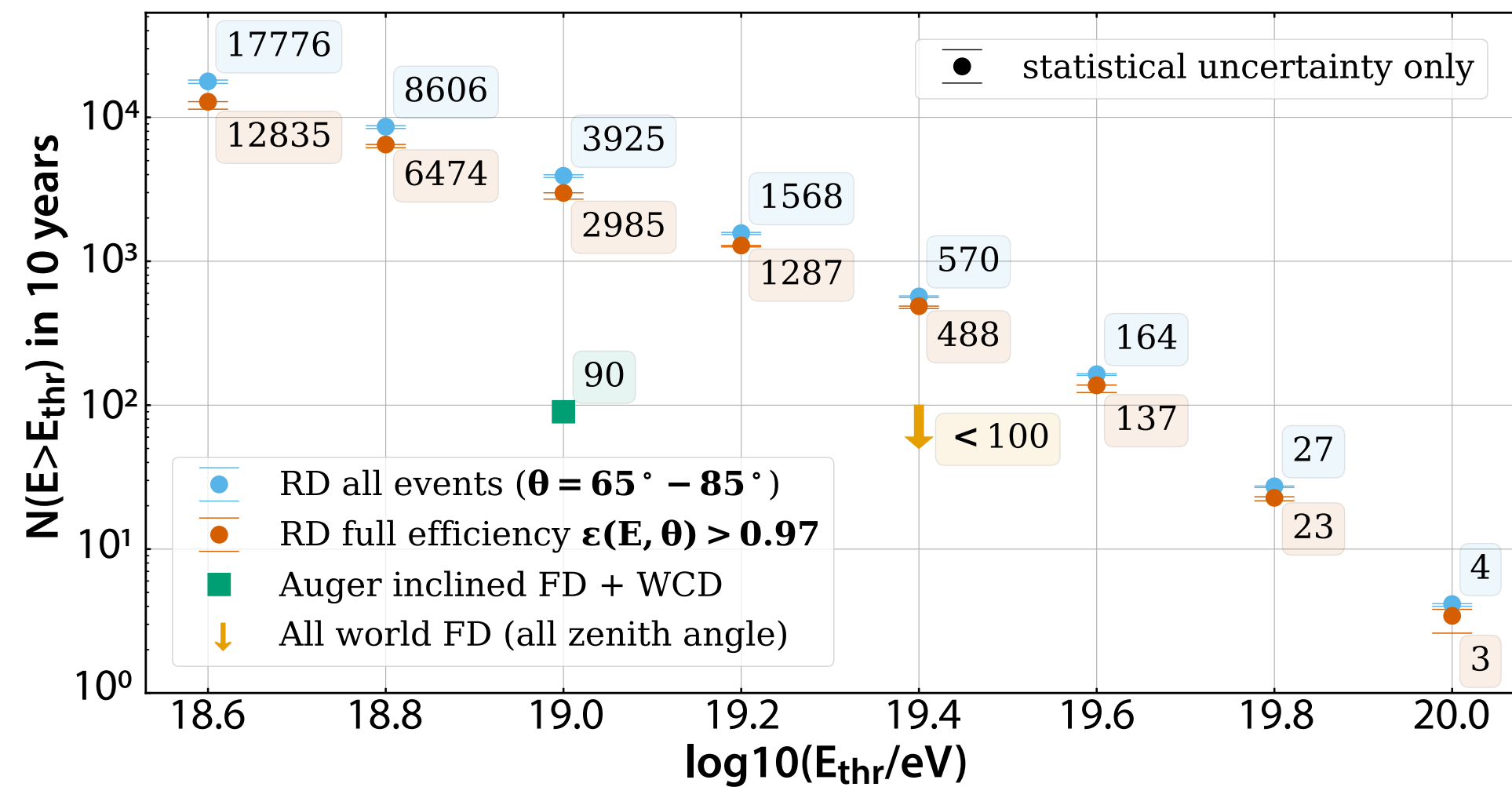


measurement of e/m energy by RD

