Ultra-high energy cosmic rays and dark matter

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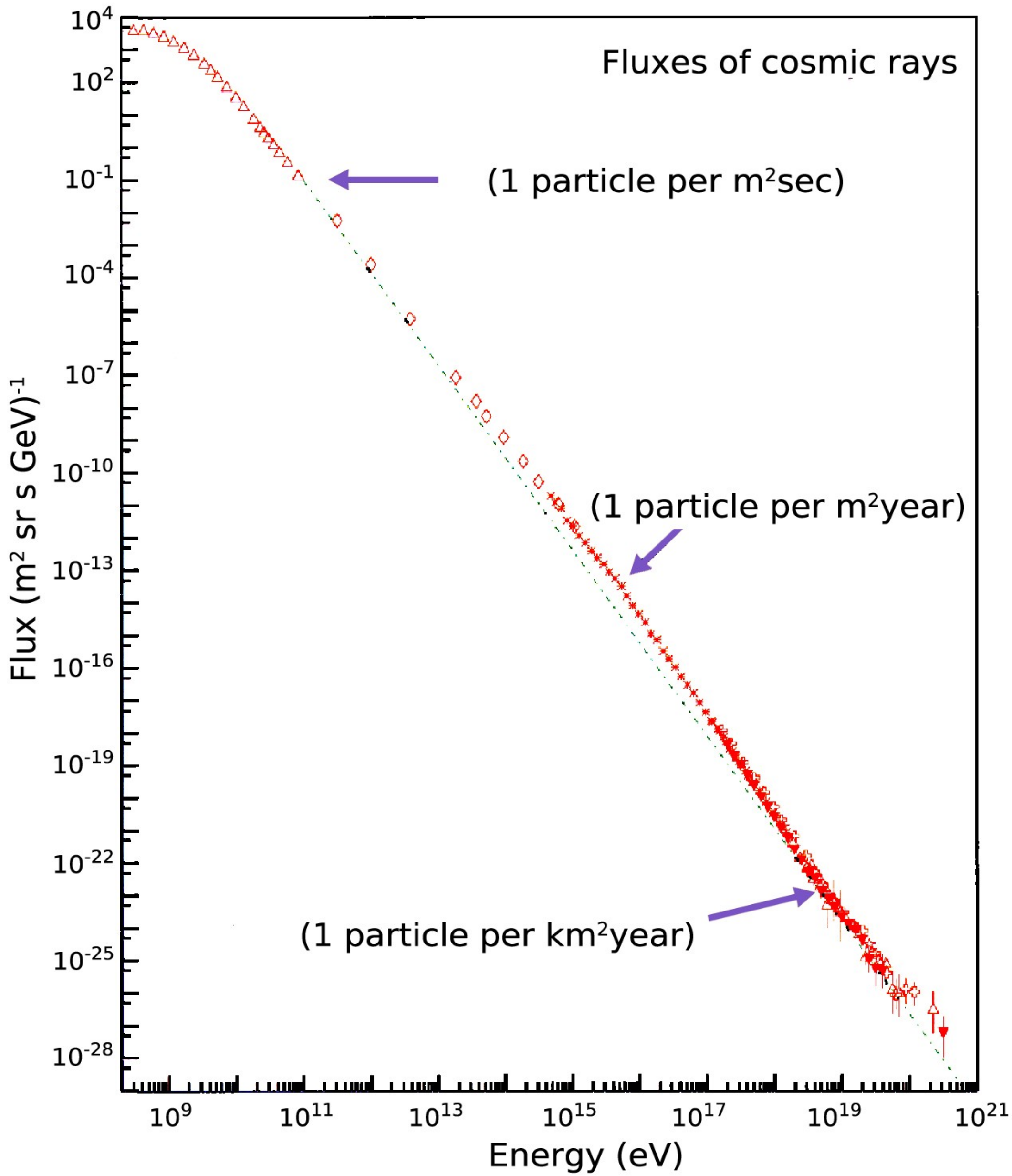
Highest energy cosmic rays



Cosmic ray spectrum extends over many orders of magnitude, reaching energies above 10^{20} eV, millions of times greater than energies achieved in the most powerful accelerators on Earth.

The origin of the particles with highest energies has not been explained:

