

SA2: Cosmic particles & fundamental physics

SA2-AUGE: Extremely energetic cosmic rays & neutrinos - Large exposure experiments

IGFAE retreat - 22 June 2026

Physics goals of SA2-AUGE

**Origin & Nature
of Ultra-High
Energy Cosmic
Rays**

**Multimessenger
Astronomy with
UHE neutrinos &
photons**

**Hadronic Physics
with air showers
beyond LHC
energies**

Main Research Activities & Lines

Pierre Auger Observatory

- Ultra-High Energy (EeV) Cosmic Rays with *inclined* showers
- Search for UHE neutrinos
- Hadronic & Air Shower Physics
- Multimessenger Astronomy at UHE



Detection of UHECR & neutrinos with radio waves (MHz - GHz)

- Modelling radio signal from particle showers
- Analysis of data of radio detectors
- New radio detectors of UHE neutrinos
- Multimessenger Astronomy at UHE



Sources of funding ($\cong$ 3 M€)

Agencia Estatal de Investigación (AEI)

- Generación de Conocimiento 2023/26 (230 k€)
- Cooperación Internacional 2023/26 (215 k€)
- Consolidación Investigadora 2025/27 (150 k€)
- Ramon y Cajal (Lorenzo Cazón) 2021/26 (40 k€)

European Union

- ACME 2024/28 (170 k€)
- ERC-SyG 2025 – HERON 2026/32 (2 M€)

Xunta de Galicia

- Inv. emerxentes 2021/26 (115 k€)

+ María de Maeztu + CIGUS + Consolidación Xunta de Galicia

SA2-AUGE (Astroparticle Physics) group

Permanent staff



Enrique Zas
Professor



Gonzalo Parente
Professor



Jaime Alvarez-Muñiz
Professor



Lorenzo Cazón
Ramón y Cajal
Sept. 2021

RyC



Joaquin de Jesús
Nov. 2025



Marina Scornavacche
Feb. 2026



Carmina Pérez-Bertolli
March 2026



Fernando Gollán
Feb. 2026

Postdoctoral

New Doctor 2025
@ Holland



Juan Ammerman-Yebra
IGFAE (MdM) FPI
Sept. 2021
June 2025

New Doctor 2025
@ Czech R.



Miguel A. Martins
INPhINIT La Caixa
Jan. 2022
Oct. 2025



Sergio Cabana-Freire
Xunta de Galicia
Oct. 2022



Yago Lema-Capeáns
Xunta de Galicia
Oct. 2022



Francisco Sánchez
IGFAE-FPI
March 2024



Carmen Pavón
Xunta de Galicia
Oct. 2024



María Durán
Research contract IGFAE
Feb. 2026

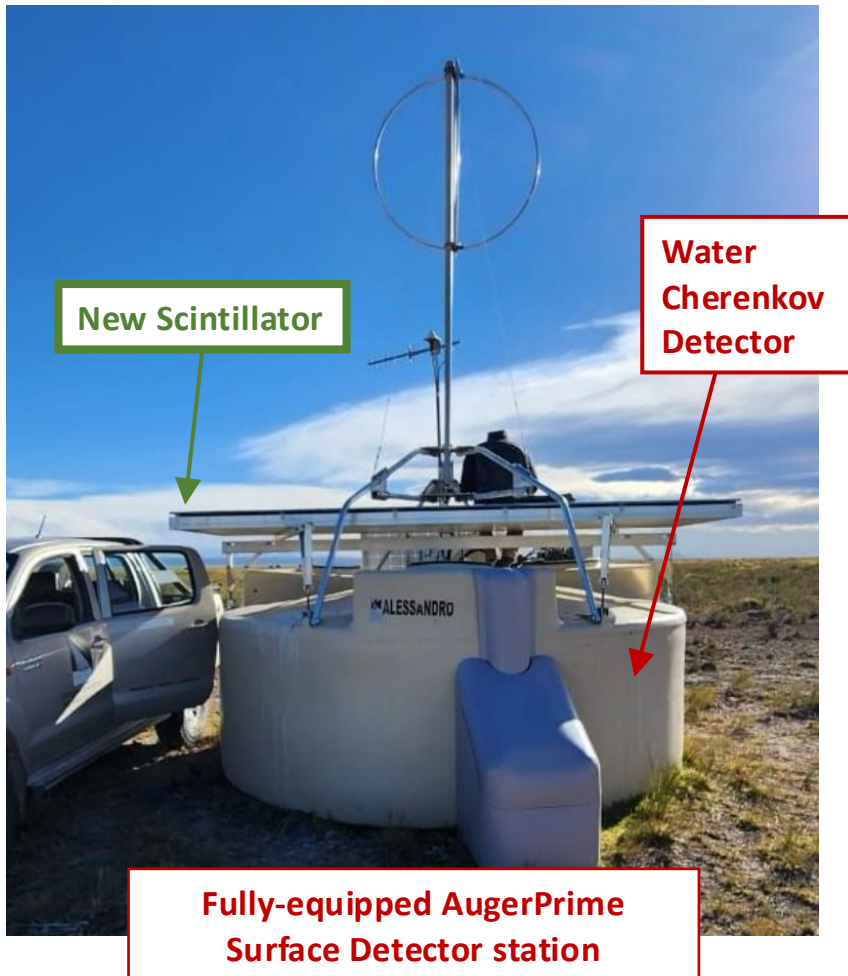


Brais Rocha
Research contract
Feb. 2026

PhD Students

A selection of scientific highlights 2025

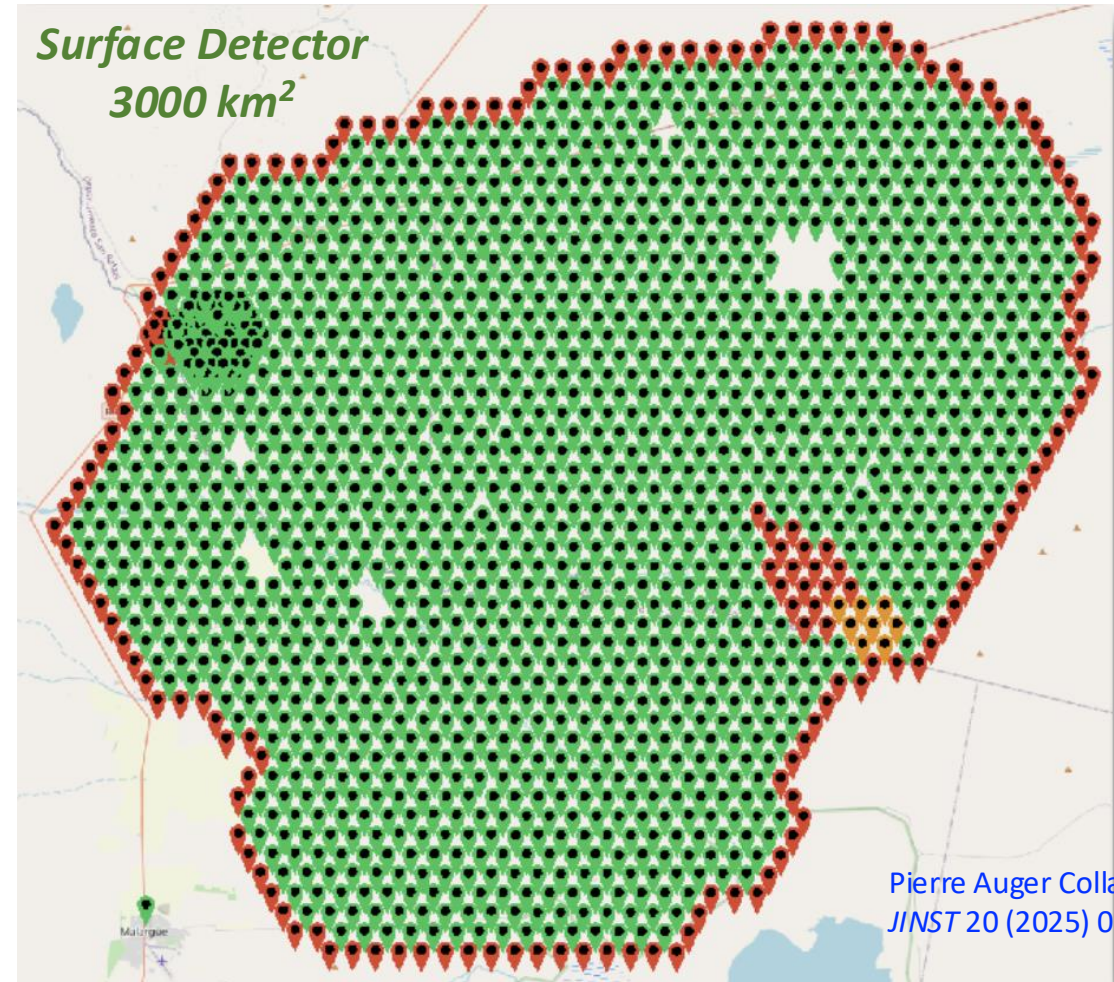
AugerPrime: extending the Pierre Auger Observatory to 2035+



