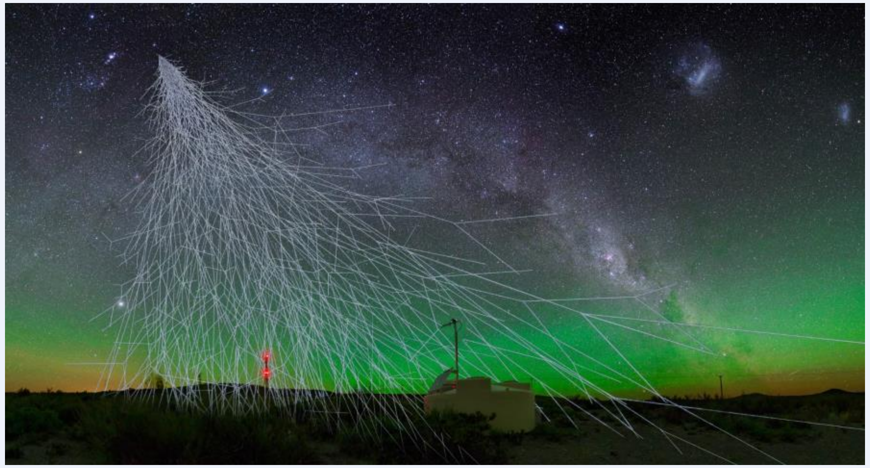
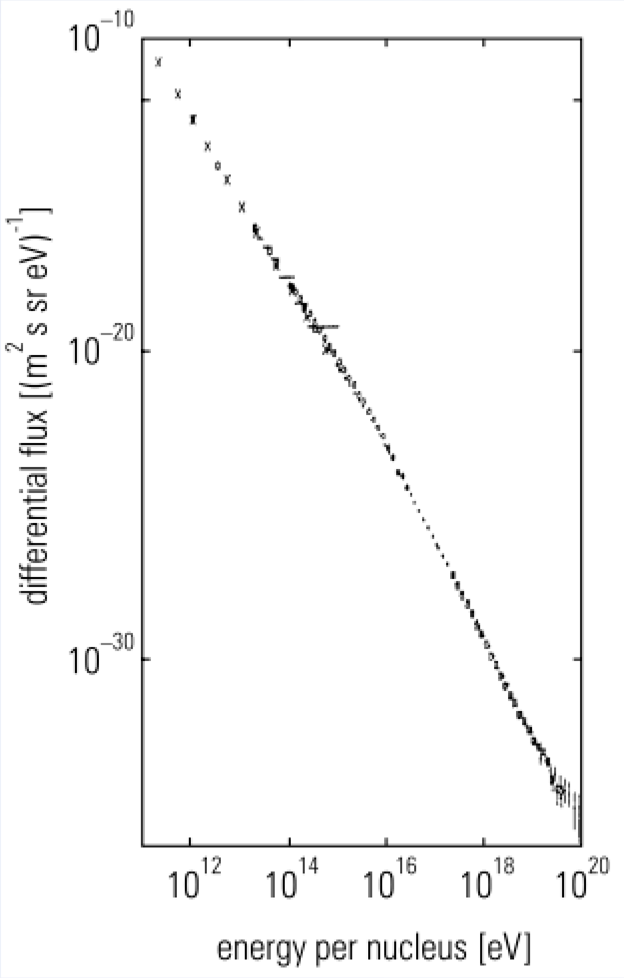
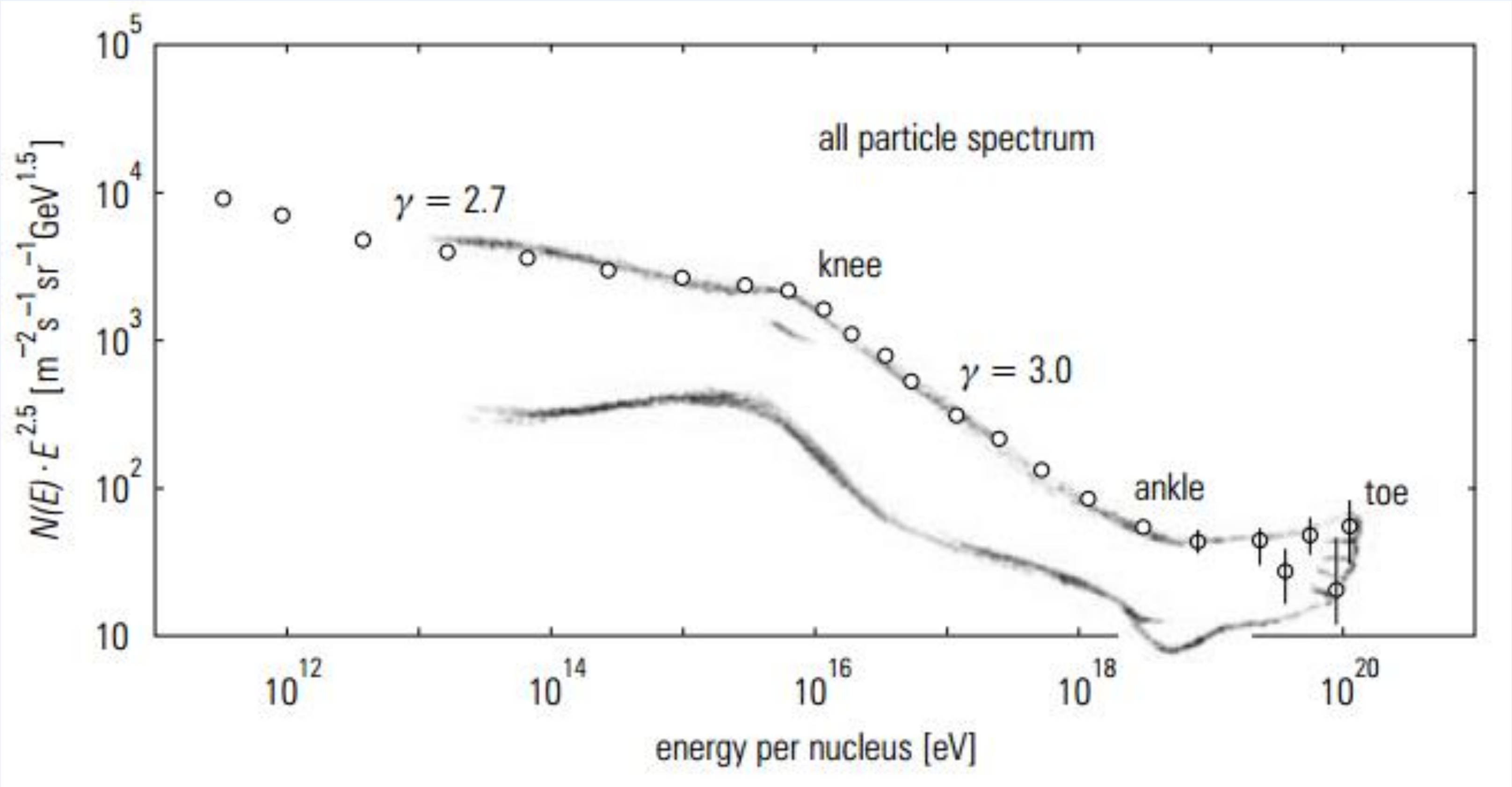
Ultra high energy cosmic rays

