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The highest energy cosmic rays: observations and search for new physics

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We review the status and results of experiments detecting ultra-high energy cosmic rays ($E > 10^{18}$ eV), including Yakutsk Array, AGASA, HiRES, Pierre Auger and Telescope Array. Recent data on energy spectrum, chemical composition, search for sources and neutral component are interpreted in relation with new physics models, e.g. super-heavy dark matter, Plank-scale Lorentz invariance violation, black-hole production at TeV scale.

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1. In memory of S.N. Vernov

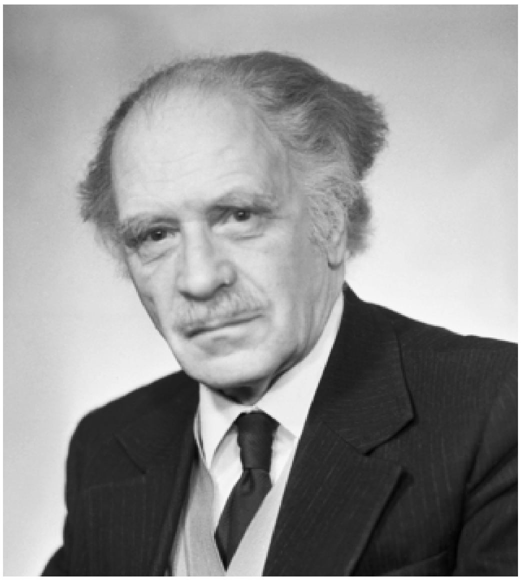

Figure 1: Sergey Nikolaevich Vernov, 1910-1982.

In 2010 the nuclear science community celebrates the 100th anniversary of Sergey Nikolaevich Vernov (1910-1982), prominent Russian scientist, one of the world's pioneers in cosmic ray studies. His name is known for groundbreaking results in cosmic ray science and accompanying research in elementary particle physics, space plasma phenomena, astrophysics and geophysics. S.N. Vernov was one of the founders and former director of the Skobeltsyn Institute of Nuclear Physics of the Lomonosov Moscow State University [1].

It's impossible to exaggerate the contribution of S.N. Vernov to the studies of high energy cosmic rays. Here we mention only the results related to the title of the *Talk*. At the end of 1950's a unique Extensive Air Shower (EAS) array have been built under supervision of S.N. Vernov at Lomonosov Moscow State University. EAS MSU array was designed to detect and analyze extensive air showers induced by primary particles with energies 10^{14}–10^{17} eV and includes ground detectors of different type. In 1958 Kulikov and Khristiansen have discovered the knee in the cosmic ray spectrum at energies about $3 \cdot 10^{15}$ eV based on the measurements of MSU EAS array [2]. In 1963 S.N Vernov proposed to build large scale array to study the properties of the highest energy part of cosmic ray spectrum $E > 10^{17}$ eV. Yakutsk EAS Array is built in 1973 using experimental facilities of Skobeltsyn Institute of Nuclear Physics under general supervision of S.N. Vernov [3]. The expertise of Skobeltsyn Institute experimental group allowed to synchronously use scintillator, muon and Cherenkov detectors in one setup which predetermined long-term success of the experiment.

Yakutsk Array is the first experiment capable to target all aspects of ultra-high energy cosmic ray (UHECR) physics. Yakutsk Array is designed ahead of it's time and still competitive today, although size advantage of new setups [4].

2. UHECR experiments today

In the *Talk* we define ultra-high energy cosmic rays (UHECR) as cosmic rays having energies above 10^{18} eV. Two techniques are widely used for UHECR detection: surface detector array and fluorescence telescope. The latter operates on moonless nights and detects fluorescence of nitrogen atoms excited by charged particles of the shower core. Surface array register particles at the periphery of the shower and operate continuously. The fact that these two techniques are focused on different part of the shower enables hybrid technique based on simultaneous detection of the shower by the surface array and by fluorescent telescopes. In Table 1 we briefly overlook ongoing and recently finished UHECR experiments without goal of historical completeness, for more details please refer to [5, 6]. The latest experiments Pierre Auger observatory and Telescope Array benefit from the high accuracy of hybrid technique and at the same time from the large exposure of surface detector array. The measurements of surface detector are verified and energy is calibrated using hybrid events subset in these experiments [12, 13].

