The 100 most energetic showers recorded with

the Pierre Auger Observatory cosmic-ray detector.

In December 2022 the Pierre Auger Collaboration, that runs the largest and most accurate cosmic-ray detector of energies above and around 1 EeV = 10^{18} eV, released a catalog containing details of the 100 highest-energy cosmic rays recorded between 1 January 2004 and 31 December 2020 through the detection of extensive air-showers. Details are also given of a further nine very-energetic events that have been used in the calibration procedure adopted to determine the energy of each primary. The catalog is open online for anyone´s scrutiny and enjoyment:

https://opendata.auger.org/catalog/

The Pierre Auger Observatory is the world's largest cosmic ray observatory to study the extensive air-showers produced by cosmic rays with energies above and around 1 EeV = 10^{18} eV. It is located on a vast, plain in Argentina at 1400 m above sea level, in the Province of Mendoza. The intensity of high energy cosmic rays decreases rapidly with energy, and above 10^{19} eV the rate is only about 1 per km^2 per year. For this reason, the phenomenon of extensive air-showers must be exploited to study cosmic rays at very high energies. An air-shower is a cascade of particles created by the interaction of a single cosmic-ray with the Earth atmosphere. They can be observed by telescopes that pick up the fluorescence radiation emitted from nitrogen molecules excited as the shower crosses the atmosphere, while the particles reaching the ground can be sampled by large arrays of detectors. The properties of these extensive air-showers are measured to determine the energy and arrival direction of each cosmic ray and to provide a statistical determination of the distribution of primary masses.

The Pierre Auger Observatory features an array of 1600 water-Cherenkov particle detector stations (SD, black dots in the map in the figure below) spread over 3000 km^2 on a 1500 m triangular grid. Each water-Cherenkov station is filled to a depth of 1.2 m with highly-purified water where shower particles entering the station emit Cherenkov light that is detected with three photomultiplier tubes. This vast array, that spreads over an area approximately equal to that of the island of Majorca, is overlooked by 24 air-fluorescence telescopes at the edges of the array (FD, gray squares in the map in the figure below). Data-taking started on 1 January 2004 and the installation was completed in June 2008 and has been taking data continuously since that date.

The Observatory is operated by the Pierre Auger Collaboration of more than 400 scientists, engineers, and technicians from more than 90 institutions in 18 countries with Spanish institutions IGFAE at Univ. de Santiago de Compostela and Univ. of Granada, playing a leading role in data analysis. See https://www.auger.org/ for more details on the Observatory.

Members of IGFAE and of the University of Granada have played a crucial role in the collection, reconstruction, and analysis of these events, as well as on the preparation of the journal publication to appear in Astrophysical Journal Supplement Series (https://iopscience.iop.org/article/10.3847/1538-4365/aca537/pdf), one of the journals with the largest impact factor (9.2 in 2021) in the field of Astrophysics and Astroparticle Physics.

The highest energy event ever detected in Auger (event #1 in the catalog) was recorded on November 10, 2019 and has an energy of 166 EeV, arriving at 58.6 degrees zenith angle with respect to the vertical to ground, and producing signal in 34 water-Cherenkov stations. This is 10 million times more energetic than the protons accelerated in the most powerful man-made accelerator on Earth, the Large-Hadron Collider or LHC. This particle has reached us after traveling hundreds of millions of light-years at a speed 0.999999999997 times the speed of light. The amount of energy needed to accelerate a macroscopic object such as a grain of beach sand, weighting about 15 micro-grams, to this speed would be comparable to the estimated total world annual energy consumption. How Nature accelerates individual protons and atomic nuclei to these phenomenal energies is one of the main questions in Astroparticle Physics.

In particular, the members of the IGFAE Astroparticle Physics group are the world´s experts on the reconstruction of those showers that arrive at a large angle (more than about 60 degrees) with respect to the vertical to the ground, the so-called inclined shower data set. The highest energy event in this set has an energy of 117 EeV (event #17) and was detected on September 26, 2015 arriving with a zenith angle of 77.2 degrees and producing signal in 75 water-Cherenkov stations, with the particles in the shower covering an impressive total distance of 35 km along the array as shown in the figure below.