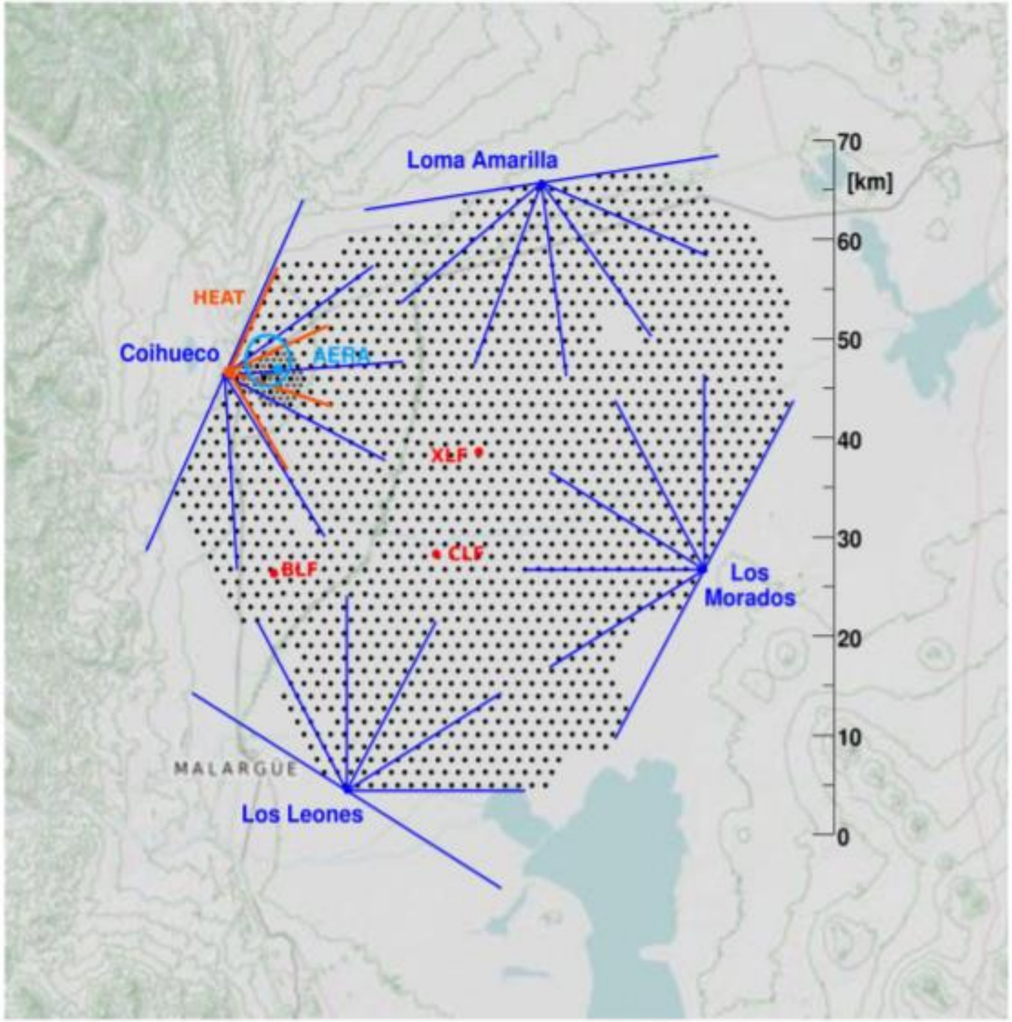


Cosmic ray spectrum





Pierre Auger Observatory



Surface detector (SD)

•1500 m array
3000 km² – 1600 detectors
1500 m grid
E > $10^{18.5}$ eV

•750 m array
24 km² – 61 detectors
750 m grid
E > $10^{17.5}$ eV

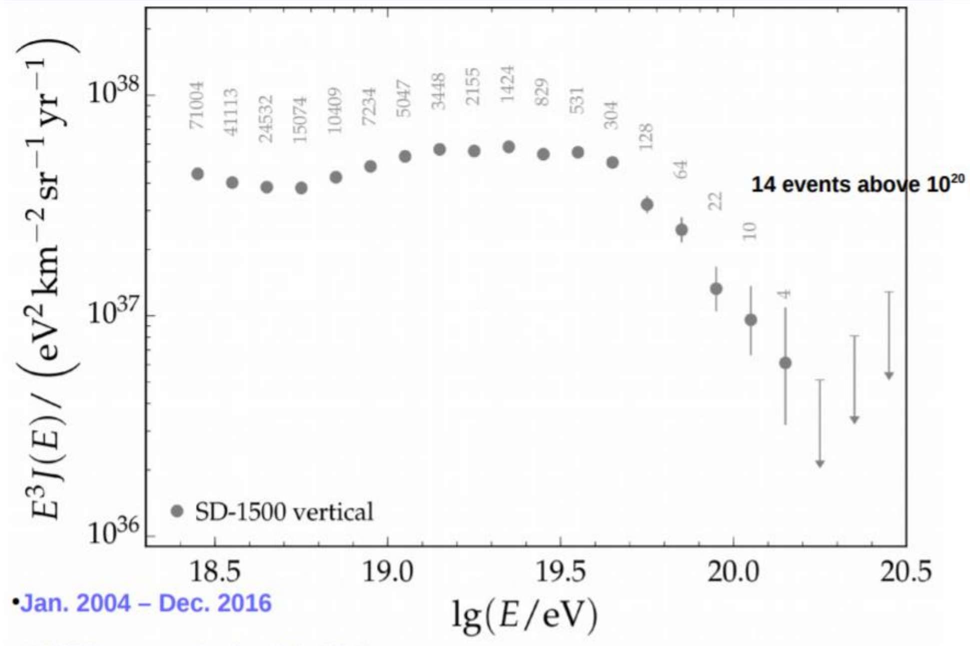
Fluorescence detector (FD)

•24 telescopes in 4 building
Elevation 0-30^0
E > 10^{18} eV

•3 additional telescopes
Elevation 30-60^0
E > 10^{17} eV

Spektrum UHECR namerané Pierre Auger Observatory

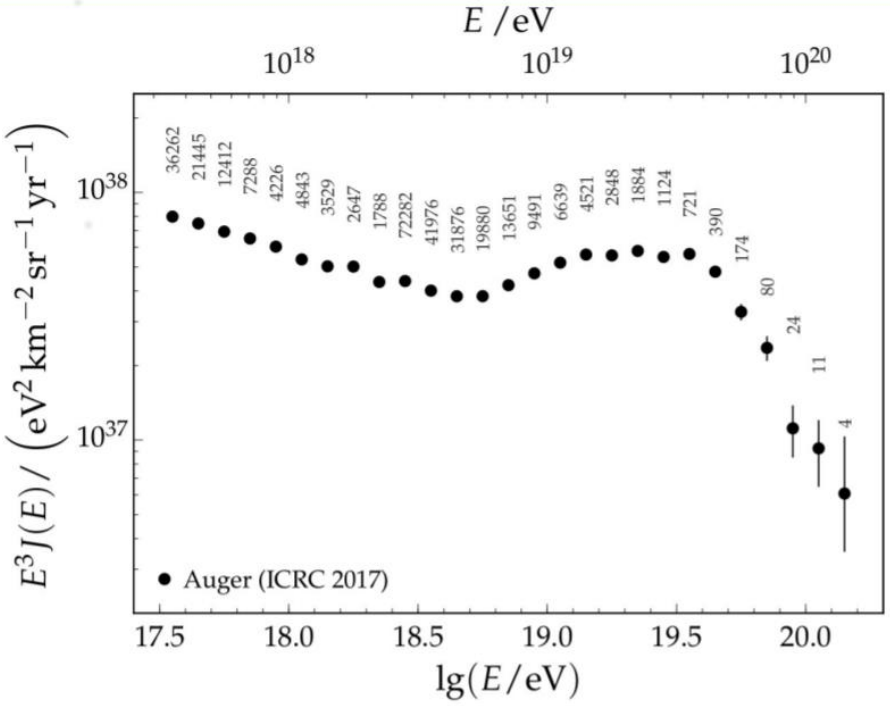
The SD-1500 vertical spectrum



- Jan. 2004 – Dec. 2016
- 183332 events for log(E)>18.4
- Exposure = 51588 km^2 sr yr (~20% more than for ICRC15)

