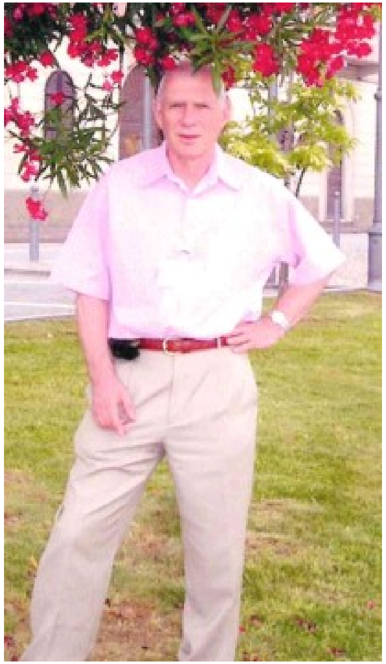
Theoretical aspects of UHECR transport



A. Gazizov

Conference in memory of
Veniamin Sergeyevich Berezinsky

GSSI, L'Aquila, 01/10/2024

V.S. Berezinsky

An outstanding Soviet, Russian and Italian physicist.
Born: 17/04/1934 (*Volgograd, USSR*)
Died: 16/04/2023 (*L’Aquila, Italy*)

Istituto Veneto di Scienza, Lettere ed Arti

International Humboldt prize of 1991
O’Ceallaigh medal of 2007
M.A. Markov prize of 2010
E. Fermi prize of SIF 2017

An article: "In memory of Veniamin Sergeevich Berezinsky" Physics-Uspekhi **66** (5) 534-536 (2023)

A special talk on “38-th All-Russian Cosmic Ray conference”, July 2024.

VS, supervisor and colleague

VS – abbreviation: *V* - Veniamin (*Venya*, as he preferred to be named, *Ben* for some of his friends) ; *S* – Sergeyevich (patronymic).

Collaboration with *Venya* began in 1976, when I was a student of the Moscow Engineering-Physics Institute, and we kept in touch untill his last days. Venya involved me in one theoretical problem related to the project *DUMAND:* the resonance production of cascades by UHE $\bar{\nu}_e$ in

$$\bar{\nu}_e + e^- \rightarrow W^- \rightarrow \bar{q}_u + q_d \ ,$$

now known as the *Glashow* resonance.

S.L. Glashow

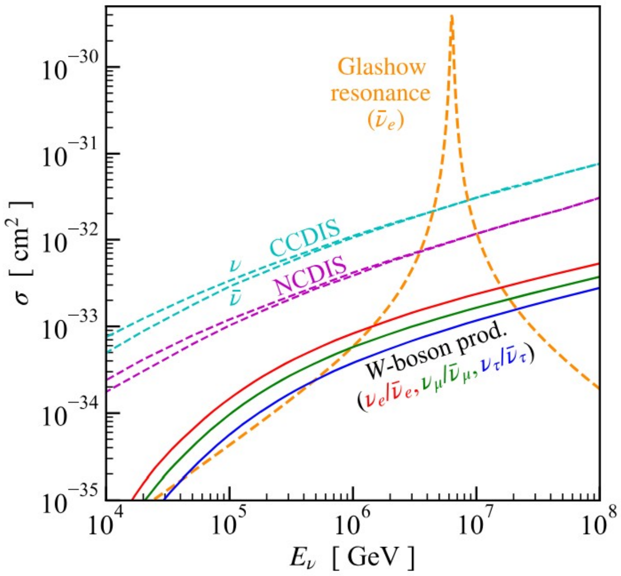
Note, that *Glashow* discussed just muons production in

$$\bar{\nu}_e + e^- \rightarrow W^- \rightarrow \bar{\nu}_\mu + \mu^-$$

for *m_W ~ (0.7– 1) GeV.* No resonance pike in the energy spectrum of muons could be produced in this reaction.

S.L. Glashow, Resonant Scattering of Antineutrinos, Phys. Rev. **118** (1960) 316.

W-boson to quarks



In the resonance process proposed by Venya, all energy of the UHE $\bar{\nu}_e$ is transferred to the cascade. Calculations of νN-cross-sections and the account for quark colors were due to advice of another my supervisor *Yuriy Nikitin.* It was shown, that the number of resonance events exceeds the rate of background $\nu_l + N \rightarrow l + X$, mainly $\nu_e N$, events:

$$N_{res} = 3\sqrt{2}\pi^2 \gamma N_e G_F F_{\bar{\nu}_e}(>E_{res}),$$

where γ is the index of integral power-law neutrino spectrum, N_e is the number of electrons in a detector, $\Omega_{eff} = 2\pi$ *ster* accounts for the effective solid angle (upper hemisphere).

V.S. Berezinsky, A.G., JETP Lett. **25** (1977) 254,
V.S. Berezinsky, G.T. Zatsepin, Sov. Phys. Usp. **20** (1977) 361

Later these papers were cited in books:
L.B. Okun, Leptons and Quarks (1980) (project *DUMAND*),
V.L. Ginzburg et al., Astrophysics of Cosmic Rays (1990).

νN- and νe-cross-sections

Different aspects of νN- and νe-cross-sections were later studied in

V.S. Berezinsky, A.G., