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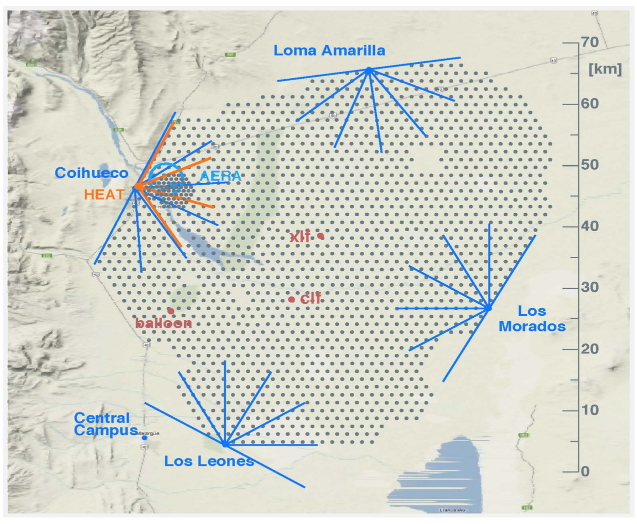
THE NEXT FUTURE OF THE PHYSICS OF ULTRA-HIGH ENERGY COSMIC RAYS

IL PROSSIMO FUTURO DELLA FISICA DEI RAGGI COSMICI DI ALTISSIMA ENERGIA

In the past decade the number of ultra-high energy cosmic rays detected has increased enormously. This is mostly due to the building of the Pierre Auger Observatory, in Argentina, the largest cosmic ray detector ever built. Through this detector we now know better the most energetic particle in the known universe, but still some of the most important questions remain open: where do they come from? What are they? How do they interact with the atmosphere? To answer those questions new data will be taken, using an updated detector that is now being tested.

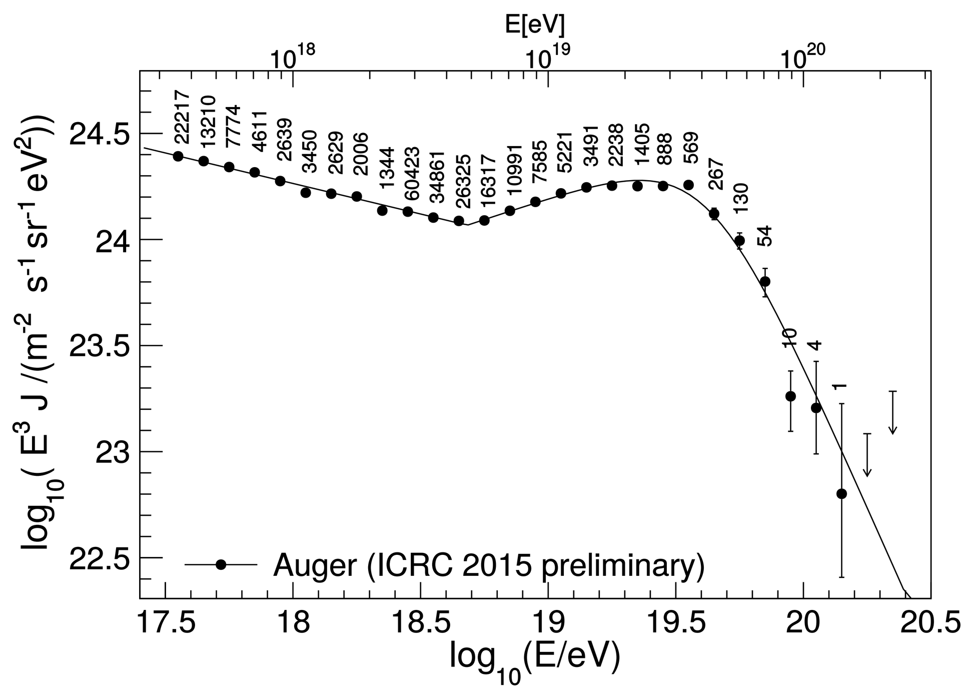
Nel decennio passato il numero di raggi cosmici di altissima energia rivelati è aumentato enormemente, principalmente grazie alla costruzione dell'Osservatorio PIerre Auger, in Argentina, il più grande rivelatore di raggi cosmici mai costruito. Attraverso questo rivelatore ora conosciamo meglio le particelle più energetiche dell'universo, ma alcune delle più importanti domande rimangono ancora aperte: da dove arrivano? Cosa sono? Come interagiscono con l'atmosfera? Per rispondere a tali domande si dovranno raccogliere nuovi dati, con un rivelatore migliorato che è ora in fase di test.