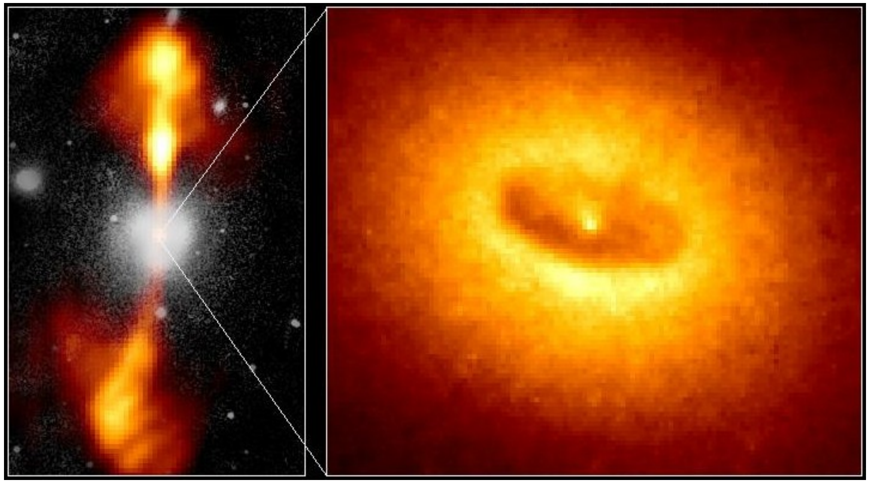
– experimental work is being done: gathering information about particles arriving at Earth,

– also theoretical work: models of possible sources.

Origin of cosmic rays – particle acceleration („bottom-up”)

Fermi acceleration on shock waves – energy depends on source size, magnetic field, particle charge.

Maximum energy attainable in supernova remnants is limited ($\lesssim 10^{15}$ eV).



Higher energies can be reached in larger objects or in stronger magnetic fields, e.g.:
↑ *active galactic nuclei*,
← *colliding galaxies*,
but it's not certain if the particles with the highest observed energies can be produced there.

GZK effect (interaction with microwave background photons) limits the range of particles with the highest energies.

Origin of cosmic rays – exotic models („top-down”)

Particles with the highest observed energies may not be the result of acceleration, but rather a product of interactions or decays of particles yet to be discovered directly.

Some of the proposed scenarios of cosmic ray production:

- *superheavy dark matter (SHDM), possibly concentrated near galaxies/clusters – metastable particles could decay or annihilate,*
- *relic topological defects (TD): monopoles, cosmic strings or others, undergo decays and produce cascades of energetic particles,*
- *„Z-Burst”* (ZB) – highest energy neutrinos annihilate on background antineutrinos, producing Z bosons that decay into observed particles.

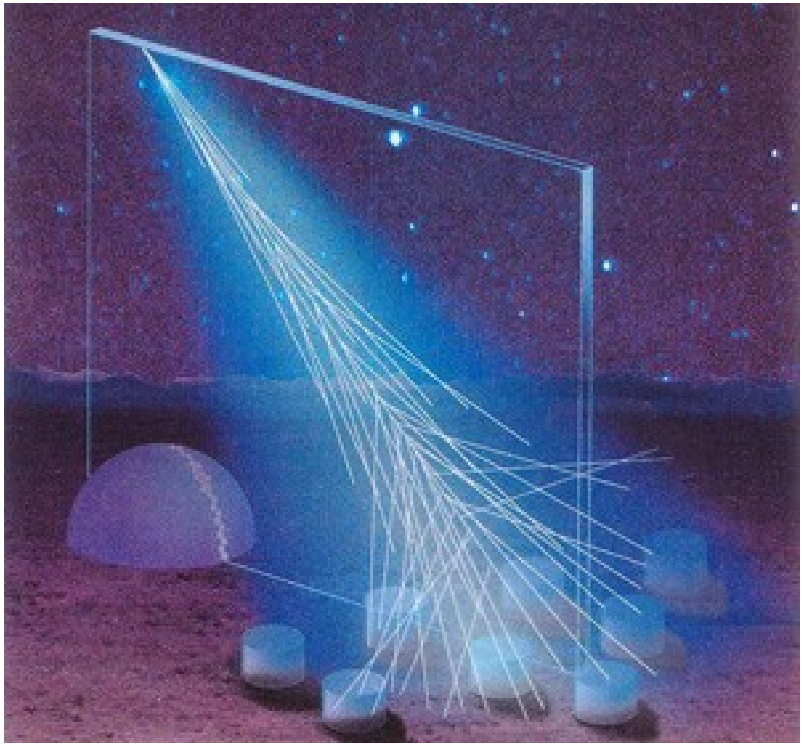
All these models predict a large fraction of photons and neutrinos (tens of percent) in the cosmic rays of highest energies.

⇒ Experimental determination is necessary.