Experiment	Dates	Location	SD area, km^2	Number of FDs	Ref.
Yakutsk Array	1973 - now	Yakutsk, Russia	18	-	[7]
AGASA	1990 - 2004	Akeno, Japan	100	-	[8]
HiRes	1998 - 2006	Dougway, Utah, USA	-	2	[9]
Pierre Auger Observatory	2004 - now	Malargue, Argentina	3000	4	[10]
Telescope Array	2008 - now	Delta, Utah, USA	700	3	[11]

Table 1: UHECR experiments discussed in this *Talk*. Operation dates, site location, surface detector area and number of fluorescent detectors are given.

3. Spectrum and GZK cut-off

In the highest energy region two spectrum features are theoretically predicted. First is Greisen-Zatsepin-Kuzmin cut-off [14, 15] at $E \gtrsim 10^{19.7}$ eV due to proton interaction with cosmic microwave background (CMB) photons

$$p + \gamma_{2.7K} \to n + \pi^+ \qquad (3.1)$$
$$\to p + \pi^0 .$$

Second feature is a dip at $E \sim 10^{19}$ eV due to e^+e^- pair production on CMB background [16]

$$p + \gamma_{2.7K} \to p + e^+ + e^- . \qquad (3.2)$$

A dip is observed in spectra measured by Yakutsk, AGASA, HiRes, Auger [17] and Telescope Array [13] while the situation with a GZK cut-off have been controversial until recently. A spectrum measured by AGASA experiment doesn't show a cut-off [18]. There are 11 AGASA events with $E > 10^{20}$ eV while 1.9 events are expected in the uniform sources model. HiRes experiment observed a cut-off in the spectrum with 5σ significance [19]. Pierre Auger Observatory confirmed

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a spectrum suppression at high energies with 20σ significance [12, 20]. Recently Telescope Array experiment confirmed a cut-off with significance of 3.5σ in surface detector based spectrum [13]. The latter is important since Telescope Array has very similar surface detectors with AGASA[1].

Today the cut-off predicted by Greisen, Zatsepin and Kuzmin is observed in 3 independent experiments. On the other hand cut-off observation is not a direct proof that the process in Eq. 3.1 really takes place. The cut-off in the spectrum may be generated by sources exhaustion or in case of primary nuclei by photodisintegration. The process in Eq. 3.1 if confirmed would be the highest energy known process and would provide a test for Lorentz-invariance and other fundamental principles of physics. To confirm the GZK process one should unambiguously determine primary composition of UHECR and observe secondary photons, produced in decays of π^0.

4. Primary composition

To determine primary composition several observables should be measured simultaneously: one so called E-observable to reconstruct primary energy and C-observable sensitive to primary particle type [21]. For surface detector E-observable is signal density at the fixed distance from the core and for C-observable depending on the detector one may use either muon density or characteristics of shower front (e.g. front curvature or rise time). In fluorescent method E-observable is an intensity of fluorescence signal at the shower maximum while the depth of the shower maximum X_{max} may serve as C-observable.

Surface detector technique. Pierre Auger Observatory compared shower attenuation curves in data and simulations and concluded that there is an excess of muons in data [22] compared to to simulations with QGSJET II [23] and SIBYLL 2.1 [24] hadronic interaction models for both proton and iron primaries. At that time Pierre Auger Observatory didn't have muon detectors and therefore estimation of muon density is indirect.

Yakutsk array is equipped with muon detectors and measures muon density directly. The muon excess comparing to the model have been reported [25, 26]. It was shown that measured muon density for $E > 10^{19}$ eV showers is factor 1.5 higher than SIBYLL 2.1 [24] model prediction for iron primary and may be interpreted using EPOS model [27] with mixed proton and iron composition [28]. Yakutsk muon data suggest that composition become heavier at energies $E \gtrsim 10^{19}$ eV [29].

In EPOS model more muons are produced comparing to the other models as a result of the enhanced production of baryons in highest energy interactions. Composition measurements with a muon technique strongly depend on the interaction model and therefore have an uncertainty. On the other hand if the primary composition is known muon density at the ground will be extremely useful for understanding the hadronic interactions.