- Systematic uncertainty on energy 14%
- Systematic uncertainty on flux 5.8%

The combined spectrum



Upper limits for UHE photons

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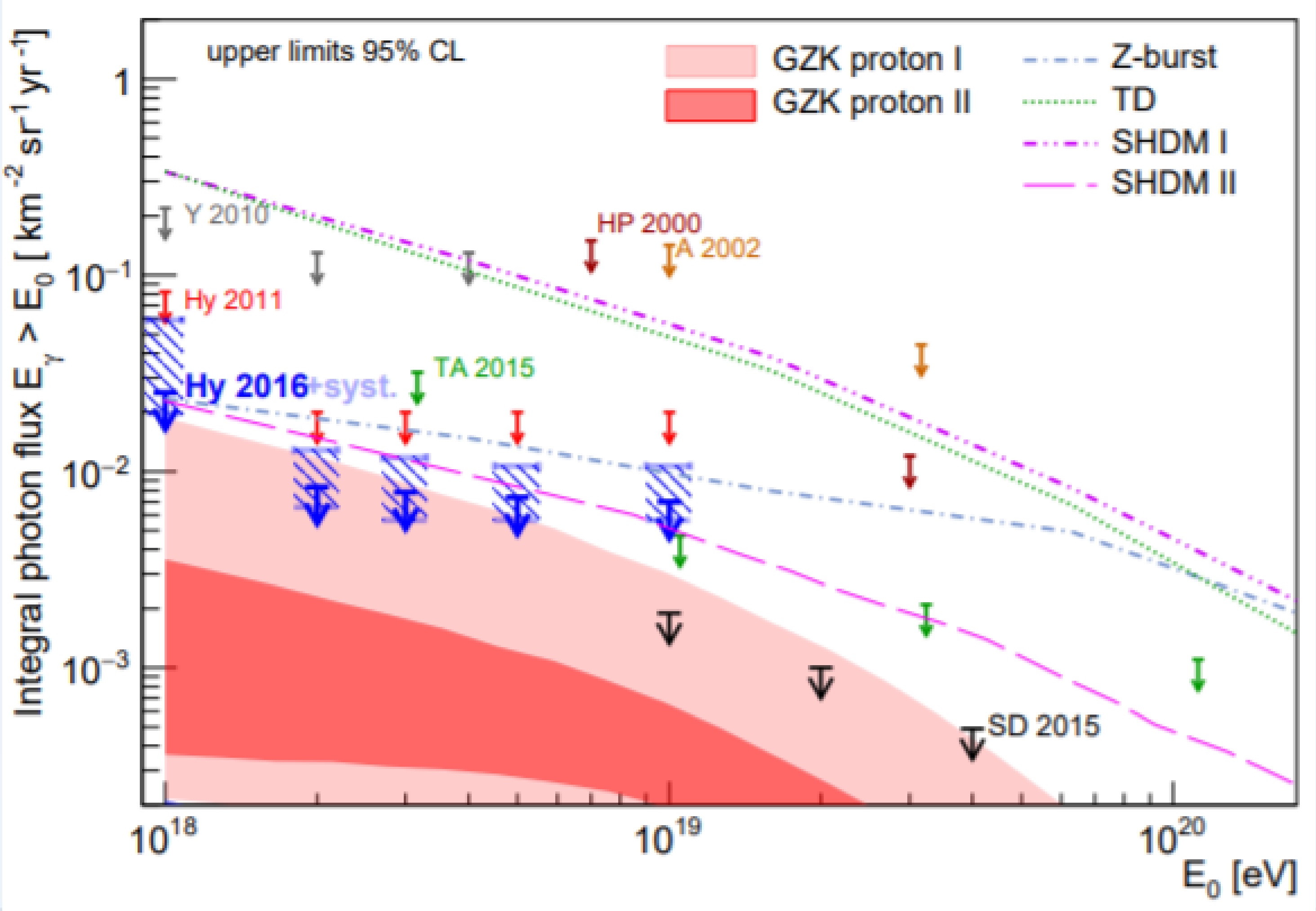


Motivácia
Lorentz Invariance Violation - LIV

- string theory,
- Loop QG,
- non-commutative geometry,
- space-time foam,
- some braneworld backgrounds,
- condensed matter analogues of “emergent gravity”.

Modification of the dispersion relations

$$E_i^2 - p_i^2 = m_i^2 \Rightarrow \mu_i^2(E, p, M_P) \approx m_i^2 + \frac{f_i}{M_P^n} E_i^{2+n}$$

- Dôsledok

$$E_{GZK} \approx \frac{m_p m_\pi}{2\omega_\gamma} \Rightarrow E_{GZK} \approx \frac{\mu(E_p, p_p, m_p, M_P)\mu(E_\pi, p_\pi, m_\pi, M_P)}{2\omega_\gamma}$$

- A pre $f_i < -2.5 \times 10^{-14}\ (n = 1)\ [f_i < -4 \times 10^{-7}\ (n = 2)]$
- Nemá riešenie, protóny sa propagujú voľne

Coleman and Glashow

Coleman and Glashow

$$\mathcal{L} = \partial_\mu \Psi^* \mathbf{Z} \partial^\mu \Psi - \Psi^* \mathbf{M}^2 \Psi, \quad \mathcal{L} \to \mathcal{L} + \partial_i \Psi \epsilon \partial^i \Psi$$

$$E^2 = \vec{p}^2 + m^2 + \epsilon \vec{p}^2$$

$$m \to m/(1+\epsilon)$$

$$c_{\mathrm{MAV}} = \sqrt{(}1+\epsilon) \simeq 1 + \epsilon/2$$

$$E^2 = \vec{p}\,^2 c_{\mathrm{MAV}}^2 + m^2 c_{\mathrm{MAV}}^4$$

$$c_i - c_j = \frac{\epsilon_i - \epsilon_j}{2} \equiv \delta_{ij}.$$

Tests of LIV and Auger

- **Future prospects of testing Lorentz invariance with UHECRs -** Denise Boncioli
- **Searching for new physics with ultrahigh energy cosmic rays –** Stecker & Scully
- **Astroparticle Physics Tests of Lorentz Invariance Violation –** Lang
  - New test of Lorentz symmetry using ultrahigh-energy cosmic rays