Observation of highest energy cosmic rays

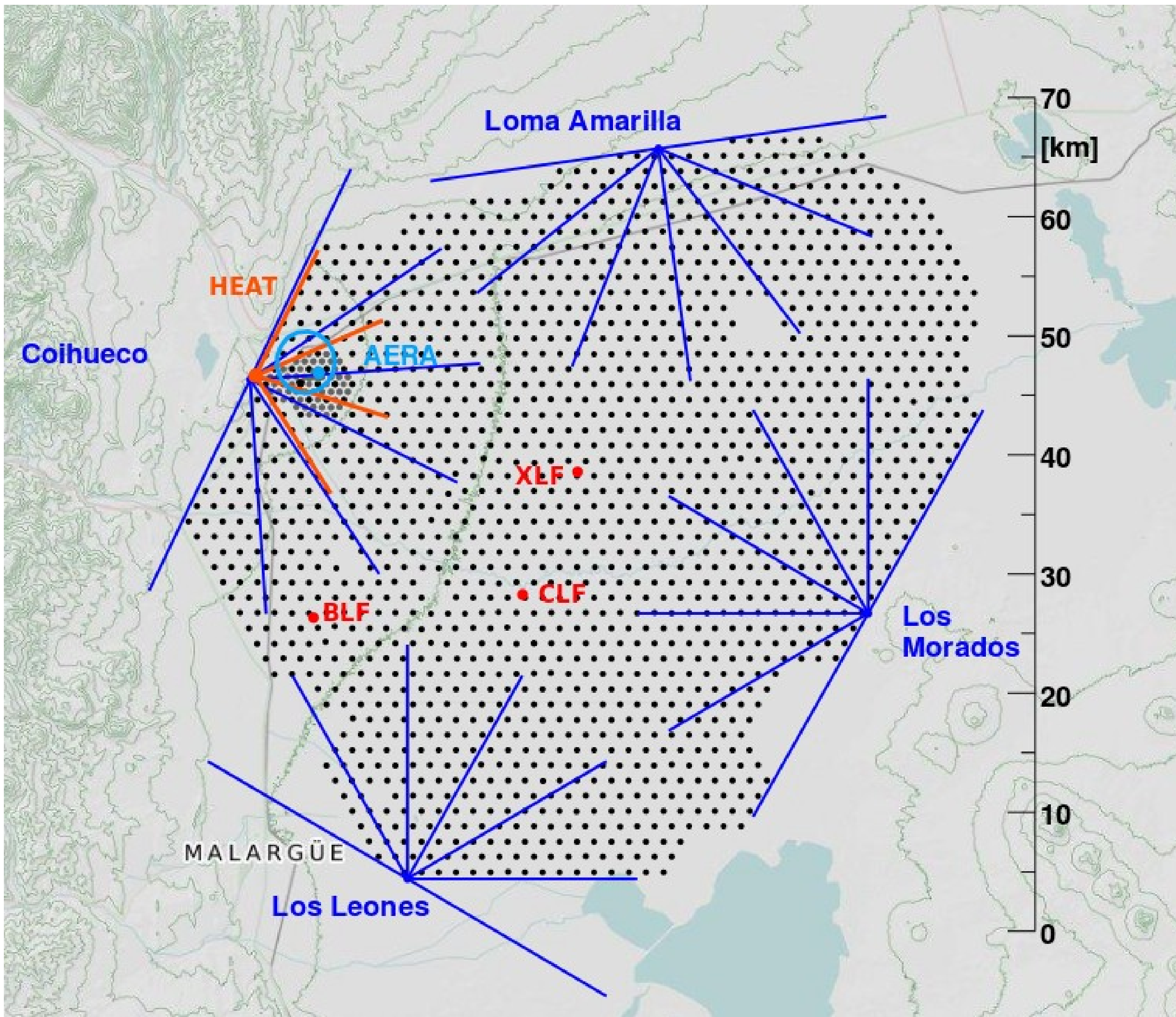
Particle flux drops with the rise of energy – it is not feasible to directly observe the primary particles at energies $\gtrsim 10^{15}$ eV.

We observe extensive air showers – cascades of secondary particles.