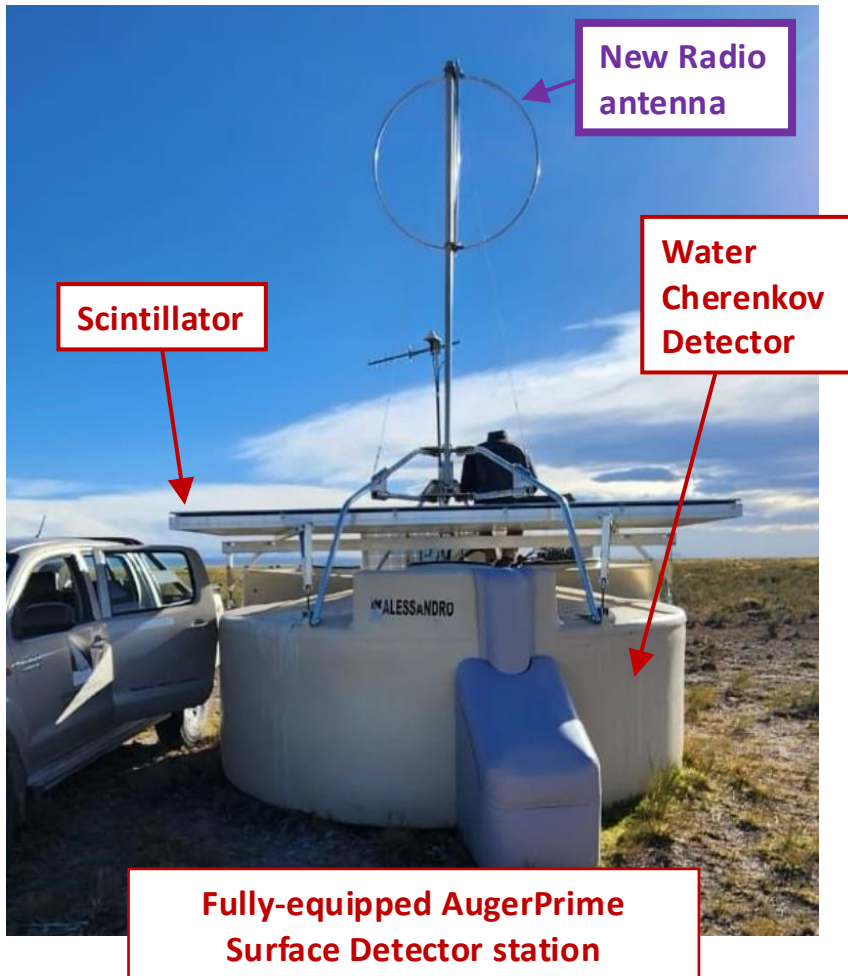
Particle detector array – completed Summer 2023
(1478 Scintillator detectors + new electronics + small PMTs)

**Improve primary particle identification by measuring the electrom.
& muonic components of the shower**

Taking data !



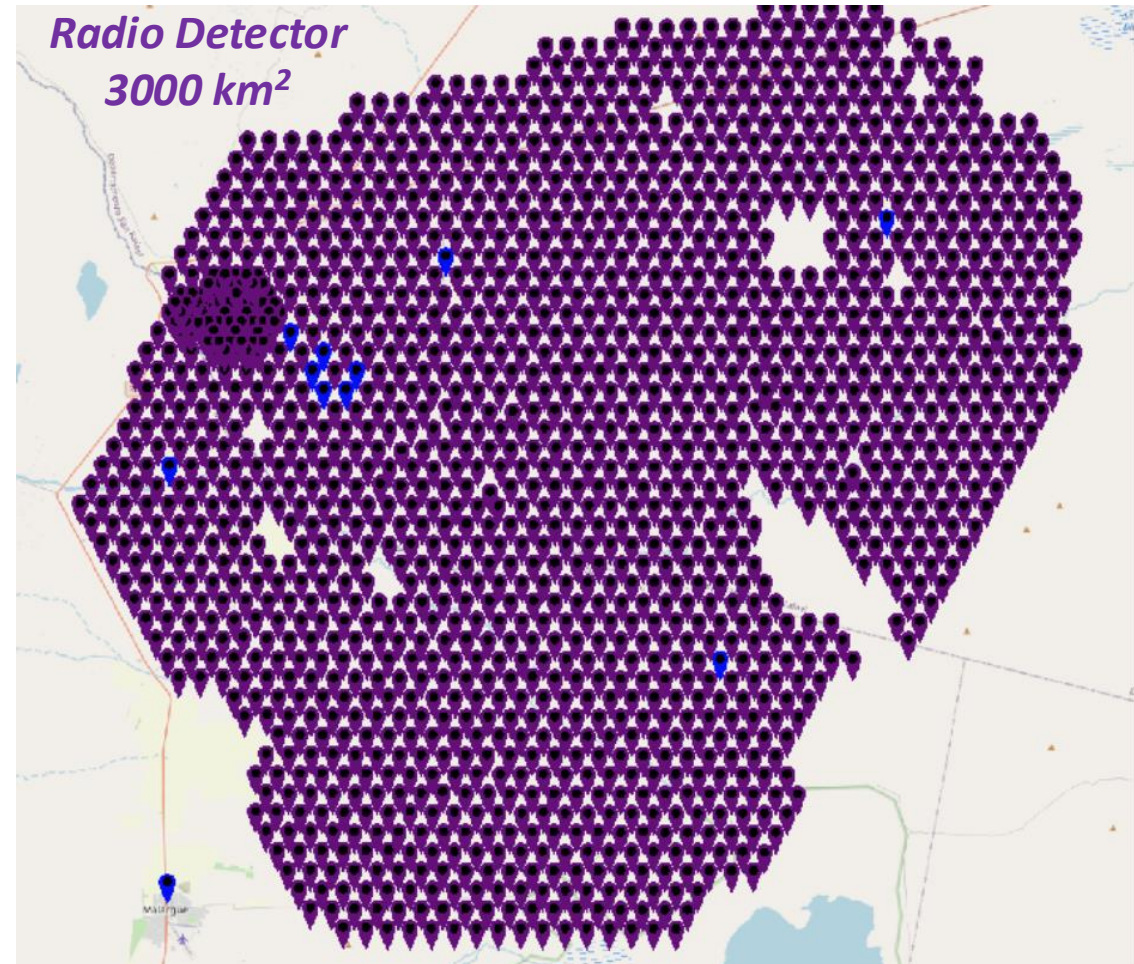
AugerPrime: extending the Pierre Auger Observatory to 2035+



Radio detector array – completed Dec 2024
(1605 SALLA radio antennas + digitizers)

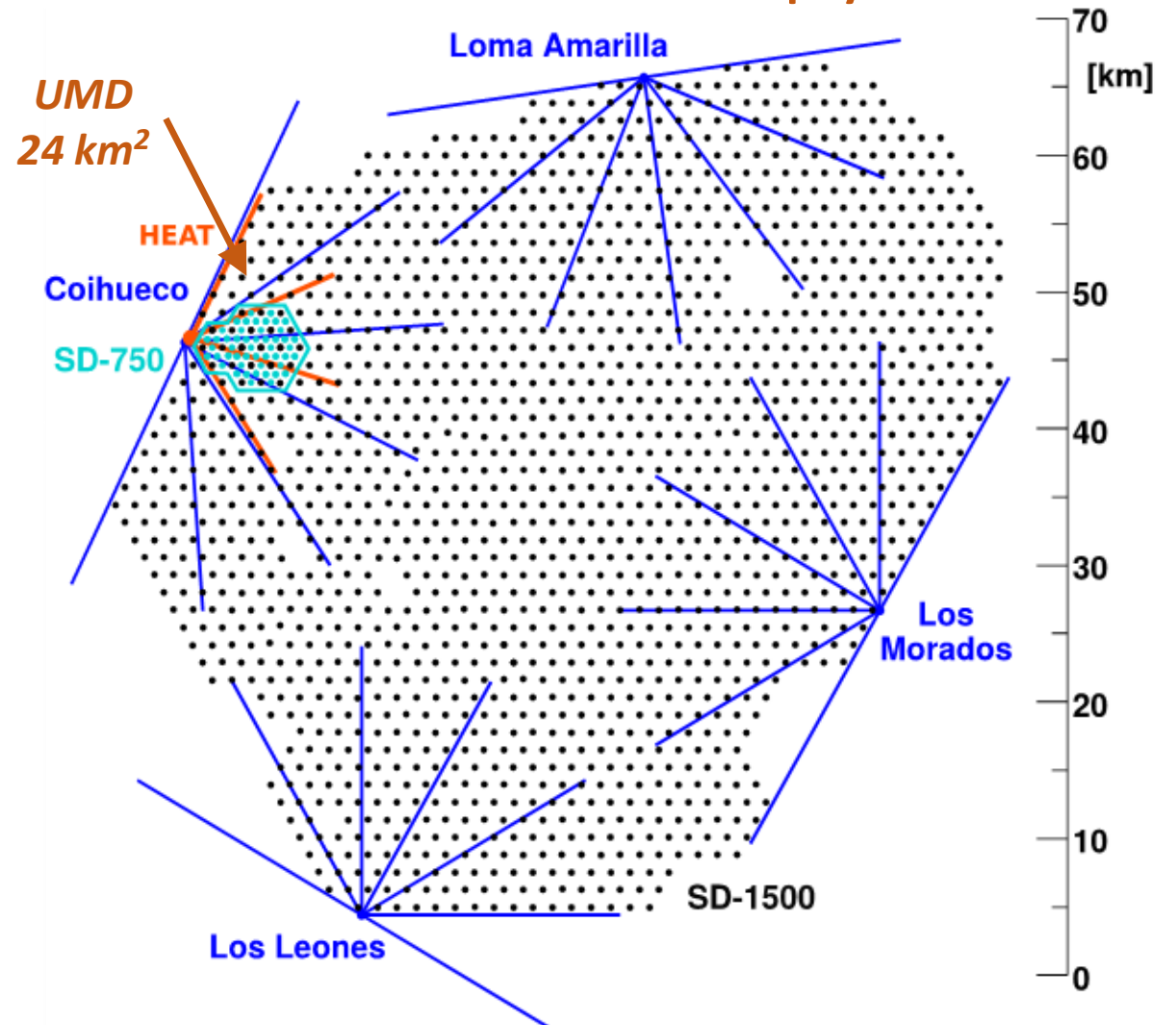
Measure electromagnetic energy of showers with 100%
duty cycle & enhance primary identification

Taking data !



Underground Muon Detector – nearly completed
(72 x 3 modules of 10 m² - buried scintillators)

Taking data !