    Luis A. Anchordoqui and Jorge F. Soriano

    Phys. Rev. D **97**, 043010 – **Published 12 February 2018**

• Future prospects of testing Lorentz invariance with UHECRs - Denise Boncioli

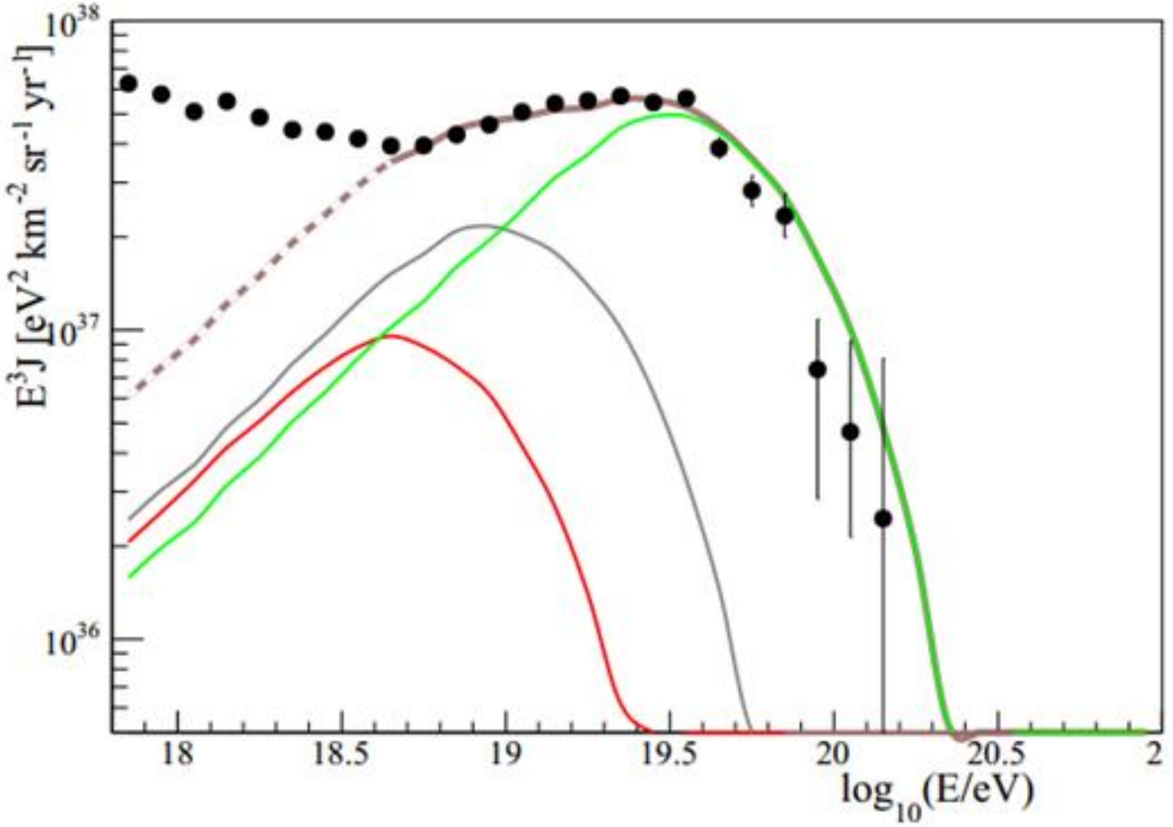
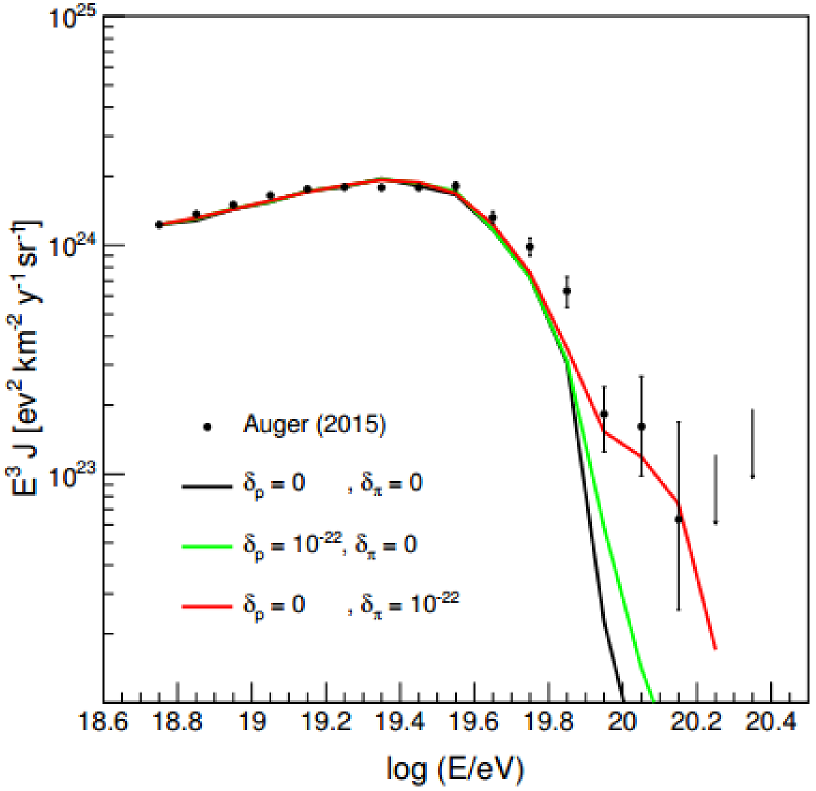


Figure 1: Simulated energy spectrum of UHECRs (multiplied by E^3) at the top of the Earth's atmosphere with maximum source rigidity $R_{max} = 5 \times 10^{18}\ V$ and $\gamma = 2$, along with Auger data points. The propagation is simulated switching off the interactions with photon backgrounds. Partial spectra are grouped according to the mass number as follows: $A = 1$ (red), $2 < A < 4$ (grey), $5 < A < 14$ (green), total (brown).

Astroparticle Physics Tests of Lorentz Invariance Violation – Lang



Proton spectrum with LIV. The black dots represent the data from Auger. (10) The black line represents the LI scenario, the red line the scenario with LIV for the pion ($\delta_\pi = 10^{-22}$), and the blue line the scenario with LIV for the proton ($\delta_p = 10^{-22}$). The spectra are multiplied by E^3 to highlight their structures.

Searching for new physics with ultrahigh energy cosmic rays – Stecker & Scully

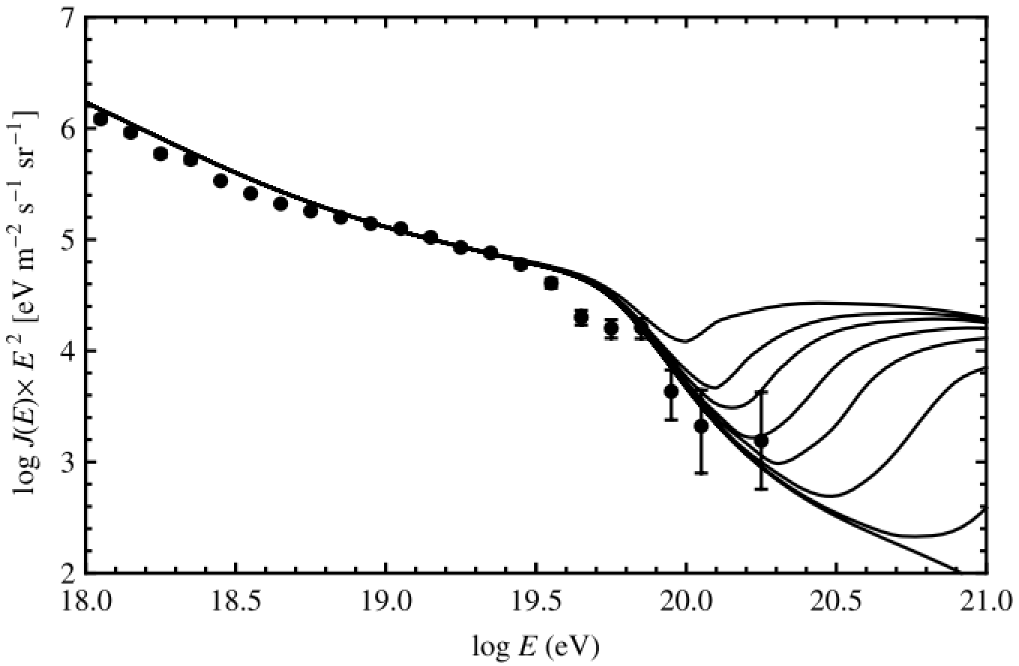


Figure 4. Comparison of the latest Auger data with calculated spectra for various values of $\delta_{\pi p}$, taking $\delta_p = 0$ (see text). From top to bottom, the curves give the predicted spectra for $\delta_{\pi p} = 1 \times 10^{-22}$, 6×10^{-23}, 4.5×10^{-23}, 3×10^{-23}, 2×10^{-23}, 1×10^{-23}, 3×10^{-24} and 0 (no Lorentz violation).