Pierre Auger Observatory

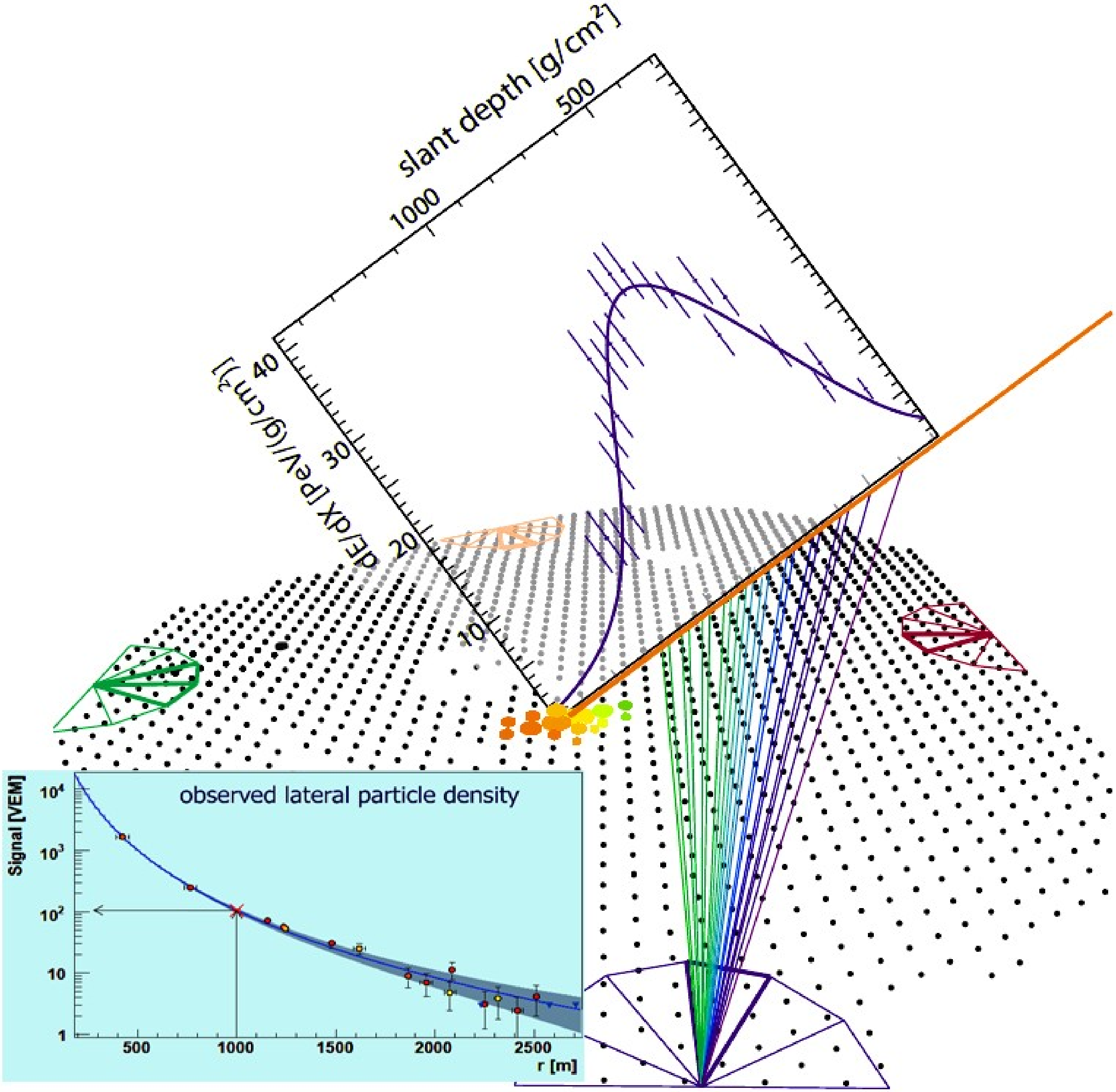
World's largest system of detectors dedicated to observations of highest energy cosmic rays ($\gtrsim 10^{18}$ eV).



Surface Detector:
~1600 water Cherenkov detectors ($3000\ km^2$), operating constantly.

Fluorescence Detector:
27 optical telescopes, nighttime observations.
Supported by a network of equipment for atmospheric monitoring.

Reconstruction of properties of primary particle



The trace observed in telescopes and the timing information from surface stations suffice to calculate the arrival direction.

Light profile measured in the fluorescence detector provides information for a precise (calorimetric) measurement of energy.

Atmospheric depth of air shower maximum (X_{max}) and particle distribution on the ground depend on the properties of the primary particle – but determination of the primary cosmic ray composition is very difficult.

How to identify air showers induced by photons?

Cross section smaller for photons than for hadrons:

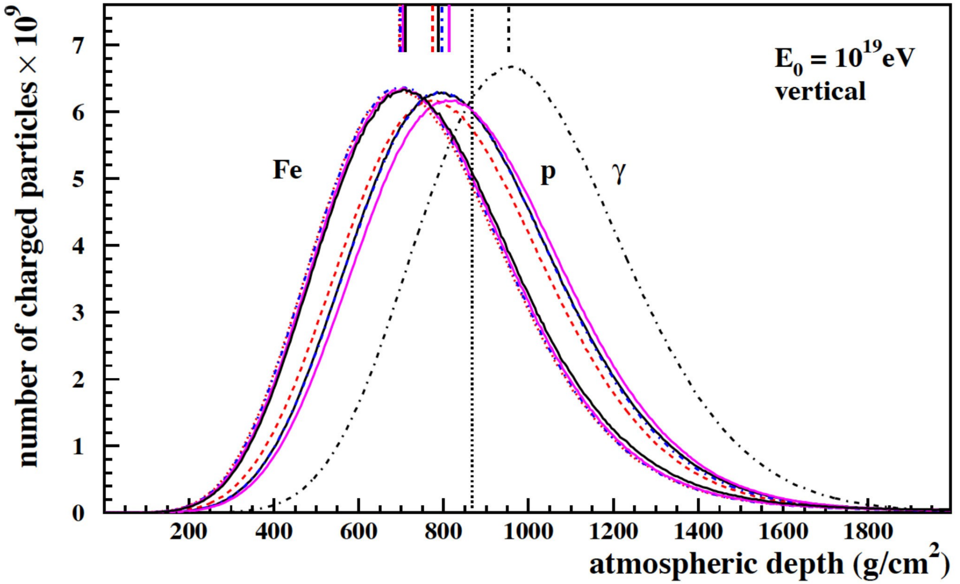
⇒ cascade develops deeper in the atmosphere – larger X_{max}