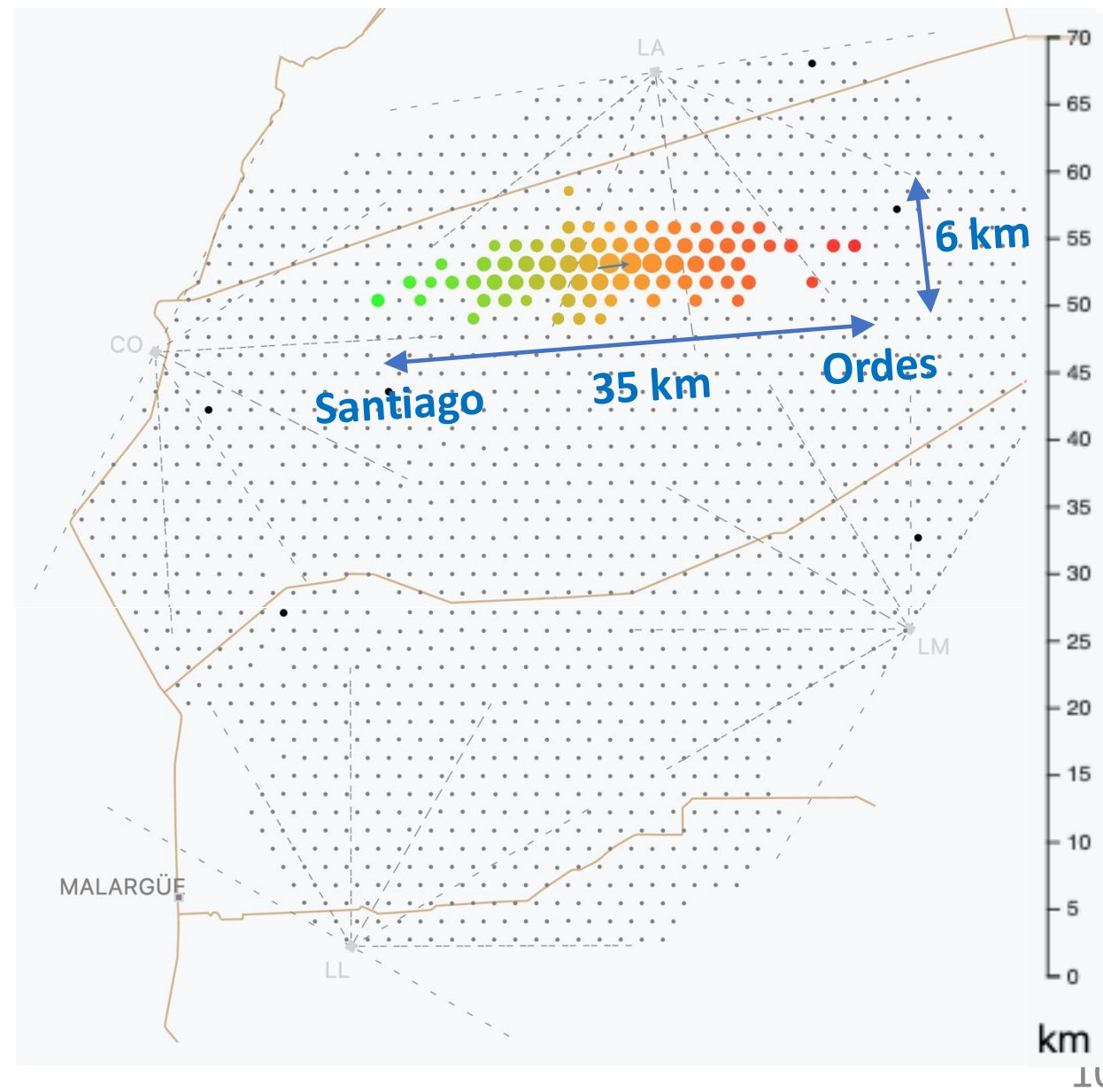


Inclined showers in the Pierre Auger Observatory

Event PAO150926

Date	2015-09-26
Energy [EeV]	$113 \pm 14 \sim 18$ Joules
θ [deg]	77.2
ϕ [deg]	188.0
α [deg]	21.7
δ [deg]	-13.8
Multiplicity	75

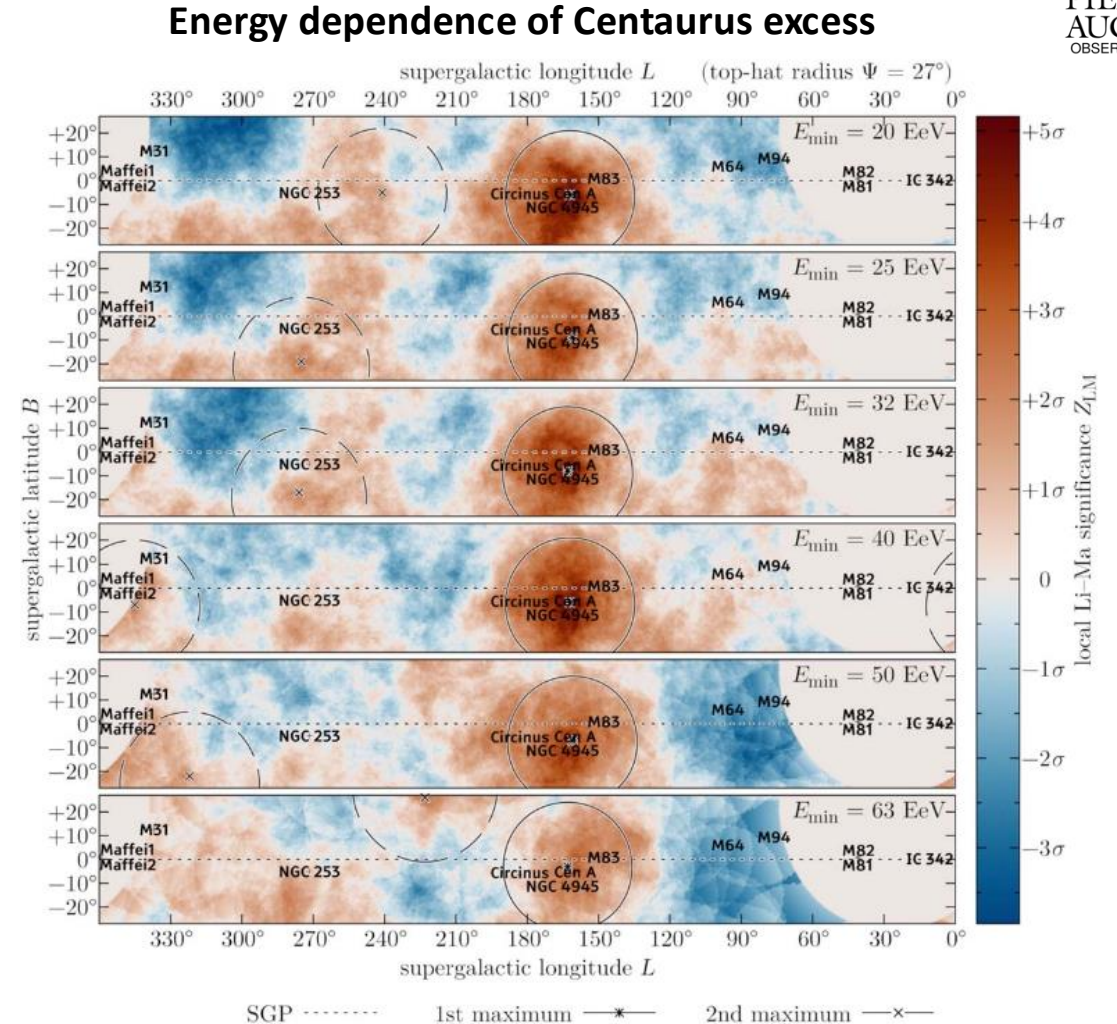
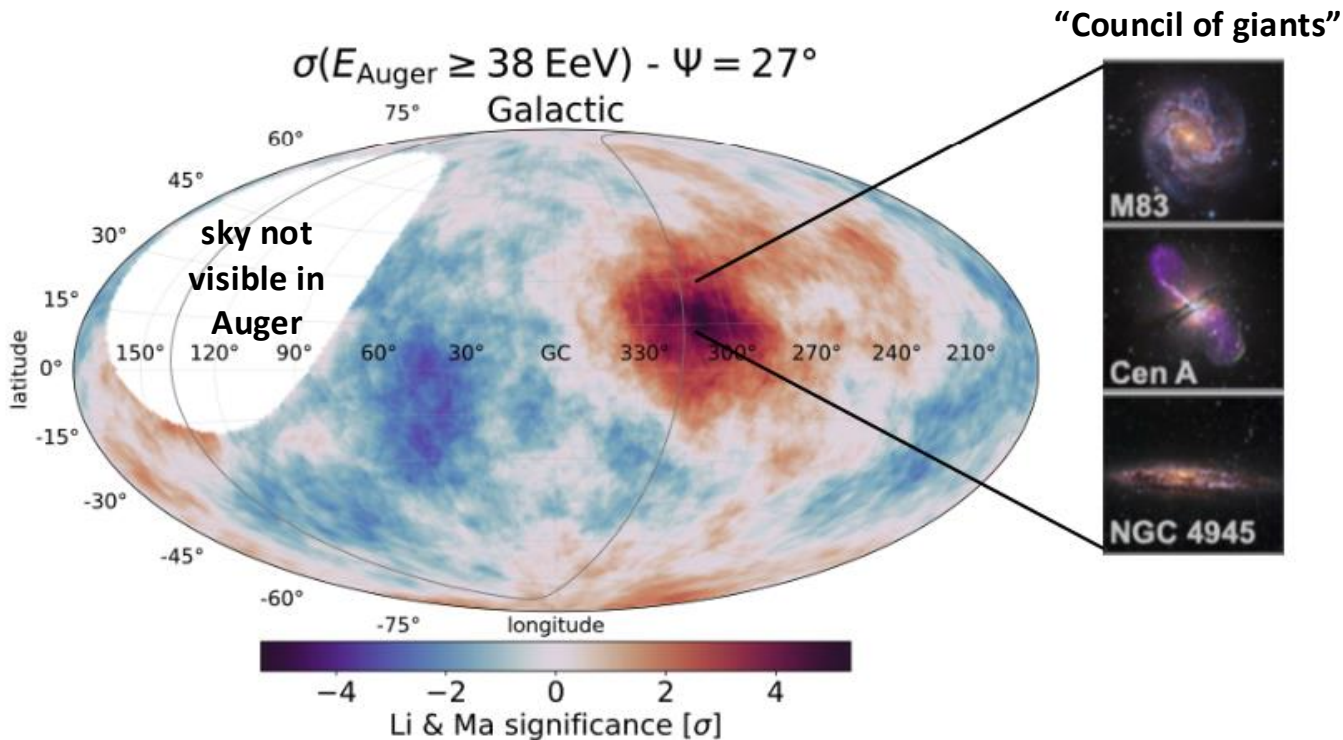
- ☐ Zenith angle above 60 deg. Access to Northern sky from Auger located South
- ☐ Electromag. component absorbed in atmosphere
 $\Rightarrow$ provide direct measurement of muonic component
- ☐ Neutrino searches in Auger based on inclined showers