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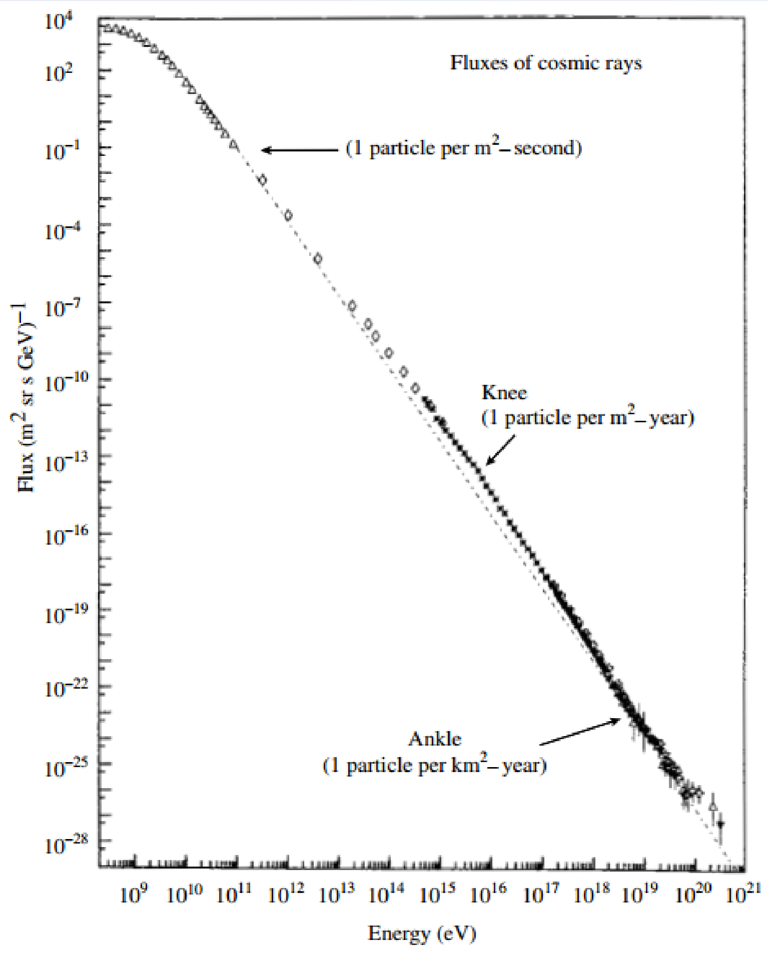
END

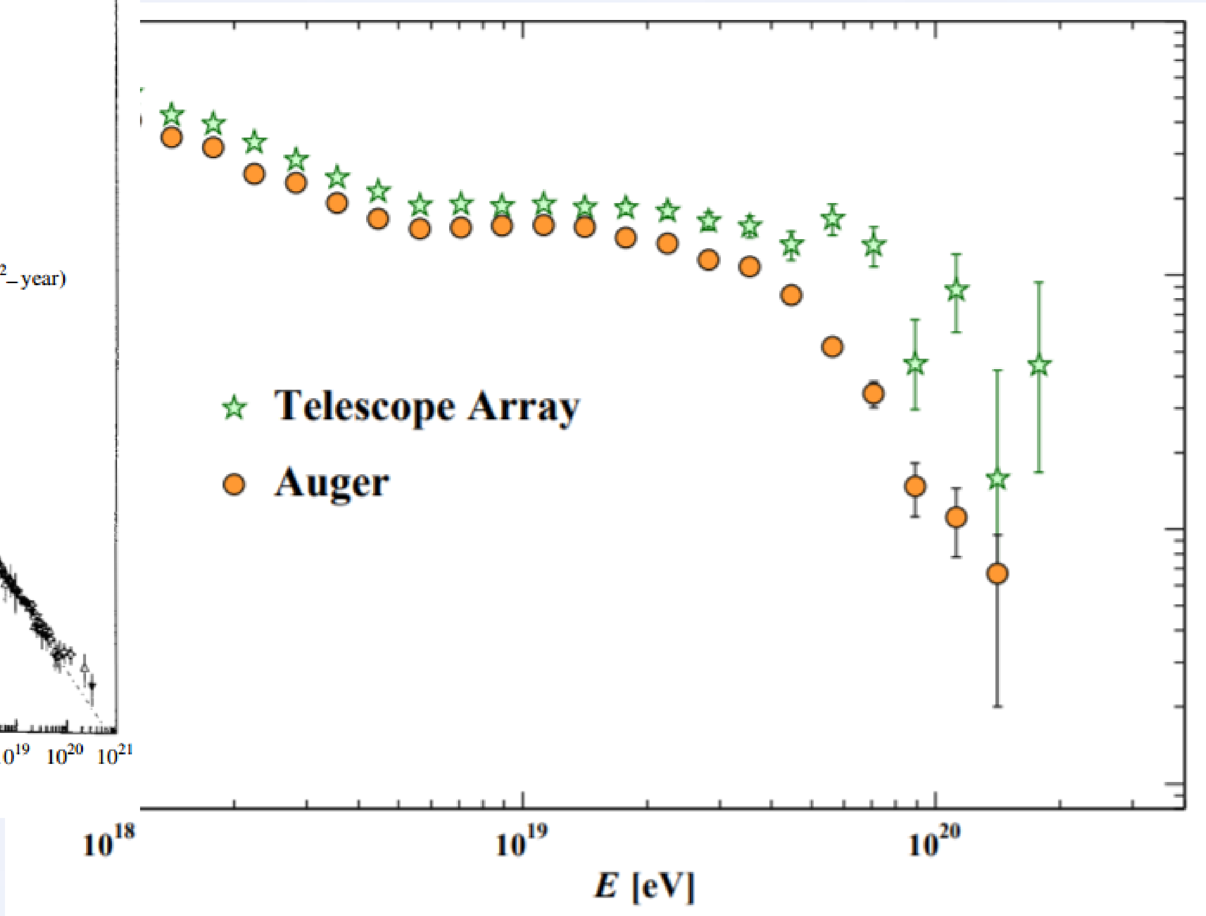
- Pokračovanie o rok...

Frameworks for Lorentz violation

- Systematic modified dispersion
- Robertson-Mansouri-Sexl framework
- c2 framework
- “Doubly special” relativity
- Non-systematic dispersion
- Effective field theory
- Non-commutative spacetime
- Symmetry and relevant/irrelevant Lorentz violating operators
- Lorentz violation with gravity in EFT



Fluxes of cosmic rays
(1 particle per m²– second)
Knee
(1 particle per m²– year)
Ankle
(1 particle per km²– year)
Flux (m² sr s GeV)⁻¹
Energy (eV)



Telescope Array
Auger
E [eV]