Fluorescence technique. In 2010 both HiRes and Pierre Auger collaborations published measurements of the depth of the shower maximum ($\mathrm{X_{max}}$) and the width of the $\mathrm{X_{max}}$ distribution [30, 31]. HiRes results are based on stereo technique and lead to a conclusion of proton dominance in the composition in the wide energy range $E \in [2\cdot 10^{18}, 5\cdot 10^{19}]$ eV [30]. Pierre Auger results are based on a hybrid technique and suggest heavy composition at energies above

[1] The only difference is a width of scintillator: 5 cm for AGASA and 1.2 cm for TA.

10^{19} eV [31]. This dichotomy is a puzzle to be resolved by future measurements and interpretations. Furthermore possible difference of northern and southern UHECR skies is not excluded.

There exists alternative interpretation of Pierre Auger X_{max} data. Both measured X_{max} and width of it's distribution may be explained by proton primaries assuming increase of proton-air cross-section at high energy comparing to presently used in the models [32]. The hadronic cross-section used in the hadronic models at the energy region of interest is a result of extrapolation and is generally unknown. This illustrates model dependence of composition studies with fluorescent technique. It should be noted that above interpretation of Pierre Auger results doesn't help to resolve the difference with HiRes results.

Recently reported preliminary Telescope Array results on X_{max} are consistent with proton composition [33]. The result is based on first 34 months of stereo observation and therefore the statistics is not yet high enough to estimate the width of X_{max} distribution.

5. Search for sources

Active galactic nuclei (AGN) are the most natural candidates for point sources of UHECR [34]. It have been shown that black hole in the center of AGN is capable to accelerate protons up to energies 10^{20} eV [35].

A correlations of HiRes events detected in stereo mode with BL Lac type objects (subclass of AGN) have been found at $E > 10^{19}$ eV [36, 37]. The fraction of correlating events is 3% and the correlation angular scale is less than 1° which is significantly smaller than the expected deflection of protons in cosmic magnetic fields. This suggests that some fraction of the UHECRs are neutral (see Ref. [38] for a particular mechanism).

In November 2007 Pierre Auger observatory claimed correlation of the UHECR with nearby (< 71 Mpc) active galactic nuclei [39]. 9 of 13 events with energies above $5.7 \cdot 10^{19}$ eV correlate with corresponding AGNs within 3.1° with 2.7 background events.

HiRes collaboration have tested the Auger hypothesis in the northern sky and have seen no correlations in the data: 2 of 13 events correlate with expectation of 3 background events [40]. Shortly after Pierre Auger paper a comment appeared [41] (see [42] for extended version) with two main points:

- Events in Pierre Auger dataset do not follow the prediction of AGN hypothesis. E.g. nothing comes from Virgo, while it contains a significant fraction of nearby AGNs.
- A nearest radiogalaxy Cen A may be a single source with correlation angle about 20°.

Later it was noted that the AGNs correlating with Pierre Auger events are not strong enough to accelerate protons to observed energies, while heavier nuclei would be deflected by Galactic magnetic field spoiling the correlations [43, 44].

The dataset collected by Pierre Auger after the initial publication didn't confirm previous claim: 12 of 42 events correlate when expected background is 8.9 [45]. On the contrary, the hypothesis of Cen A was strengthened with a new data [45].

Telescope Array experiment operating in the northern hemisphere doesn't see the correlations with AGNs in preliminary data: 5 of 15 events correlate with background 3.6 [46]. It should be