UHECR arrival directions: intermediate-scale anisotropies

Pierre Auger Observatory

Excess of UHECR in the Centaurus region:
4.0 σ significance



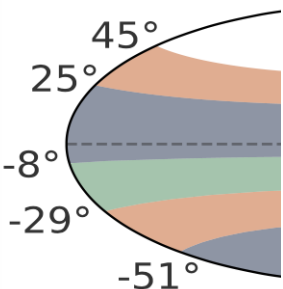
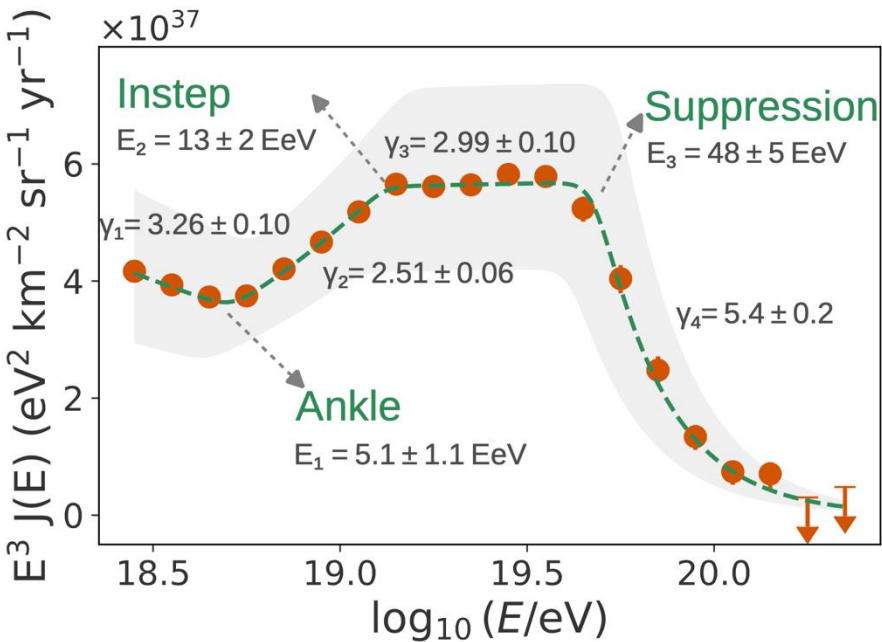
position of Centaurus-region excess remains constant with energy:

- ❑ CR rigidity ($R=E/Z$) remains constant $\Rightarrow$ Z increases with E
- ❑ no strong coherent deflections: subdominant regular magnetic field in the direction of Centaurus?

UHECR energy spectrum: declination dependence

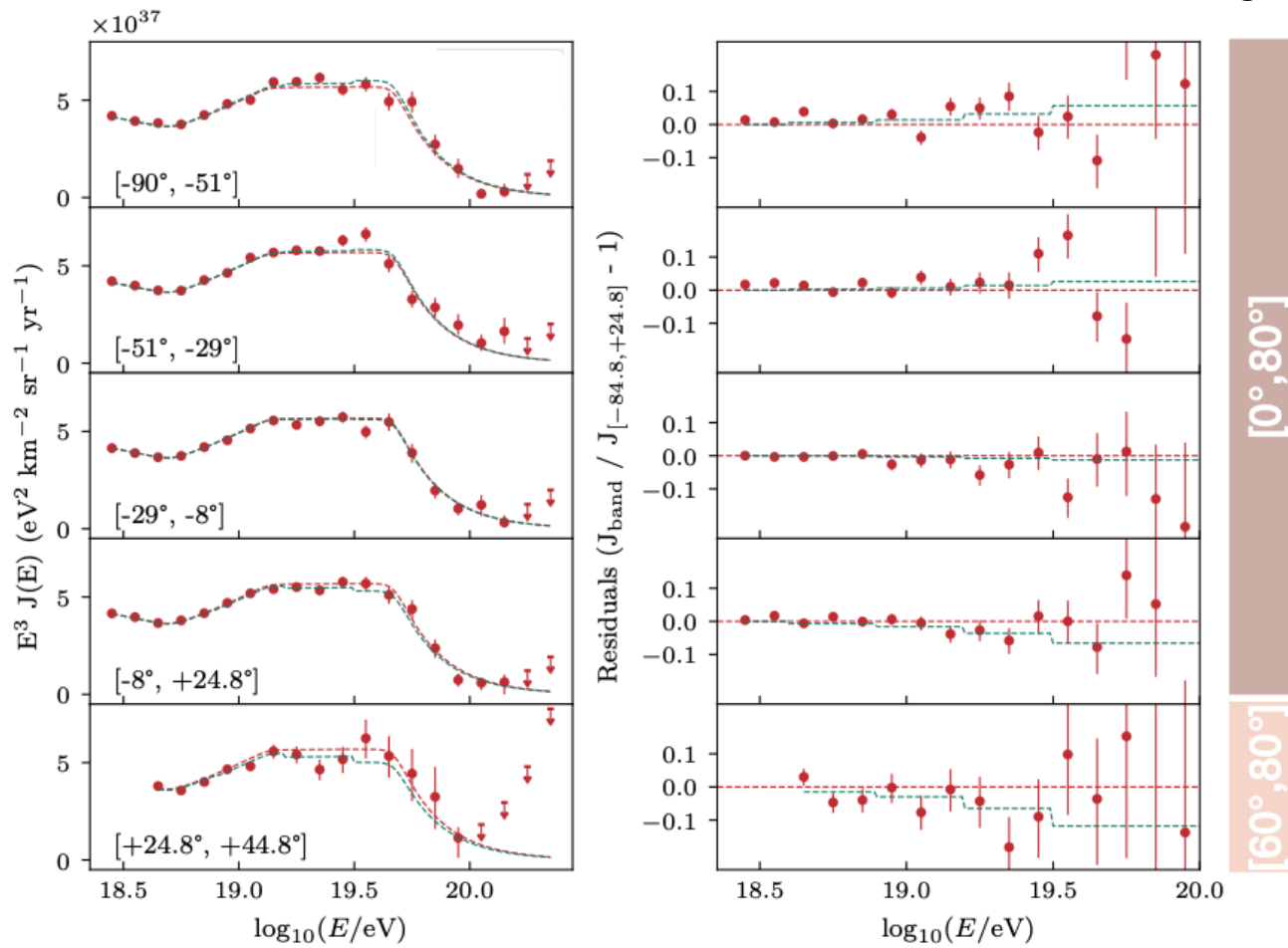
Pierre Auger Observatory

all declinations $[-85^\circ, +44.8^\circ]$
based on 312,516 events



equatorial declination bands

zenith angle



No spectrum dependence on declination =>
features of energy spectrum are **universal properties** rather than being associated to local sources

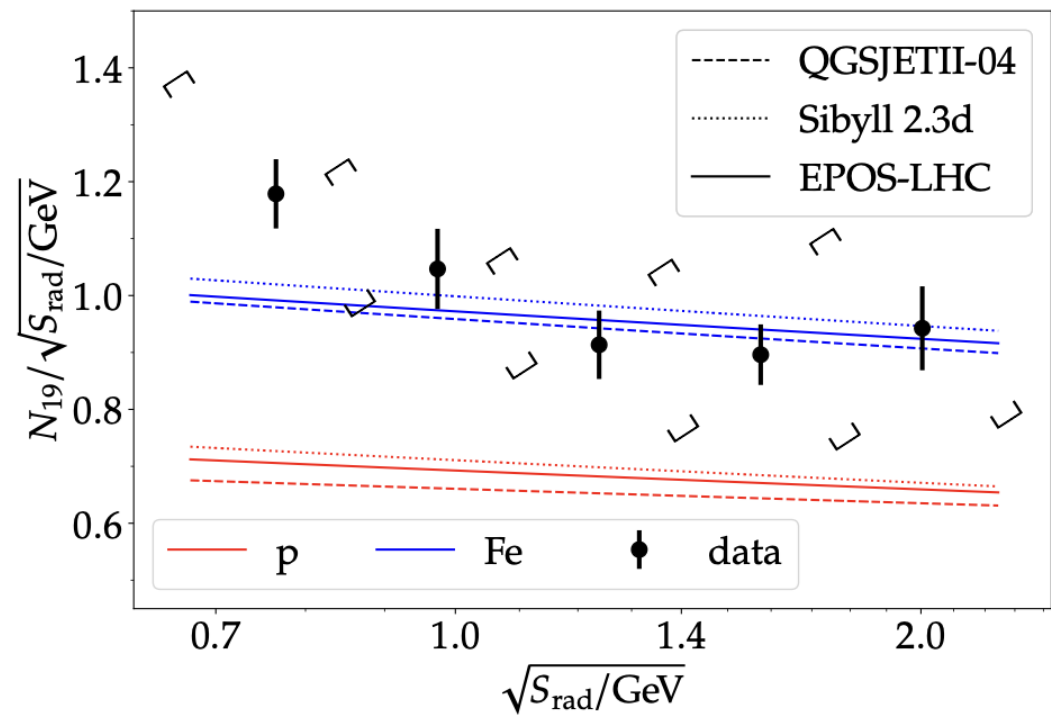
Air Showers & Hadronic interactions: Muons