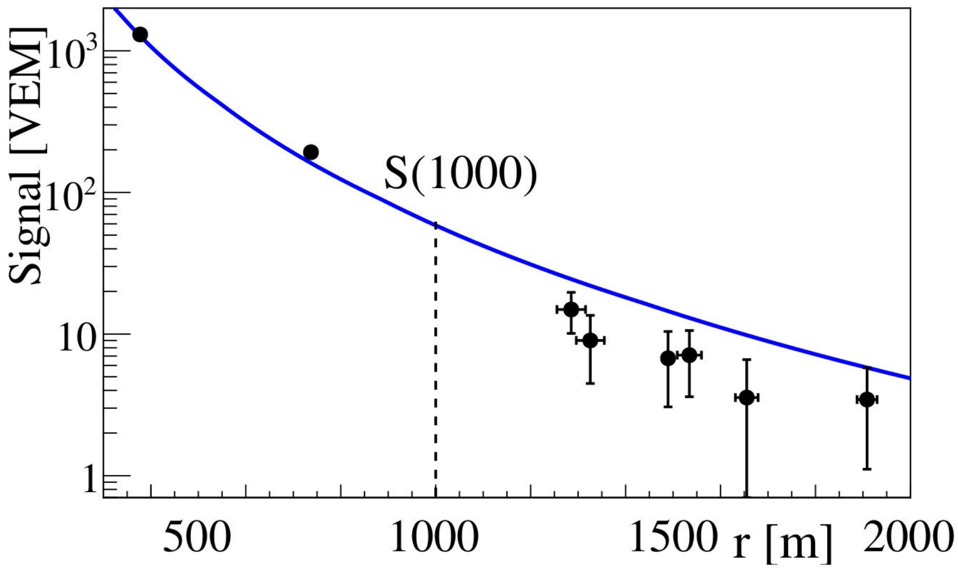
⇒ on the ground level particles are concentrated closer to shower axis – distribution described by:

$$S_b = \sum S_i \, (R_i/1000\mathrm{m})^b$$

sum of signals S_i weighted by distance from the axis R_i, $b = 4$.

Air shower induced by a photon is mostly an electromagnetic cascade (photons, electrons, positrons), contribution of other particles – mainly muons – is much smaller than in hadronic air showers.