PRESENT



The Pierre Auger Observatory [1],

located in Argentina, is the largest cosmic ray detector in the world. It is designed to detect showers induced by these energetic particles in the atmosphere. Auger is an **hybrid** detector, as it uses both a **Surface Detector (SD)** to sample the particles in the shower at ground and a **Fluorescence Detector (FD)** to measure the light emitted by the particles traveling through the atmosphere.
Auger was designed to detect cosmic rays above **3 EeV** but has later on been upgraded with a denser SD (Infill Array) and special FD telescopes (HEAT) to low down this value to 0.3 EeV.



State of the art: Spectrum

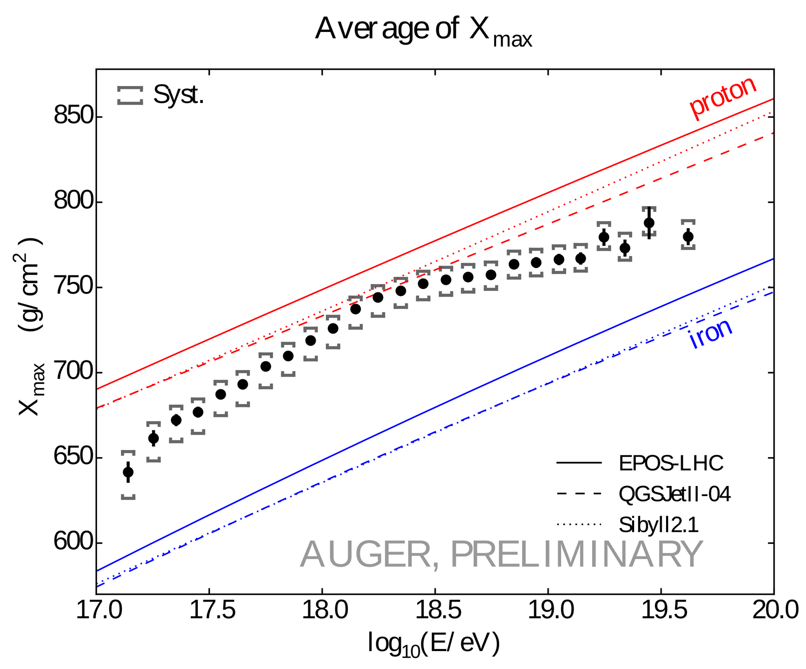
Auger measured with unprecedented precision the cosmic ray spectrum, measuring the position of the *ankle*, the point where the CR spectrum changes its steepness and proving the existence of a **cutoff at the highest energies** that is compatible with the one predicted by GZK interaction, but can as well be due to a limit to the source acceleration capabilities. The discrimination between these two models will be possible only through composition measurements [2].

The Surface Detector (SD)

The SD is made of 1600 (+60 belonging to the Infill array) tanks filled with 12 tons of ultra-pure water that detect the particles via **Cherenkov** light that is collected by 3 PMTs.
The stations are laid on a triangular grid with spacing of 1500 m (750 m, for the infill array) covering in total ~3000 km^2. Each station is equipped with a solar panel and transimts the detected signals to the **Central Data Acquisition System** located in the nearby town of Malargue. In total ~600 events with E40 EeV have been recorded by SD between 2004 and 2016.