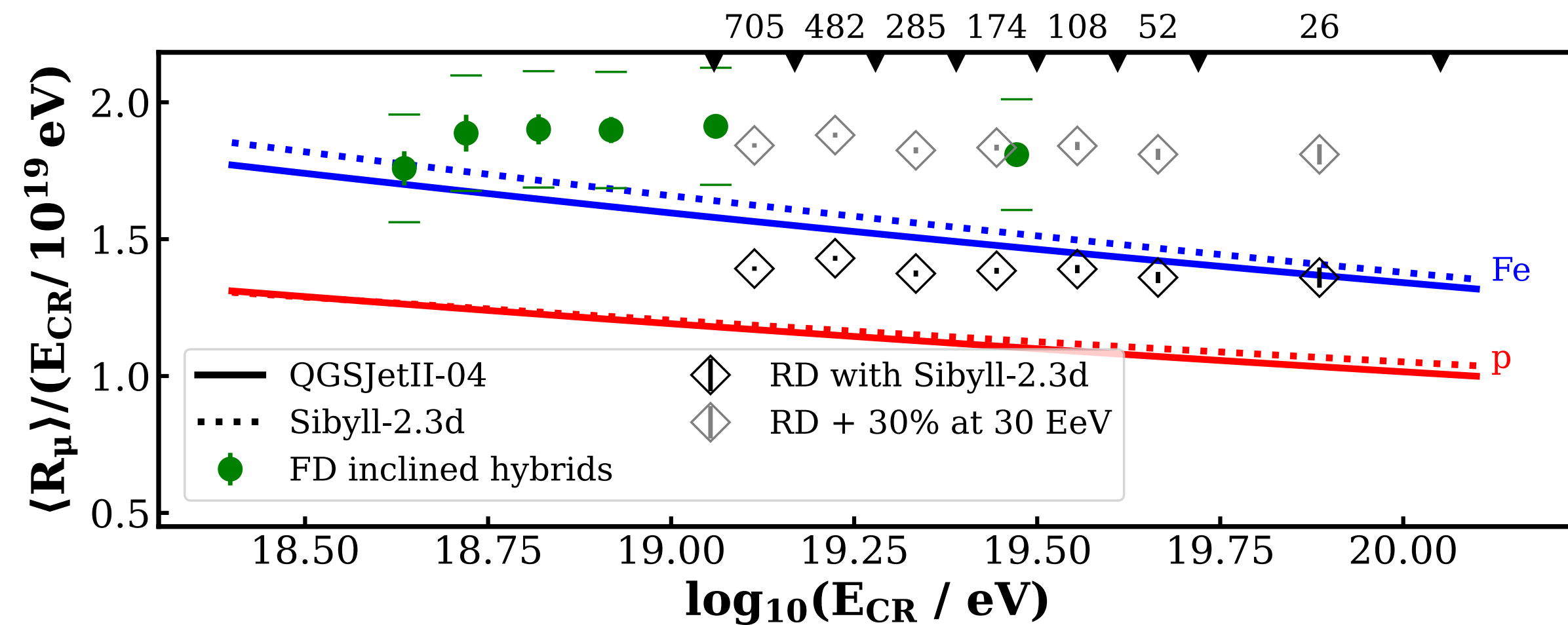
→ full end-to-end verification of complete chain