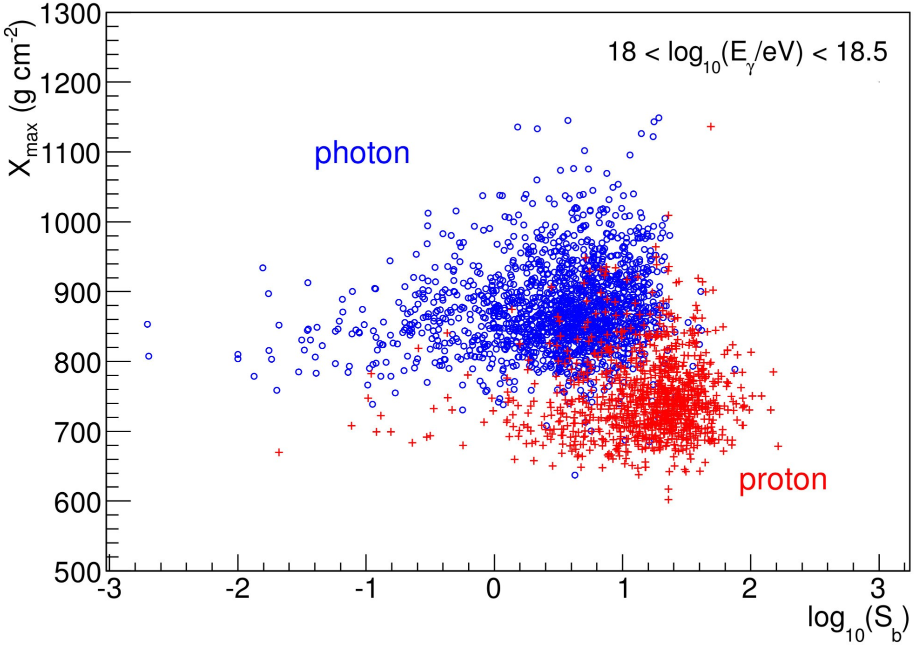


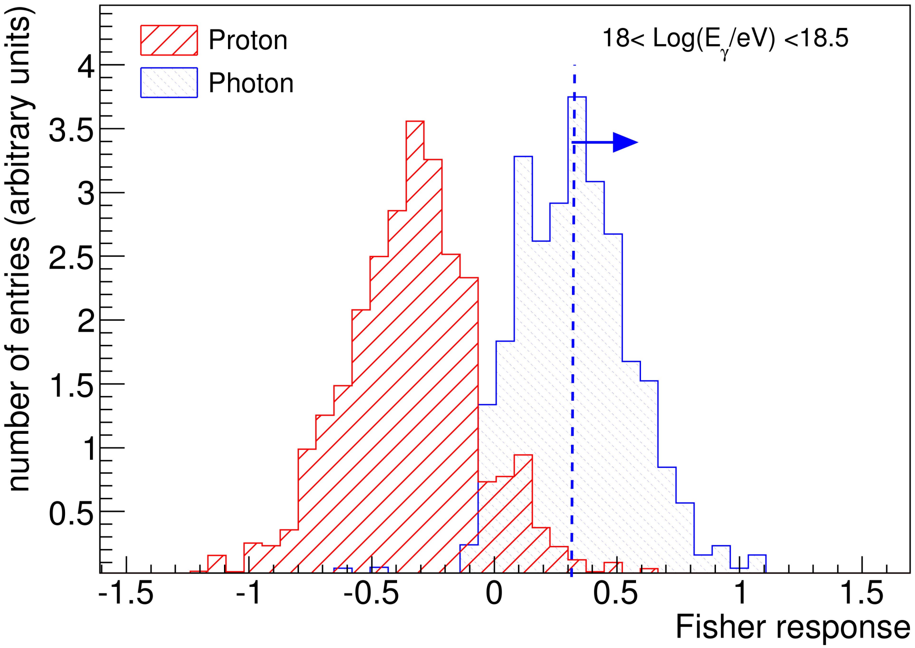
Air showers induced by photons and hadrons - differences

Using computer simulations we determine the expected properties of air showers induced by photons and protons (hadrons).

We find such a combination of observables X_{max} and S_b, that maximizes the separation between air showers induced by photons and hadrons (Fisher analysis).

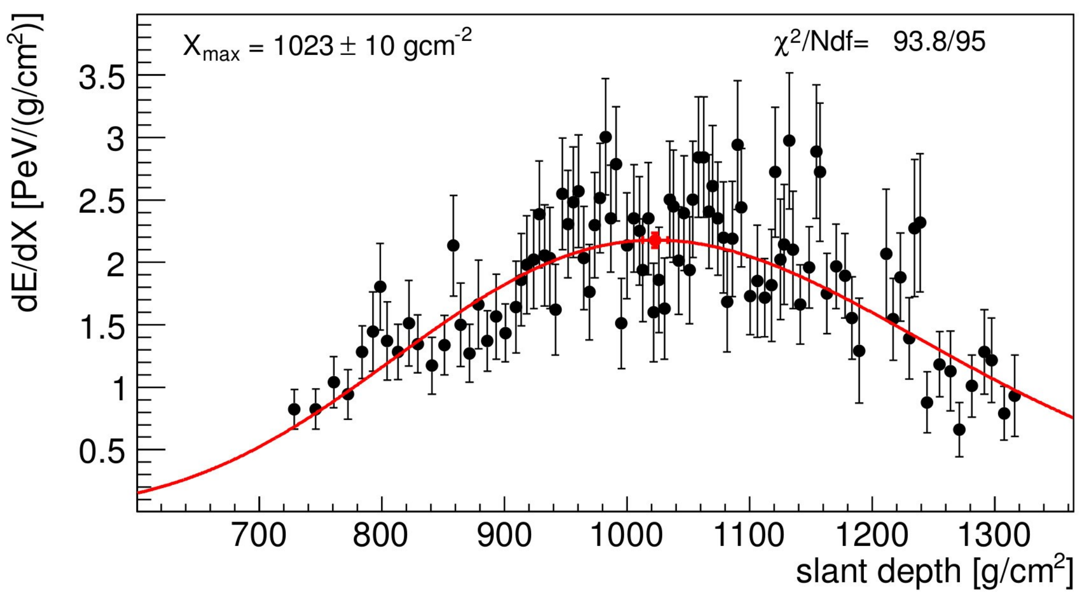
Distributions of Fisher response partly overlap
⇒ we choose a cut at the value corresponding to 50% photon detection efficiency.