1st results combining Auger data from:

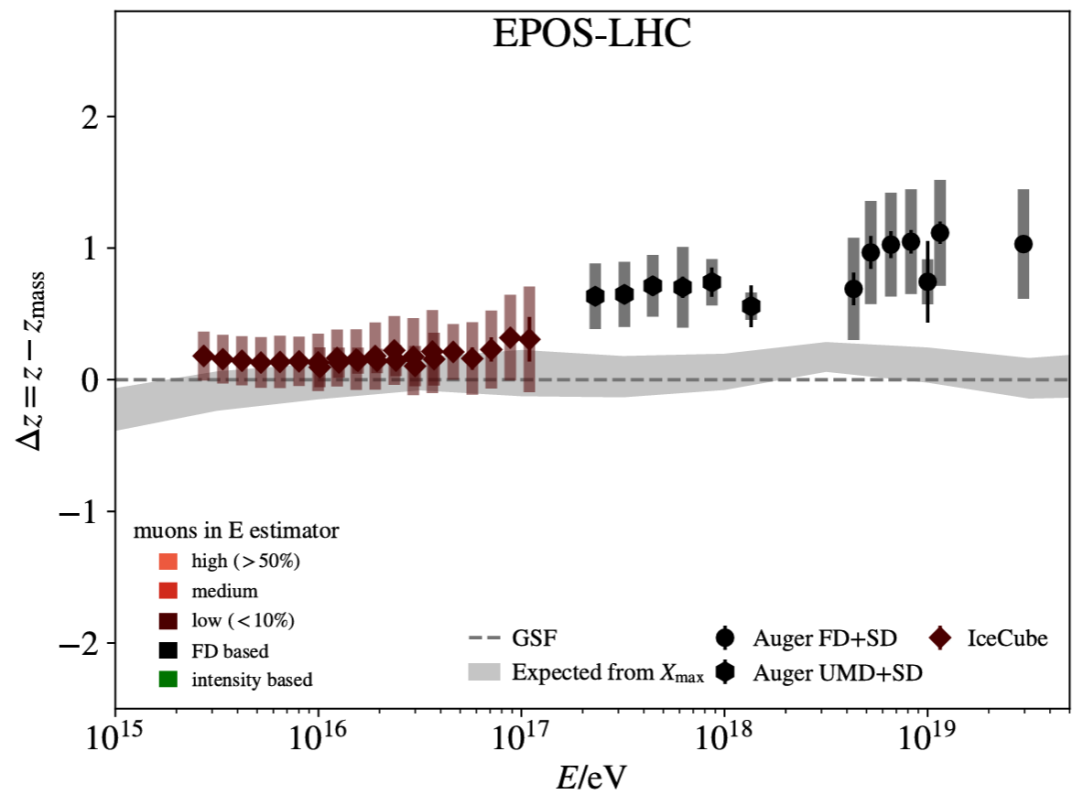
Particle detector → muon number in inclined showers

Radio prototype → proxy for shower energy



Working Group on Hadronic Interactions & Air Showers Physics

muon deficit of hadronic models gradually increases with shower energy

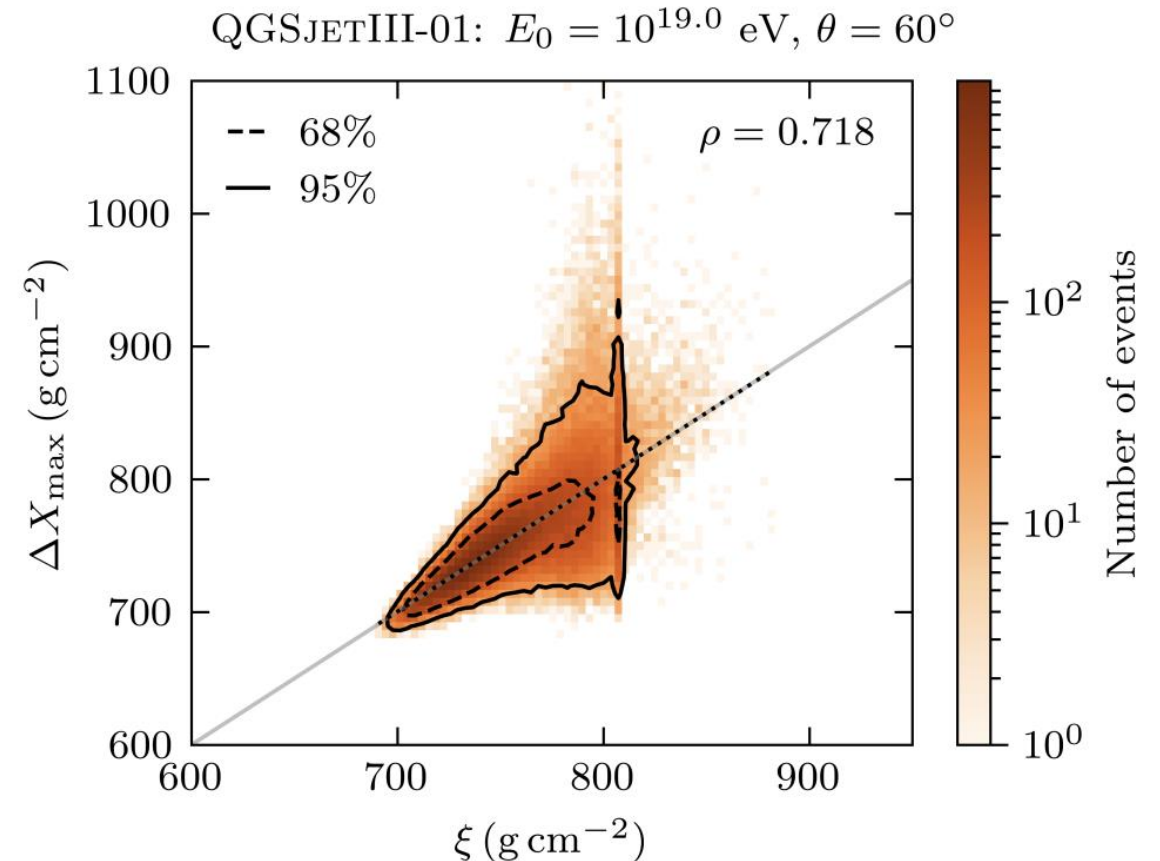
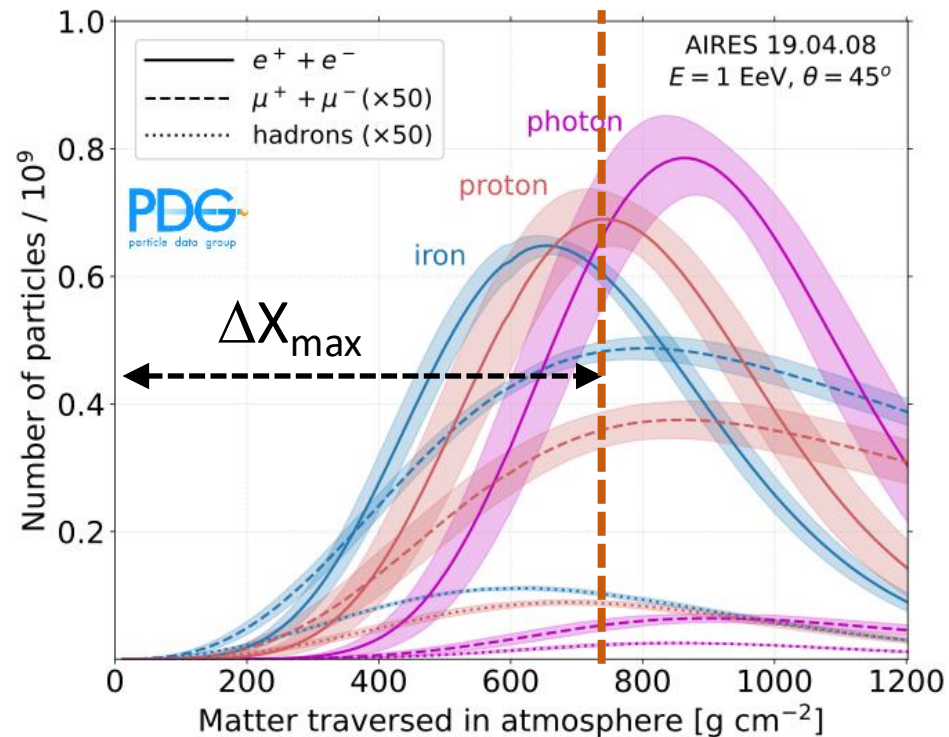


Air Showers & Hadronic interactions: connecting hadronic interactions & shower observables

Correlation between **1st shower interaction properties** (ξ -variable related to energy spectra of secondaries in p-Air collisions) and $\Delta X_{\max}$