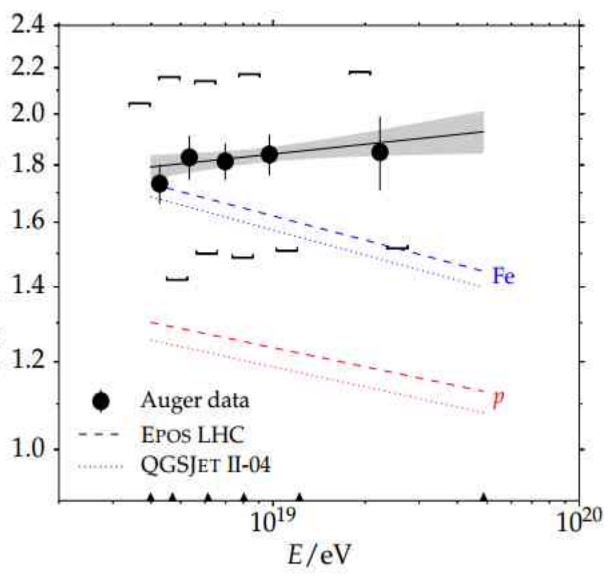
State of the art: Composition

The nature of the primary cosmic ray (i.e. whether it is a proton or a heavier nucleus) can be inferred from **composition-sensitive characteristics** of the shower such as de depth of its maximum, its lateral distribution or the number of muons.
The FD can access the best mass-related observables, in particular $\mathbf{X_{max}}$, the depth of shower maximum, and its rms. However, due to its low duty cycle this cannot be used for all events. These studies show that the composition around the *ankle* is supposed to be light while at higher energies a trend toward mixed or heavy nuclei is suggested [3].



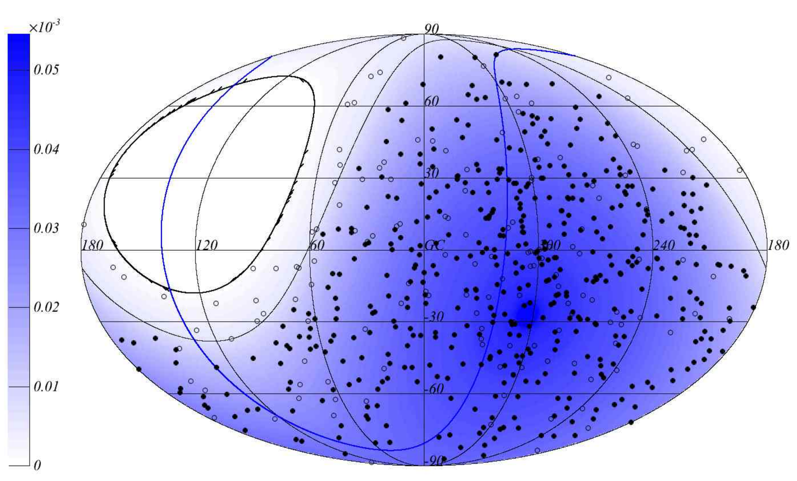
The Fluorescence Detector (FD)

The FD is composed of 24 telescopes in 4 different buildings. Each of them has a 3x3 m mirror overlooked by a camera of 64 PMTs. **It can operate only in clear moonless nights**, and therefore its duty cycle is ~10% compared to the one of SD that is nearly 100%. The observatory is equipped with complementary detectors such as lasers and cloud monitors to measure the transparency and characteristics of the air in order to reduce statistical errors on such measurement



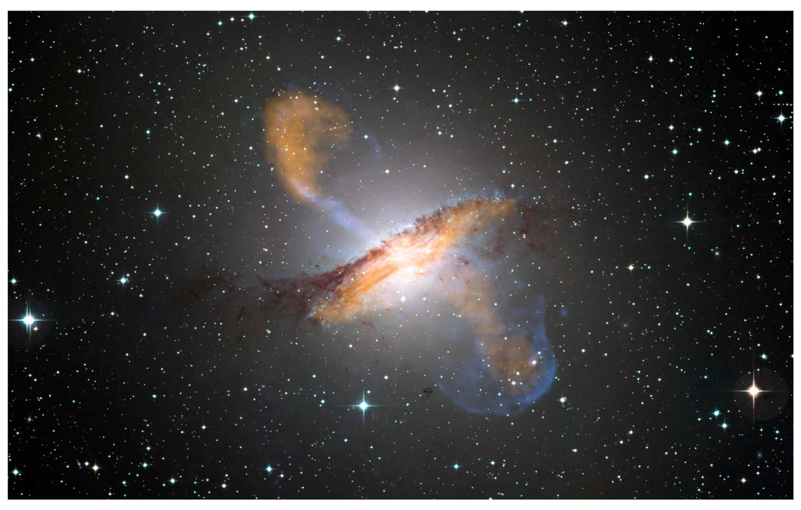
State of the art: Hadronic interaction models