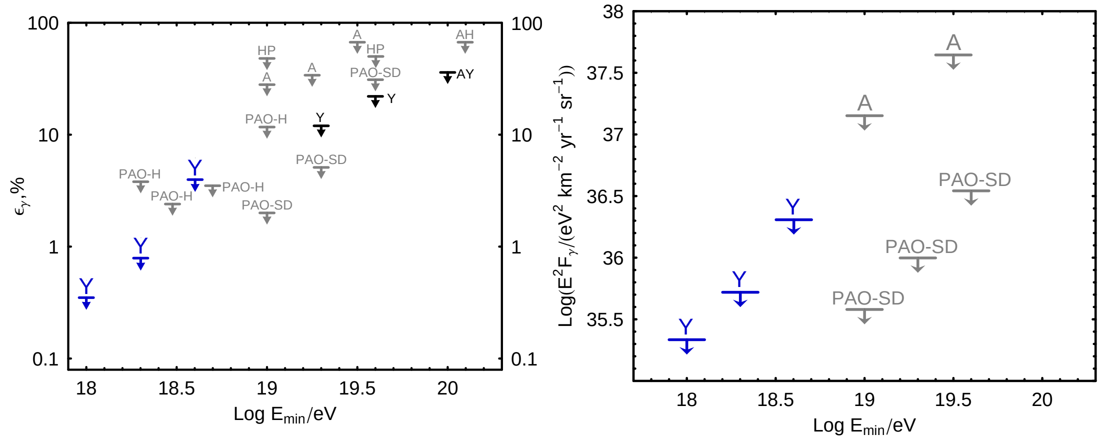

Figure 2: Limits (95% CL) on the fraction (left) and flux (right) of primary gamma rays in the integral flux of cosmic particles with $E_0 > E_{\rm min}$ from: hybrid events of the Pierre Auger Observatory (PAO-H) [57]; the surface detector of the Pierre Auger Observatory (PAO-SD) [56]; Yakutsk (Y) [52, 53]; reanalysis of the AGASA (AH) [54] and AGASA and Yakutsk (AY) [55] data; AGASA (A) [51] and Haverah Park (HP) [50].

noted that northern sky contains less AGNs than southern and the objects are different, e.g. Cen A may not be seen by HiRes and Telescope Array.

6. Search for neutral component

UHECR photons are produced by energetic protons and nuclei in their interactions both at acceleration sites and along their trajectories towards the Earth [34]. Both protons and heavier nuclei with energies $E \sim 10^{20}$ eV interact with cosmic background radiations, especially with CMB and infrared background (IRB) radiation. The processes involved in these interactions are however very different. Interactions of a *proton* at $E \gtrsim 7 \times 10^{19}$ eV with CMB photons lead to efficient pion production [14, 15], Eq. 3.1. Further decays of neutral pions produced in these interactions lead to a secondary photon flux at energies $E \gtrsim 10^{18}$ eV (so-called GZK photons) [47, 48]. On the other hand, the dominant interaction channel for *heavier nuclei* is their photodisintegration on IRB photons; the secondary photon flux is much smaller in this case [49]. Therefore, the photon flux at $E \gtrsim 10^{18}$ eV may provide an independent test of the chemical composition of CRs at $E \sim (10^{19} \dots 10^{20})$ eV.

Several limits on the UHE photon flux have been set by independent experiments (see Fig. 2), including Haverah Park [50], AGASA [51], Yakutsk [52, 53] (see also reanalyses of the AGASA [54] and AGASA+Yakutsk [55] data at the highest energies), the Pierre Auger Observatory [56, 57] and preliminary result from Telescope Array [58]. Still no evidence for primary photons found at present.

The study of UHE photons is a powerful tool for constraining new physics models. One example is provided by models with superheavy dark-matter (SHDM) particles (e.g. [59]); a substantial fraction of the SHDM decay products are photons. Another class of exotic relics to be searched for with CRs is topological defects [60, 61]; UHE photons were suggested [62] as their signature. Moreover results of the photon search severely constrain the parameters of Lorentz invariance violation at Planck scale [63, 64, 65]. Existing photon flux limits are quickly approaching the predicted flux of GZK photons, e.g. Pierre Auger limit above 10^{19} eV[56] is only twice higher than optimistic expectation of GZK photon flux. With the growth of statistics collected by Pierre Auger and Telescope Array experiments one may expect detection of the ultra-high energy photons in the medium-term.

Ultra-high energy *neutrinos* may be generated by the decay of charged pions produced as a secondaries in GZK process [67]. Neutrino flux is constrained by several experiments, see [66] and references therein, but the sensitivity of current experiments is not enough to detect theoretically expected flux [68]. Taking into account possible new physics effects makes the conclusion more optimistic. If there exists a TeV gravity, UHE neutrino will produce black holes in the atmosphere with production cross-section higher than Standard Model cross-section [69]. On the other hand the higher interaction cross-section will suppress up-going neutrino flux making Earth non-transparent. Non-observation of down-going neutrino constrain TeV gravity models while possible observation of down-going neutrino together with non-observation of up-going neutrino would be a strong indication of new physics [69].

7. Conclusions and outlook

Cut-off predicted by Greisen, Zatsepin and Kuzmin is observed in 3 independent experiments, while there is still no direct proof that the corresponding interaction with CMB really takes place. The UHECR composition, sources and photon observation are three problems with high chances to be solved by ongoing experiments or their extensions. These advancements will considerably improve our understanding of hadronic and electromagnetic interactions at the highest energy and have high discovery potential for new physics.

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