M. Martins, L. Cazon, et al. Phys. Rev. D 112 (2025) 4, 043016

Depth development of air showers



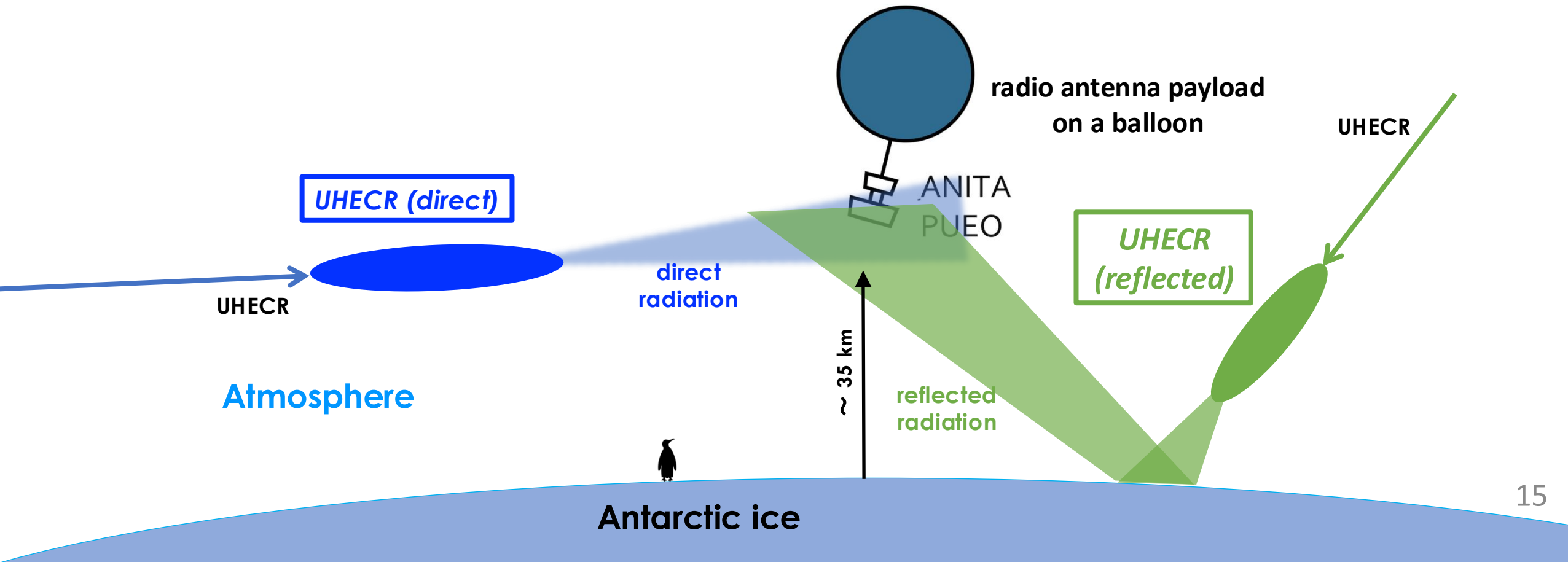
Radio detection of UHE particles

Modeling radio emission from UHECR events in atmosphere

- ❑ Reflected events (J. Alvarez-Muniz et al., Astropart. Phys. 2016)
- ❑ ARPZ model for Air-Shower radio emission (C. Pavón-Souto et al. in prep.)
- ❑ High-Altitude Horizontal Air showers (S. Cabana-Freire et al. JCAP 2025)



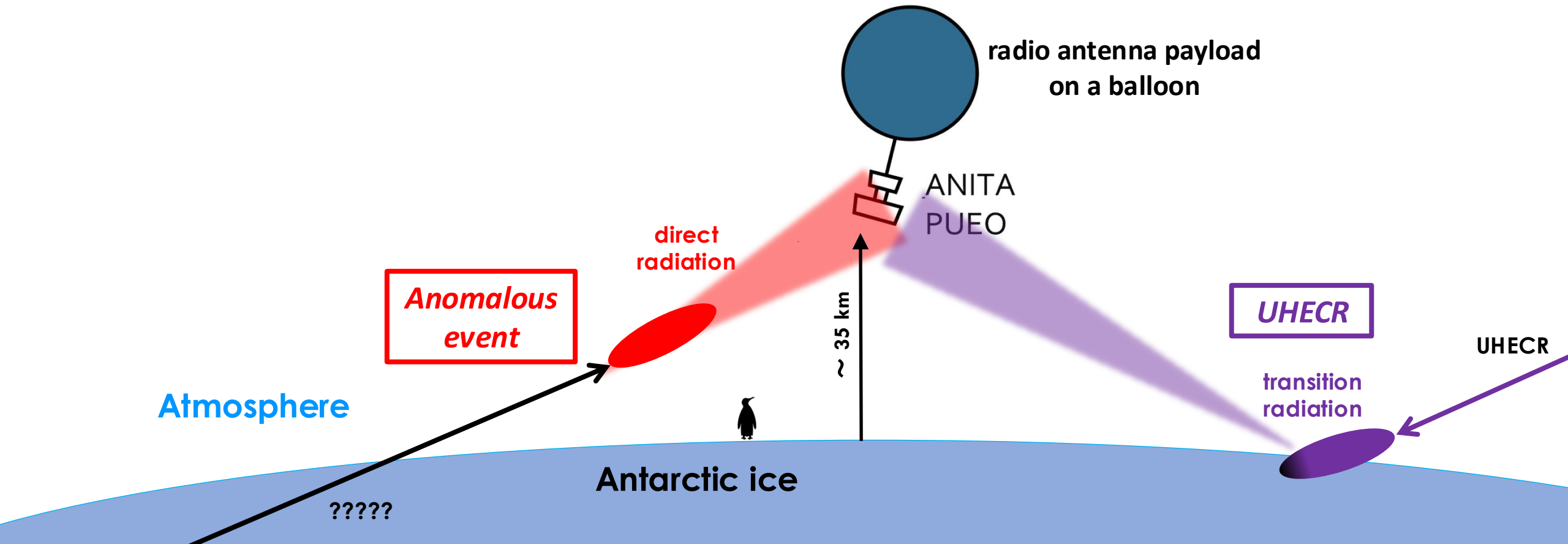
ANITA



Radio detection of UHE particles

Ruling-out SM & BSM explanations of ANITA *anomalous events*

- ❑ Tau neutrinos (J. Alvarez-Muniz et al., PRD 2019) – SM
- ❑ Transition radiation (J. Ammerman et al., JCAP 2024) – SM
- ❑ Upward-going showers (Pierre Auger, PRL 2025 – see backup) – SM & BSM



PUEO launched over Antarctica (23 days flight in December 2025)



Expect many more reflected, HAHAs,
(and maybe anomalous) events

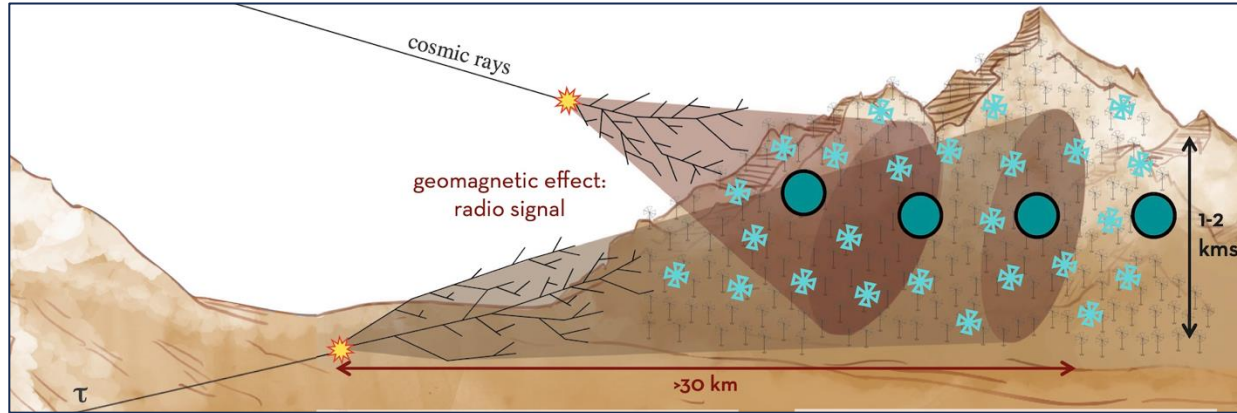


HERON - Opening Neutrino Astronomy at UHE

Hybrid Elevated Radio Observatory for Neutrinos



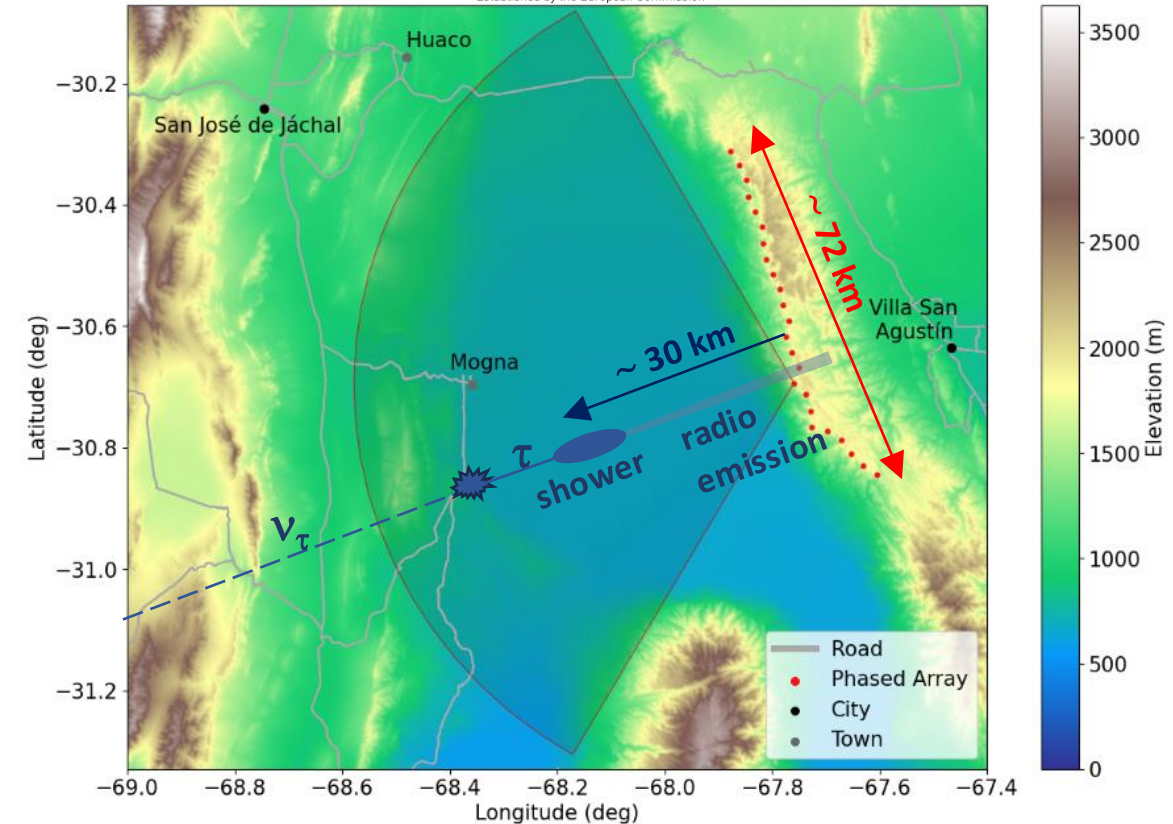
European Research Council
Established by the European Commission