One of the main issues regarding composition studies is the fact that the hadronic interaction models currently available are extrapolations from **accelerator** data that cover only **lower energies**.
Indeed, Auger has proved that there is some problems even with the most recent models, such as EPOS-LHC and QGSJETII-04, tuned on LHC data: when measuring the number of muons in the showers, **none of them can make prediction compatible with observation**, regardless of the primary composition taken into account [4]



State of the art: Arrival Directions

Auger is capable of measuring the arrival direction of each cosmic ray with a fairly good precision (1°) but cosmic rays are charged particles, and so they are **deflected by Galactic and extragalactic magnetic fields**, that we still mostly ignore.
For this reason, no clear correlation with candidate sources has been found, although interesting excesses have been observed near **Acitve Galaxies** and in particular **Centaurus A**, the closest AGN [5].
At lower energies, betweeen 4 and 8 EeV, a dipole structure has been observed. The nature of such a structure is still unclear but it is most probably of extragalctic origin [6].



Auger Prime [7]

Given the importance of the composition measurements, an update of the Auger detector has been approved and now is in development phase. This update, called Auger Prime, forsee the installation of **plastic scintillators** on top of each Auger SD station to allow for better em/muon discrimination and thus possibly an event-by-event mass composition analysis. Moreover, a **faster electronics** will be installed in each station together with a fourth, **smaller PMT** in order to better treat stations with high signals that usually saturate. The **active time of the FD** will also be extended and buried **muon counters** will be installed in some station. Auger will run this way up to **2025** at least

FUTURE

Auger @ UNIMI

The Auger group at the **Università degli Studi di Milano** and **INFN-Sezione di Milano** is active in many hot topics spanning from hardware to data analysis, its main topics being:
-**Detector and reconstruction performance and stability**, with particular interest for the highest energy events (E 40 EeV)
-**Arrival direction studies,** with particular interest in multimessenger approach (search for correlation also with **UHE neutrinos [8] [9], photons and gravitational waves [10]**)
-**Composition studies**, both with existing data and with simulations of the forthcoming Auger Prime detector, with particular interest in the highest energies.
-**Hardware production and characterization** for Auger Prime, in collaboration with the INFN group of Lecce

Essential glossary:

-EeV: 10^{18} eV
-UHECR: ultra-high energy cosmic rays charged particles that reach earth from still unknown sources at energies greater than ~1 EeV
-EAS: Extensive Air Shower. The shower of secondary particles induced in the atmosphere by UHECR. Showers can reach ~10^{11} particles and a footprint on the ground tens of km wide.
-AGN: Active Galactic Nuclei. Galaxies with a super-massive black hole in their nucleus. The accretion disk around the BH can produce jets and lobes of plasma often larger than the galaxy itself.
-GZK Effect: interaction of cosmic rays (in particular protons) with the cosmic background, causing pion production via delta resonance. Given the threshold energy for such effect (~50 EeV) a cutoff in the spectrum is expected above this energy. Given the mean free path, also a **GZK Horizon** can be computed at few hundreds of Mpc, meaning that the sources of the cosmic rays we observe at this energy should lie within this horizon**. Nuclei cosmic rays** are on the other hand subjected to photodisintegration on the cosmic background. Energy threshold and mean free path depends on the mass but for an Iron nucleus they are quite similar to the proton one (intermediate component have lower threshold and smaller horizon)

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1: Unimi 2: INFN Sezione di Milano 3: Politecnico di MIlano

Essential references:

[1] NIM A 798 (2015) 172-213
[2] JCAP04(2017)038
[3] Phys.Lett. B762 (2016) 288-295
[4] PRL 117, 192001 (2016)
[5] ApJ 804, 15 (2015)
[6] ApJ 802, 111 (2015)
[7] PDR:arXiv:1604.03637
[8] JCAP 01 (2016) 037 (with Ice Cube and Telescope Array Collaborations).
[9] Resconi et al. MNRS (2017) 468 (1): 597-606.
[10] Phys. Rev. D 94, 122007 (2016)
All by **The Pierre Auger Collaboration** except where differently specified.