Cosmic ray spectrum

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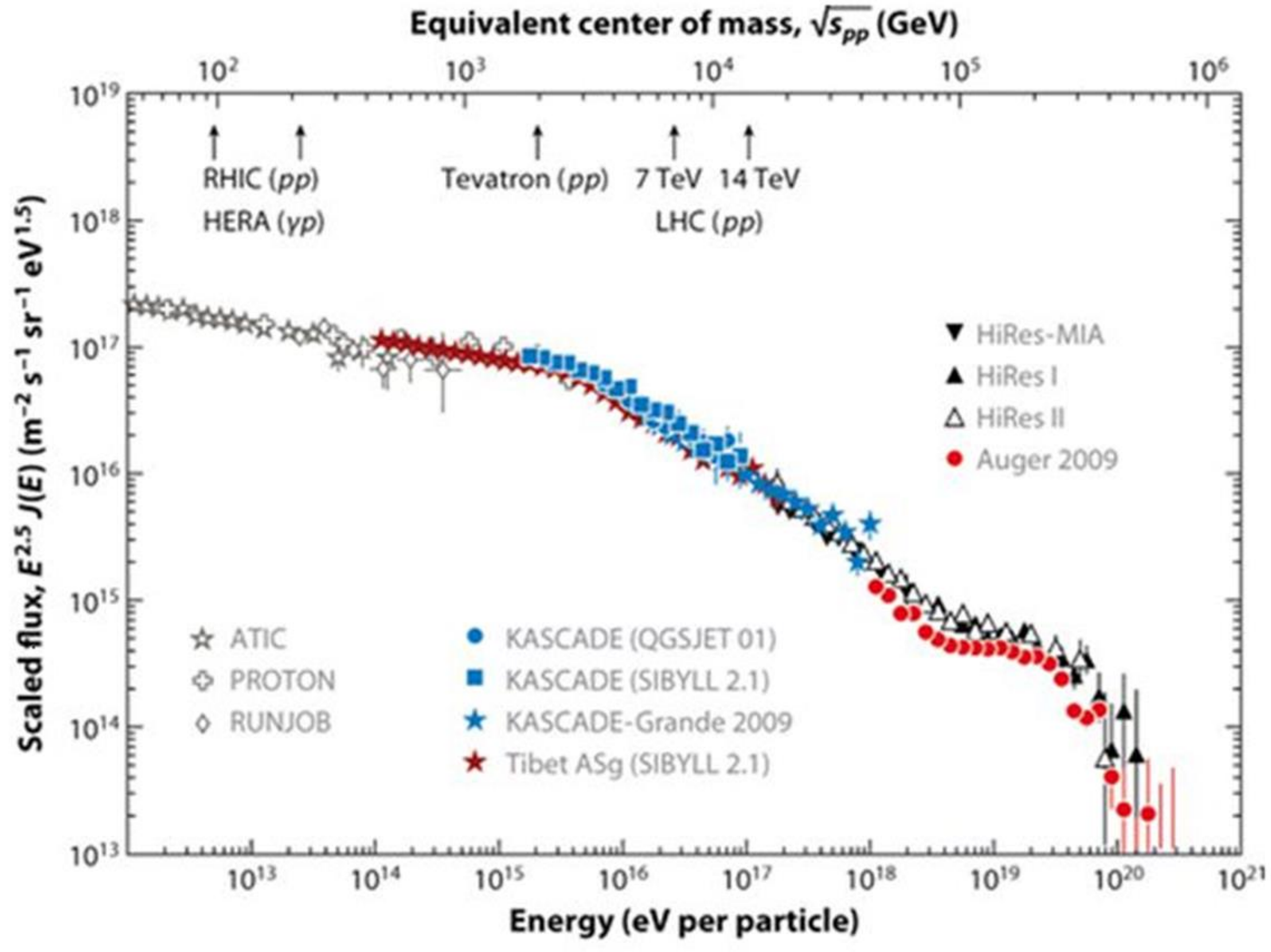

"knee" $10^{15} - 10^{16}$ eV

"ankle" 6×10^{19} eV

Greisen–Zatsepin–Kuzmin cutoff (GZK cutoff)

5×10^{19} eV

Model UHECR s LIVom

Motivácia - skúmanie alternatívnych hypotéz v súvislosti s propagáciou kozmického žiarenia.

$$\mathcal{L} = \partial_\mu \psi^* Z \partial^\mu \psi - \psi^* M \psi \qquad \mathcal{L} \to \mathcal{L} + \partial_i \psi \delta_a \partial^i \psi$$

$$E_a^2 \approx p_a^2 c_a^2 + m_a^2 c_a^4$$

$$4\omega E_\pi = \frac{m^2(2M+m)}{M+m} + 2\delta_{\pi \mathrm{p}} E_\pi^2$$

Cosmic ray spectrum

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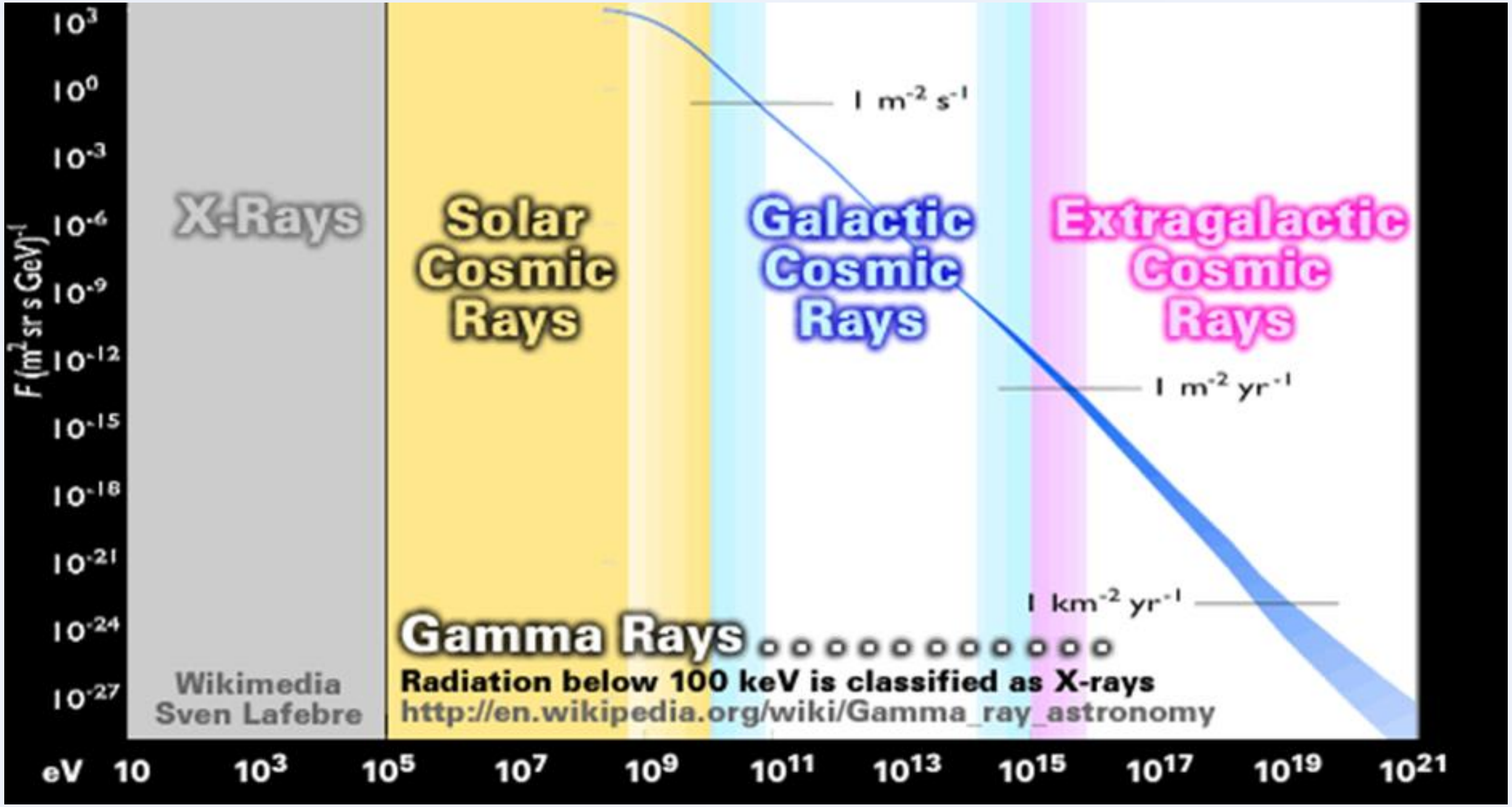

Otvorené otázky o UHECR

- Ako je možné vidieť častice s energiou väčšou ako je GZK mez?
- Aký je zdroj tak silného žiarenia E?
- Kde sú tieto zdroje?