Groundbreaking experiment for tau neutrino detection combining 2 techniques:

● **phased arrays** ✕ **parse antenna array**

- Energy threshold $< 10^{17}$ eV
- Sub-degree angular resolution
- 10x sensitivity of current experiments



San Juan, Argentina. Latitude -30.5°

Ideal site topography:

long mountain ridge 2 km altitude overlooking a valley
and a mountain ridge in front

Pierre Auger Open data

2021 → Open data portal + 10% vertical events

2022 → 10% inclined events

2023 → Catalog of 100 highest energy events

2024 → 10% low-Energy data

Next release : 30% of all data (2004-2021)

<https://opendata.auger.org/>

Pierre Auger Observatory Open Data

The Pierre Auger Open Data is the public release of 10% of the Pierre Auger Observatory cosmic-ray data published in recent scientific papers and at International conferences, following the [Auger Collaboration Open Data Policy](#). The release also includes 100% of weather and space-weather data collected until 31 December 2020. This website hosts the datasets for download. Brief overviews of the [Pierre Auger Observatory](#) and of the [Auger Open Data](#) are set out below. An online event display to explore the released cosmic-ray events, and example analysis codes are provided. An outreach section dedicated to the general public is also available.



Datasets

the released datasets and their complementary data



Visualize

an online look at the released pseudo raw cosmic-ray data



Analyze

example analysis codes in online python notebooks to run on the datasets



Catalog

of the highest-energy cosmic rays



Outreach

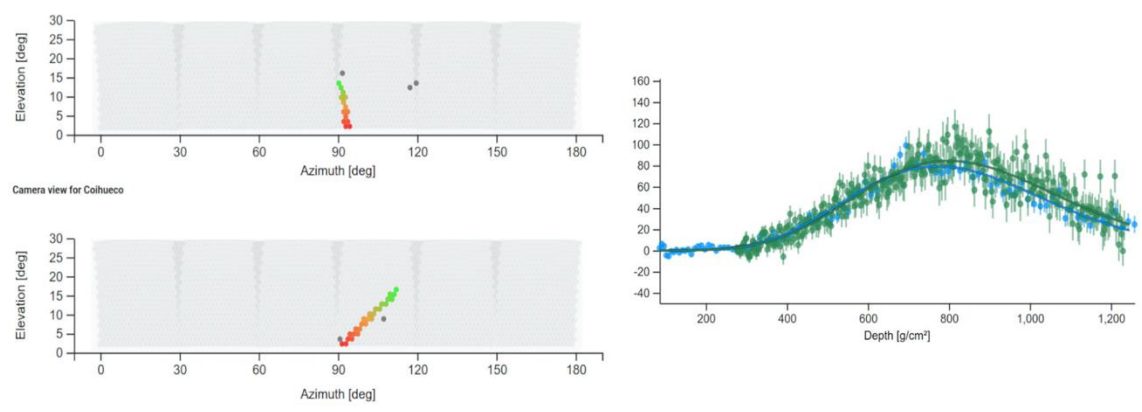
a page dedicated to the general public



Recognized by European Physical Society

Particles and Fields

From "The Pierre Auger Observatory open data"
by Pierre Auger Collaboration, Eur. Phys. J. C 85, 70 (2025).



Visualization of an exemplary event. Left panel: camera view of the fluorescence detector; the cosmic-ray shower is seen as a trace that moves along the pixels of the camera, from early (green) to late (red) pixels. Right panel: reconstructed energy deposit as a function of atmospheric depth as measured with the two telescopes participating in the event.

Outreach

❑ **VR system** used in exhibits at IGFAE and outreach talks at high schools to visualize:

- Auger physics
- Solar eclipses
- Augmented reality with quarks

❑ Initiators, promoters & organizers of **DATA SCIENCE & the Bridge to Industry** meetings + **Course in Unity**



Thanks !

Responsibilities in the Pierre Auger Observatory



Enrique Zas
Professor



**Multi-
Messenger
task
coordinator**



Jaime Alvarez-Muñiz
Professor



**Neutral
Particles
task
coordinator**



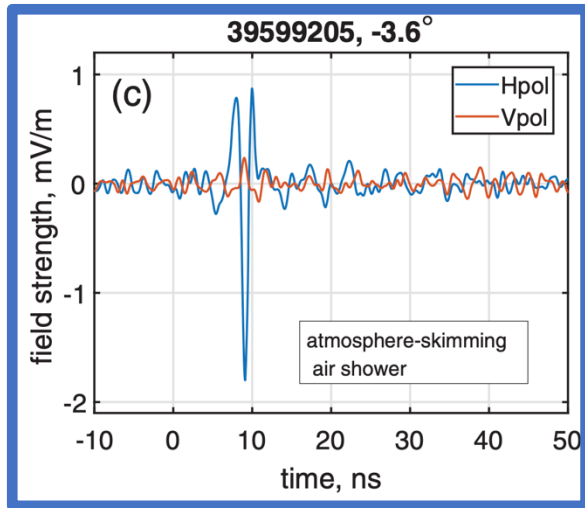
Lorenzo Cazón
Ramón y Cajal
Sept. 2021



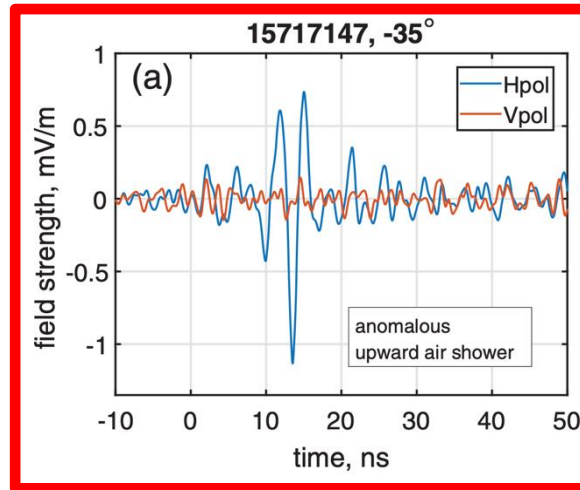
**Physics
coordinator**

Radio detection of UHE particles

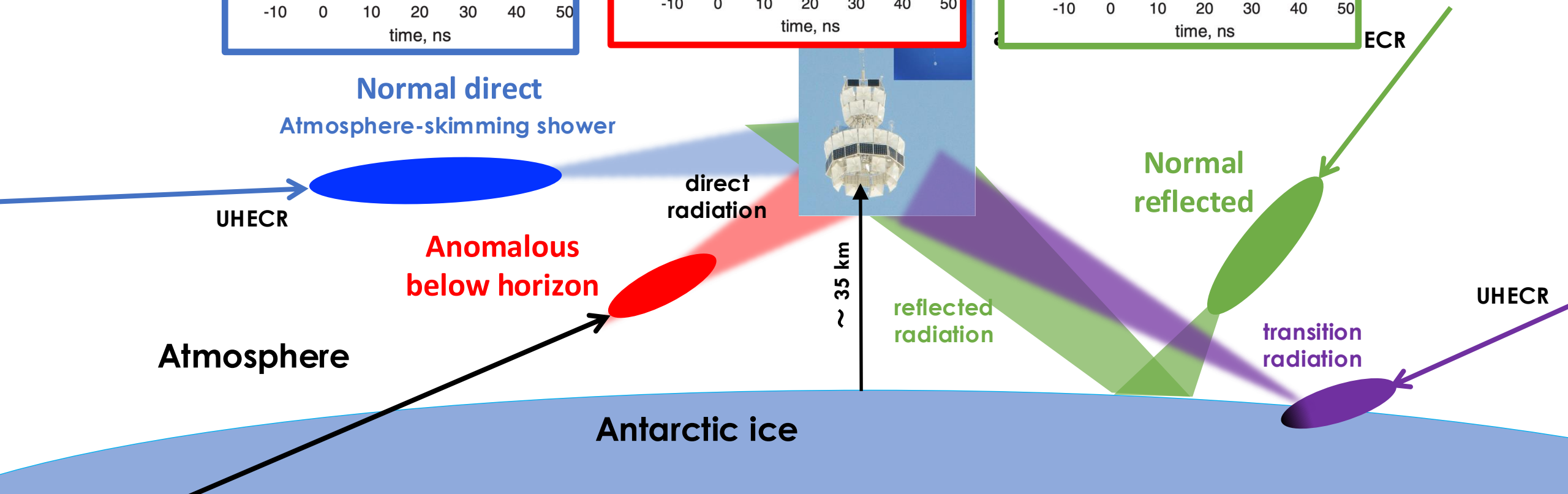
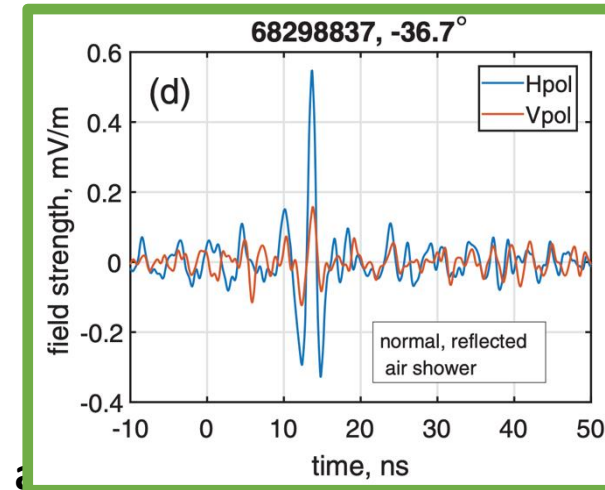
Normal direct above horizon