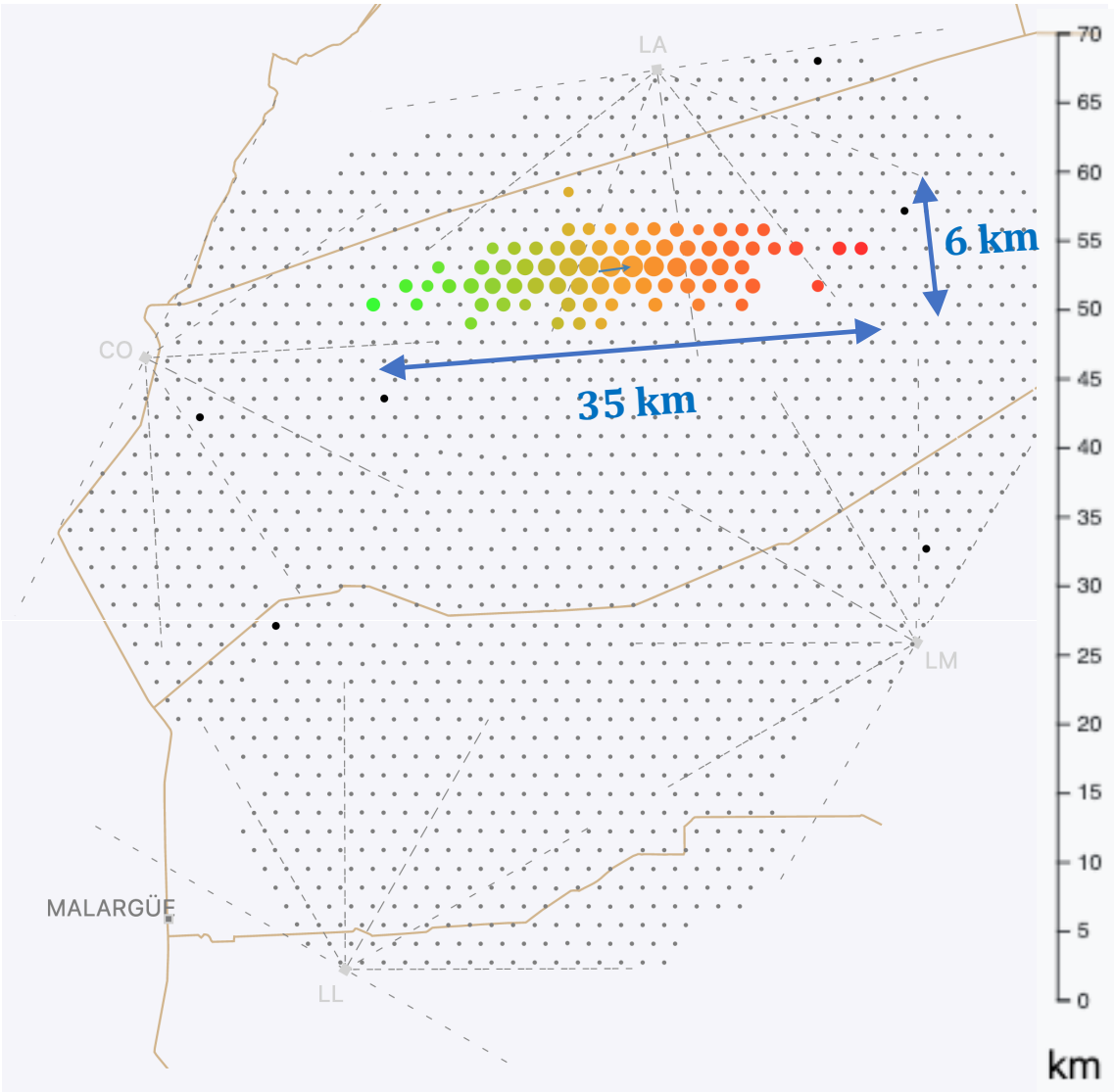

Figure caption: Footprint on the Surface Detector array of the Pierre Auger Observatory (near Malargüe in Mendoza Province, Argentina), of the highest energy inclined shower (event #17 in the Top 100 catalog of events), induced by a cosmic-ray particle of estimated energy 117 EeV arriving at a zenith angle 77.2 degrees and producing signal in 75 water-Cherenkov stations. Stations with signal are colored, with the color indicating arrival time of the particles from earliest (green) to latest (red), and with its size being proportional to the logarithm of the signal collected. Non-triggered stations are depicted as small black dots. The 6 stations depicted with large black dots were temporarily not functioning at the instant the event was detected on September 26, 2015. The hole without stations, visible in the array map to the west of the event, is due to difficulties in obtaining permission from a local landowner to install them. The four gray squares at the edges of the array (LL, LM, CO and LA) are the sites of the fluorescence telescopes. Brown lines indicate roads.