# RD expected physics contributions

## integrated # of cosmic rays



## measurement quality combining RD & WCD



## mass separation

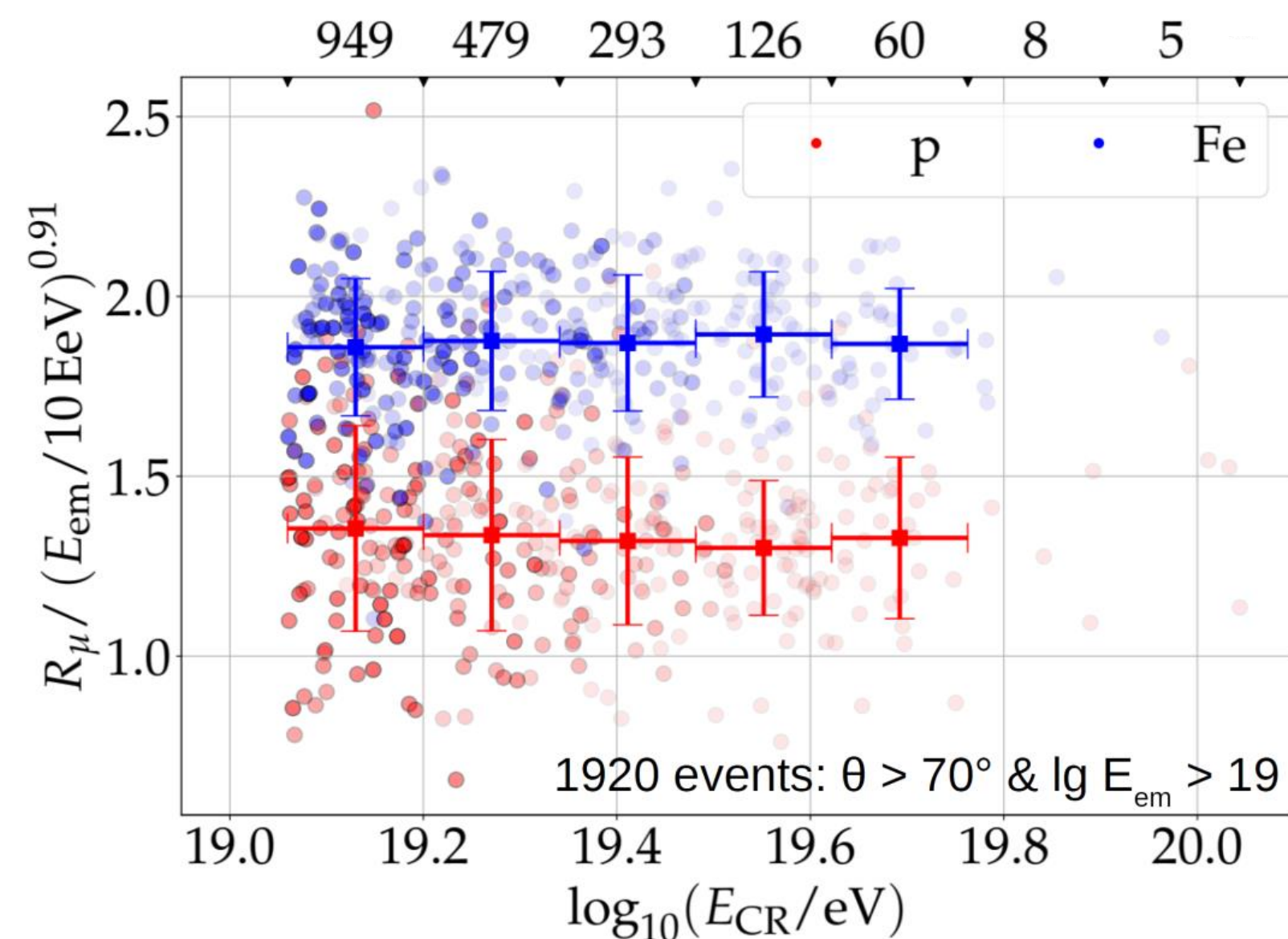


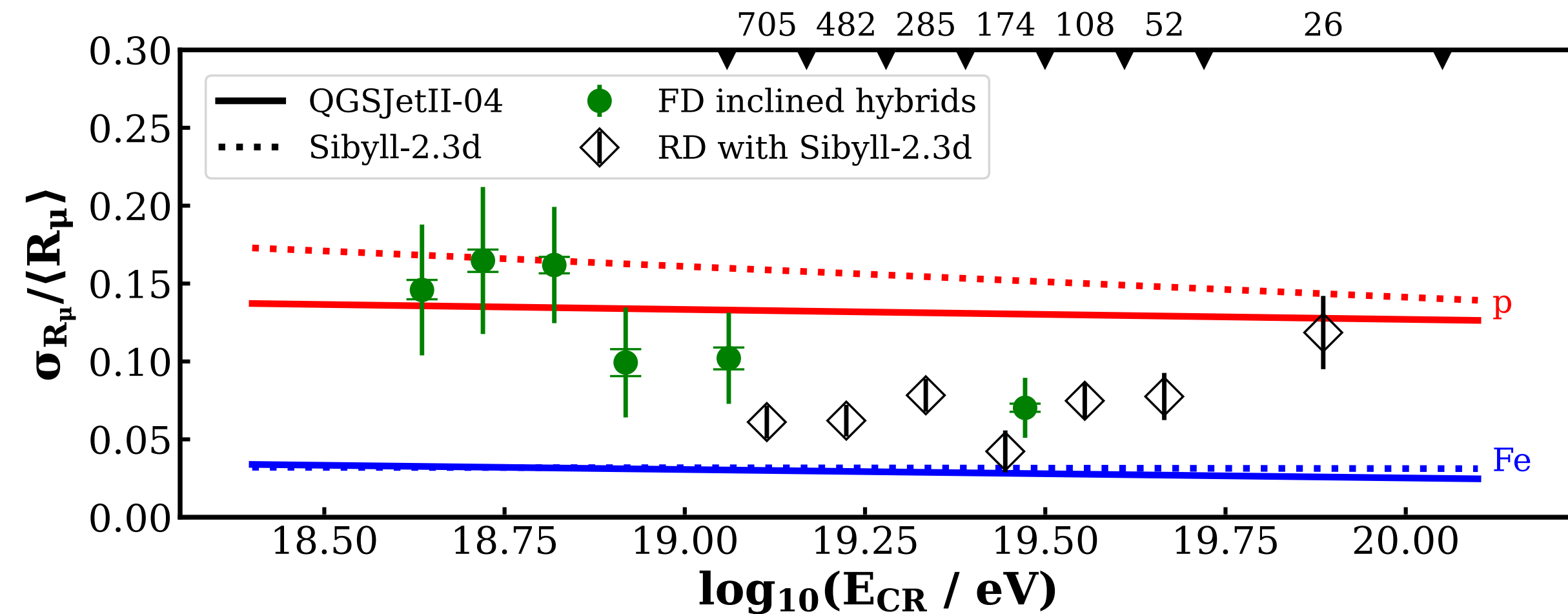
Figure of Merit:

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

**FOM =  $1.61 \pm 0.04$**

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

Goal for the Upgrade: 1.5



# Measurements of the highest-energy cosmic rays

Stay tuned for new insights into the origin of the highest-energy particles in the Universe



XIX Vulcano Workshop

## FRONTIER OBJECTS IN ASTROPHYSICS AND PARTICLE PHYSICS

Istituto Nazionale di Fisica Nucleare (INFN) and Istituto Nazionale di Astrofisica (INAF)

Ischia, Campania (Italy)

May 26th - June 1st, 2024

7<sup>th</sup> International Symposium on Ultra-High-Energy Cosmic Rays



## UHECR 2024

Malargüe, Argentina - November 17-21 2024

The symposium is the 7<sup>th</sup> edition of a series of meetings that bring together the UHECR community. It covers the latest results from UHECR observations, theoretical developments, and future plans in the field. The symposium will focus on the highest energy cosmic rays as well as on cosmic rays with energies above 1 PeV. The agenda includes invited reviews, contributed talks, and reports from inter-collaborative working groups, all in plenary sessions. Poster contributions are also foreseen.

### International Advisory Committee

R. Engel (chair), P. Blasi,  
A. Castellina, I. De Mitri, T. Ebisuzaki,  
P. L. Ghia, F. L. Halzen, Y. Itow,  
K.H. Kampert, P. Klimov, P. Lipari, J.  
Matthews, S. Ogio, I. H. Park, E. Partzot,  
E. Resconi, M. Roth, G. Rubtsov, D. Ryu,  
H. Sagawa, P. Sokolsky, Y. Tsunesada.

### Local Organizing Committee

I. Allekotte, B. Andrada, F. Gollán,  
G. Golup, F. Sánchez.

For more information:

<https://indico.ahuekna.org.ar/event/768/>  
[uhecr2024@auger.org.ar](mailto:uhecr2024@auger.org.ar)