Anomalous below horizon



Normal reflected



Radio detection of UHE particles

Ruling-out explanations of ANITA anomalous events

Tau neutrinos (J. Alvarez-Muniz et al., PRD 2019)

Transition radiation (J. Ammerman et al., JCAP 2024)

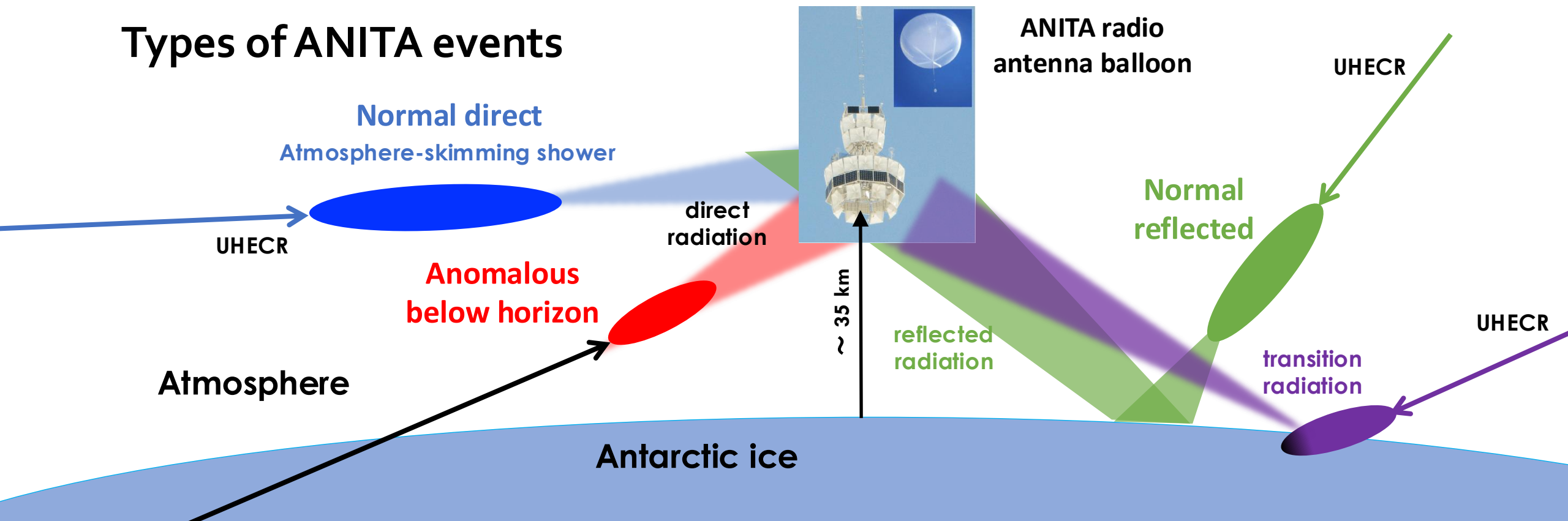
Upward-going showers (Pierre Auger, PRL 2025 next slide)

Modeling radio emission from non-standard geometries

Reflected events (J. Alvarez-Muniz et al., Astropart. Phys. 2016)

Atmosphere-skimming showers (S. Cabana-Freire et al. JCAP 2024 & 2025)

Types of ANITA events

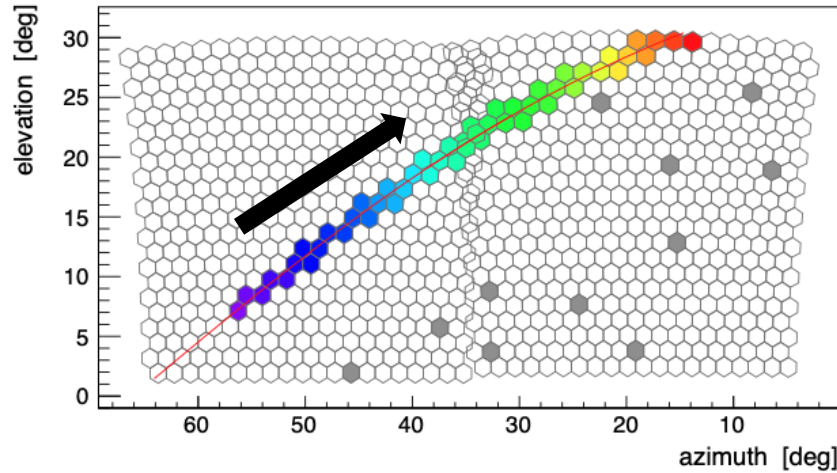


Search for upward-going showers with Auger

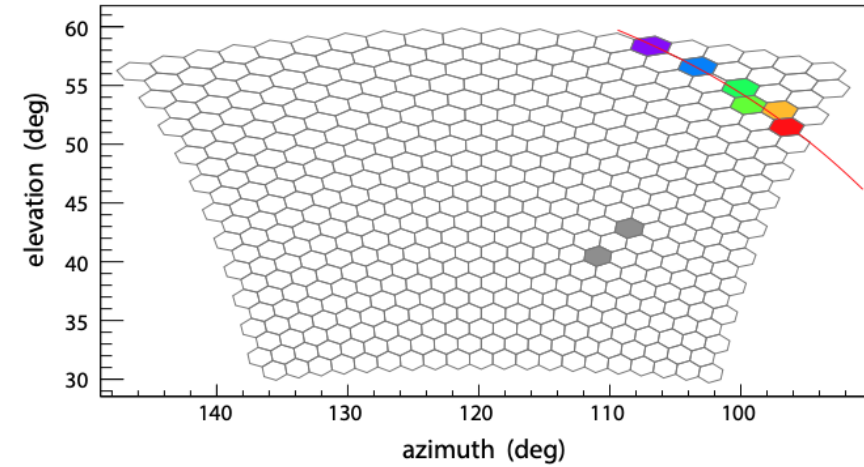
Pierre Auger Collaboration, PRL 2025

Fluorescence
Detector
pixel camera

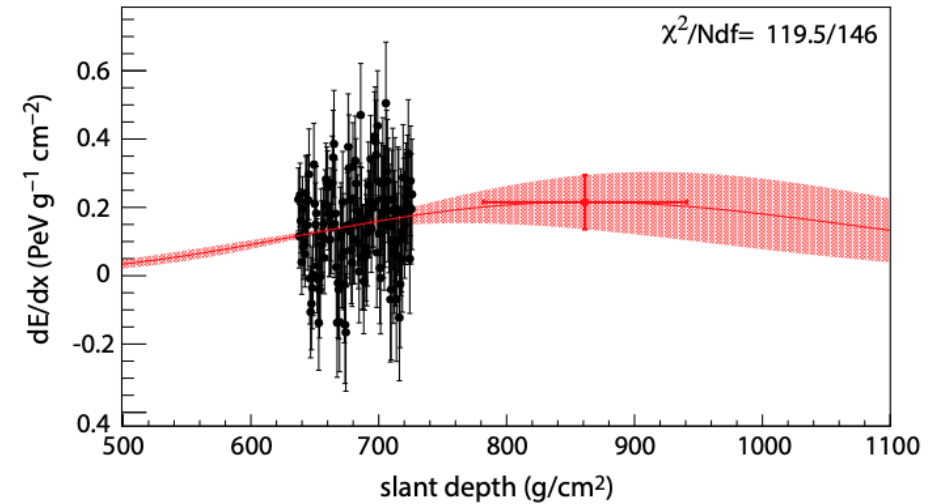
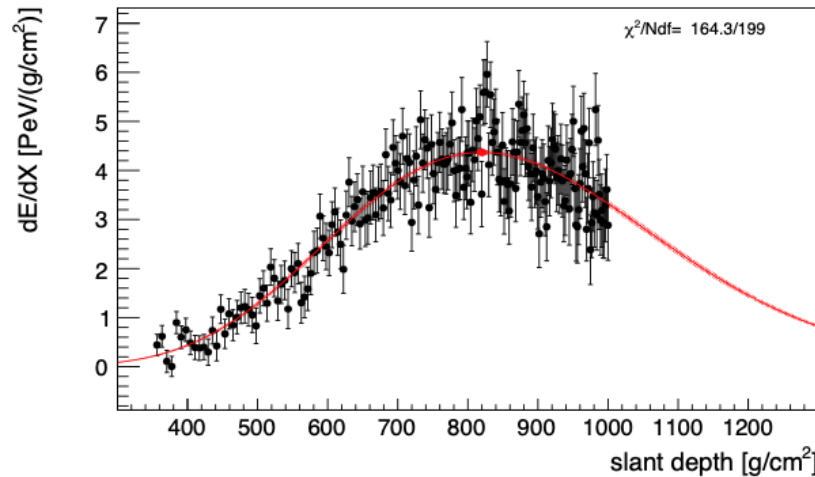
Simulated



**Only candidate
(compatible with background)**



Profile of
Energy
deposit



Auger strongly disfavors upward-shower explanation of ANITA events