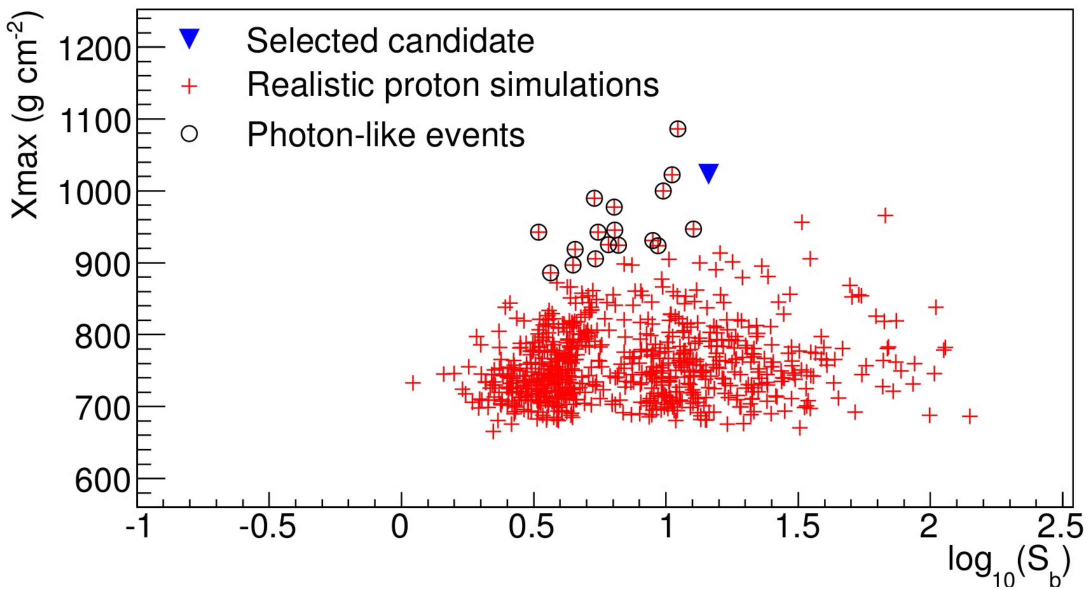
Do we see air showers induced by photons?

Among the observed air showers with energies above 10^{18} eV there are six photon candidates.



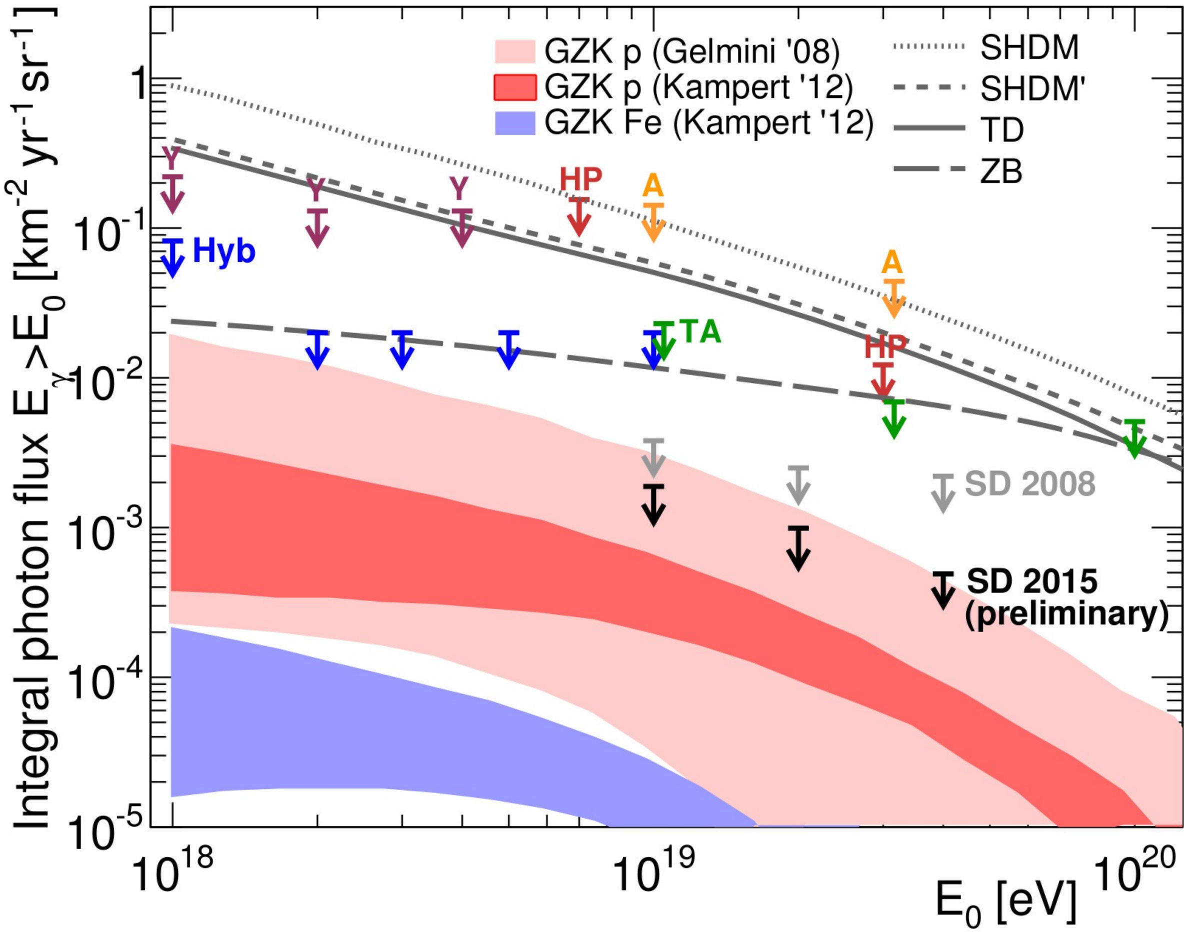
Comparison of one photon candidate with simulations of air showers induced by protons ➞

It is possible that we observed atypical proton air shower.