Odpovede na tieto otázky

- Klasické
- Exotické
  - LIV
  - Kozmologické defekty
  - Rozpad tmavej hmoty

Cosmodefekty

TOPOLOGICAL DEFECTS AND HIGHEST ENERGY COSMIC AND GAMMA RAYS

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Enrico Fermi Institute, The University of Chicago, Chicago, IL 60637-1433

Abstract. In this paper we review the hypothesis that a substantial part of the cosmic ray flux observed above about 10^{19} eV may be produced by decaying or annihilating topological defects left over from phase transitions in the early universe at grand unification energy scales ($\approx 10^{16}$ GeV). Possible signatures of cosmic ray producing defect models are discussed which could be tested experimentally in the near future. We thereby focus on model independent universal spectral properties of the predicted particle fluxes.

Key words:

highest energy γ-rays – topological defects – cosmic strings

1. Introduction

It is commonly believed that cosmic rays are mainly produced due to first order Fermi acceleration (see, e.g., Gaisser 1990) at astrophysical shocks. A potential source of cosmic rays (CR) of ultrahigh energies (UHE) (i.e. above $\approx 10^{18}$ eV) are relativistic shocks contained in radiogalaxies and active

Rozpad tmavej hmoty

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Ultra high energy cosmic ray, superheavy dark matter and extra dimension

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Abstract

We propose a new mechanism for explaining the very long lifetime of superheavy dark matter X, which is proposed as a source of the ultra high-energy cosmic rays above the GZK cutoff (5×10^{19} eV). The singlet X particle couples to the MSSM particles only through a bulk singlet field which develops the v.e.v. in the "hidden" brane. The distance between this hidden brane and the "visible" brane naturally leads to the exponential suppression of the coupling. The X particle decays predominantly into the higgsino and Higgs boson of the MSSM, and its decay spectrum is completely determined once their properties are known.

1. Introduction

Some experiments have observed [1–4] cosmic rays whose energy are above the GZK cutoff (5×10^{19} eV) [5,6]. The existence of such ultra high energy cosmic rays (UHECR) is a great puzzle not only for

generated by inflation during the reheating epoch just after the end of inflation [14,15].

As an origin of UHECR, its mass m_X, its lifetime τ_X and its abundance $\Omega_X h^2$ must satisfy specific conditions. It must be heavy enough to explain the energy of UHECR, it must survived until now, and the flux of X decay must be consistent with observation.

GZK cutoff

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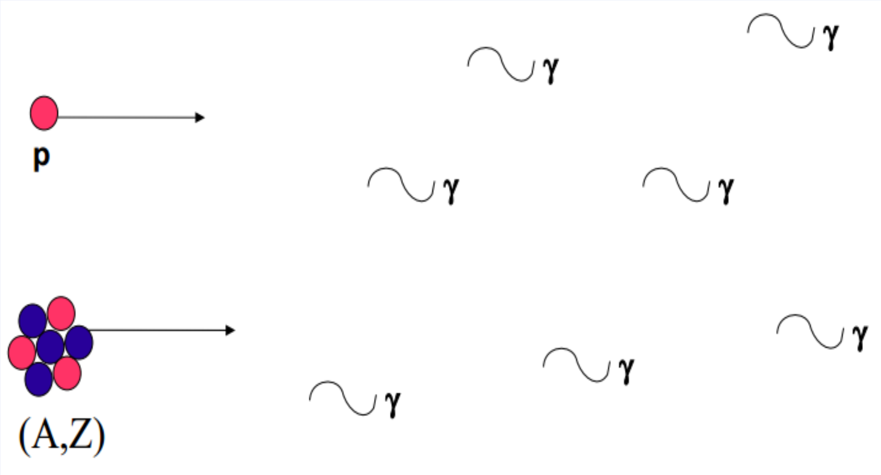
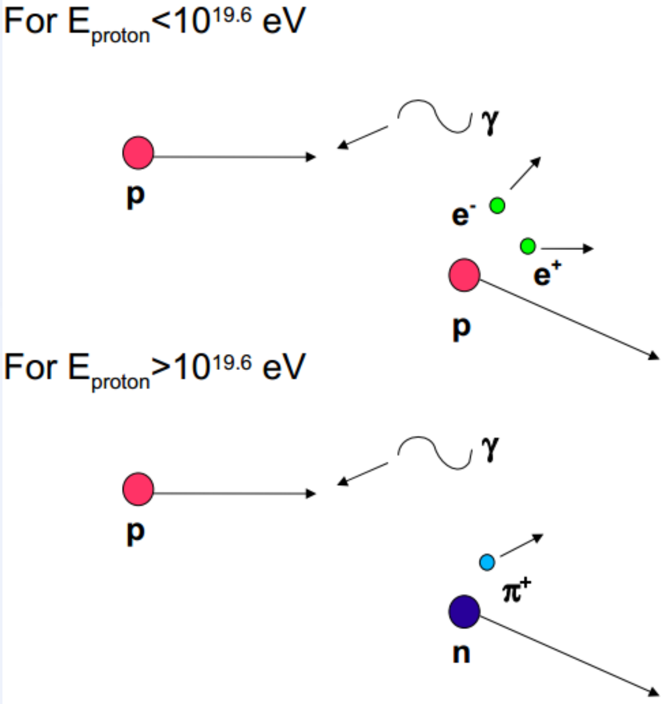
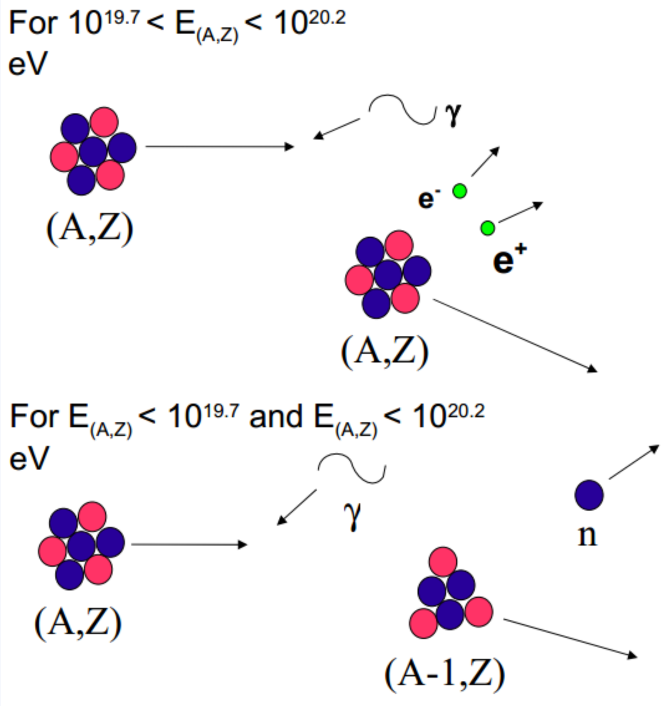


p
γ
(A,Z)



For $E_{proton}<10^{19.6}$ eV
p
γ
e-
e+
p
For $E_{proton}>10^{19.6}$ eV
p
γ
π+
n



For $10^{19.7} < E_{(A,Z)} < 10^{20.2}$ eV
(A,Z)
γ
e-
e+
(A,Z)
For $E_{(A,Z)} < 10^{19.7}$ and $E_{(A,Z)} < 10^{20.2}$ eV
(A,Z)
γ
n
(A-1,Z)

Motivácia a predpoklady LIV

- string theory,
- Loop QG,
- non-commutative geometry,
- space-time foam,
- some braneworld backgrounds,
- condensed matter analogues of “emergent gravity”.