Limits on the photon flux

No confirmed observations of air showers induced by photons.



Analysis of collected data sets upper limits on the fraction of photons in the observed particle flux:

< 0.4% for E > 10^{18} eV,

< 0.9% for E > 10^{19} eV.

Observation results are significantly different from the predictions of exotic models.

Exotic models disfavored.

Cumulated exposure of Pierre Auger Observatory will soon enable testing models of particle acceleration and the GZK effect.

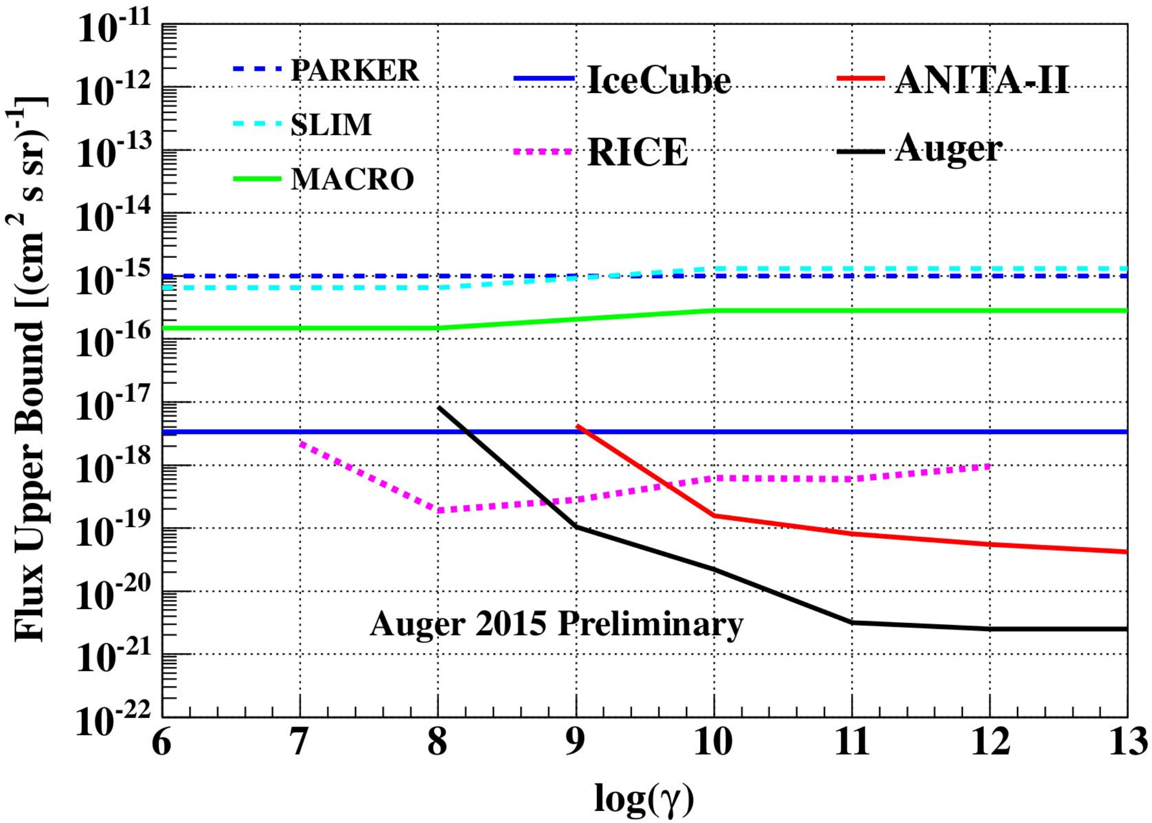
Limits on flux of magnetic monopoles

Magnetic monopoles – hypothetical relics from the early Universe; wide range of mass predictions.

Monopoles should be accelerated in (inter)galactic magnetic fields – expected energy ~10^{25} eV and ultra-relativistic velocities for monopole mass ~10^{11} - 10^{20} eV/c^2.

In the atmosphere a monopole should induce numerous particle cascades, easy to distinguish from air showers induced by hadrons.

So far no magnetic monopole event was observed.



Summary

The origin of highest energy cosmic rays remains one of the greatest puzzles of astrophysics.

A group of proposed explanations postulates the existence of exotic particles – their decays could be the source of observed cosmic rays.
Common prediction of these scenarios is a large fraction of photons and neutrinos.

Development of the observation techniques and accumulation of data enable testing these models – so far no photons or neutrinos have been identified.

„Top-down" models are disfavored – no evidence for existence of particles beyond Standard Model.

Can non-standard approach to cosmic ray data/infrastructure/theory change these conclusions?