Forbidden reactions

- *photon decay* $\gamma \rightarrow e^{+} e^{-}$
- *Pair annihilation* $e^{+} e^{-} \rightarrow \gamma$
- *Photon splitting* $\gamma \rightarrow N\gamma$
- *vacuum Čerenkov effect*

$$p^{+} \rightarrow p^{+} \gamma \qquad n \rightarrow n \gamma$$

$$e^{-} \rightarrow e^{-} \gamma \qquad \nu \rightarrow \nu \gamma$$

Inšpirácia

- This work can be used to study the effects of LIV on interactions not treated here such as the pair production for protons or the inverse Compton scattering for electrons. It can also be adapted to treat the effects of LIV in the development of extensive air showers (EASs), which would change the measured composition.

Z čoho sa vychádzalo:

- modification of the dispersion relations

$$E_i^2 - p_i^2 = m_i^2 \Rightarrow \mu_i^2(E, p, M_P) \approx m_i^2 + \frac{f_i}{M_P^n} E_i^{2+n}$$

- Dôsledok

$$E_{GZK} \approx \frac{m_p m_\pi}{2\omega_\gamma} \Rightarrow E_{GZK} \approx \frac{\mu(E_p, p_p, m_p, M_P)\mu(E_\pi, p_\pi, m_\pi, M_P)}{2\omega_\gamma}$$

- A pre $f_i < -2.5 \times 10^{-14}\ (n = 1)\ [f_i < -4 \times 10^{-7}\ (n = 2)]$
- Nemá riešenie, protóny sa propagujú voľne

$M_P \to AM_P$

Teoretický základ

$$\pi^0 \to \gamma\gamma$$

$$m_\pi^2 + \frac{1}{M_P^n}(f_\pi E_\pi^{2+n} - f_\gamma(E_{\gamma_1}^{2+n} + E_{\gamma_2}^{2+n})) - 2(E_{\gamma_1}E_{\gamma_2} - p_{\gamma_1}p_{\gamma_2}) = 2p_{\gamma_1}p_{\gamma_2}(1 - \cos\theta_{1,2})$$

Nerozpadavajú sa ak:

$$\begin{aligned} E_\pi > (M_P^n m_\pi^2/|f_\pi|)^{\frac{1}{2+n}} &\approx 6/|f_\pi|^{1/3} \times 10^{15}\ \mathrm{eV}\ (n=1) \\ &\approx 1.4/|f_\pi|^{1/4} \times 10^{18}\ \mathrm{eV}(n=2) \end{aligned}$$

Inšpirácie

- These are probably the most important affecting UHECR propagation and interaction, but certainly a <u>**general analysis of *all* aspects of LIV on cosmic ray physics would be very welcome.**</u>
- In principle, *all* aspects of UHECR physics can be modified by LIV. For instance, LIV can affect the cosmic <u>ray acceleration processes</u>, and also the <u>energy losses during acceleration</u>.
- As an example, consider LI violation with *fi* > 0. <u>In this case, as soon as the energy of the accelerated nucleus is above some threshold, vacuum Cherenkov process becomes possible and essentially no further acceleration is possible.</u>

Teoretický základ

PHYSICAL REVIEW D, VOLUME 59, 116008

High-energy tests of Lorentz invariance

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(Received 18 December 1998; published 28 April 1999)

We develop a perturbative framework with which to discuss departures from exact Lorentz invariance and explore their potentially observable ramifications. Tiny noninvariant terms introduced into the standard model Lagrangian are assumed to be renormalizable (dimension ≤4), invariant under $SU(3)\otimes SU(2)\otimes U(1)$ gauge transformations, and rotationally and translationally invariant in a preferred frame. There are a total of 46 independent *CPT*-even perturbations of this kind, all of which preserve anomaly cancellation. They define the energy-momentum eigenstates and their maximal attainable velocities in the high-energy limit. The effects of these perturbations increase rapidly with energy in the preferred frame, more rapidly than those of *CPT*-odd perturbations. Our analysis of Lorentz-violating kinematics reveals several striking new phenomena that are relevant both to cosmic-ray physics (e.g., by undoing the Greisen, Zatsepin, and Kuz'min cutoff) and neutrino physics (e.g., by generating novel types of neutrino oscillations). These may lead to new and sensitive high-energy tests of special relativity. [S0556-2821(99)00111-3]

PACS number(s): 11.30.Cp

I. INTRODUCTION

Experimental tests of Lorentz invariance have become remarkably accurate. To give a quantitative measure of this accuracy, one imagines adding tiny Lorentz-violating terms to a conventional Lagrangian. Experiments can test Lorentz invariance by setting upper bounds to the coefficients of these terms. One common choice [1] is to alter the coefficient of the square of the magnetic field in the Lagrangian of quantum electrodynamics:

$$\vec{B}^2 \to (1+\epsilon)\vec{B}^2. \qquad (1.1)$$

This effect, which we call vacuum Čerenkov radiation, is absent below a characteristic energy and turns on abruptly once that energy is reached. Such is not always the case, as the following example shows.

Let Ψ denote a set of n complex scalar fields assembled into a column vector. If we assume invariance under the $U(1)$ group $\Psi \to e^{-i\lambda}\Psi$, the most general free Lagrangian is

$$\mathcal{L} = \partial_\mu \Psi^* Z \partial^\mu \Psi - \Psi^* M^2 \Psi, \qquad (1.2)$$

where Z and M^2 are positive Hermitian matrices. We can always linearly transform the fields to make Z the identity and M^2 diagonal, thus obtaining the standard theory of n

Teoretický základ

$$\mathcal{L} = \partial_\mu \psi^* Z \partial^\mu \psi - \psi^* M^2 \psi \qquad \mathcal{L} \to \mathcal{L} + \partial_i \psi \delta_a \partial^i \psi$$

$$E_a^2 = p_a^2 c^2 + m_a^2 c^4 + \delta_a p_a^2 c^2$$

$$E_a^2 = p_a^2 c^2 (1 + \delta_a) + m_a^2 c^4 \qquad c_a = c\sqrt{1 + \delta_a}$$

$$E_a^2 = p_a^2 c_a^2 + m_a^2 \frac{c_a^4}{(1 + \delta_a)^2} \approx p_a^2 c_a^2 + m_a^2 c_a^4$$

$$\sqrt{s_a} = \sqrt{E_a^2 - p_a^2} = \sqrt{m_a^2 + \delta_a p_a^2}$$

.

Z čoho sa vychádzalo

$$p + \gamma \to p + \pi$$

$$4\omega E = m(2M + m)$$ threshold energia proton

$$4\omega E_\pi = \frac{m^2(2M + m)}{M + m}$$ threshold pion

$$4\omega E_\pi = \frac{m^2(2M + m)}{M + m} + 2\delta_{\pi p} E_\pi^2$$

ak $c_\pi > c_p$ tak
kvadraticka rovnica ktora ma realne korene pre

$$\delta_{\pi p} \leqslant \frac{2\omega^2(M + m)}{m^2(2M + m)} \simeq \omega^2/m^2$$

$$\omega_0 \equiv kT_{CBR} = 2.35 \times 10^{-4}\,\text{eV}$$

$$T_{CBR} = 2.725 \pm 0.02\,\text{K}$$

$$\delta_{\pi p} \leqslant 3.23 \times 10^{-24} \left(\frac{\omega}{\omega_0}\right)^2$$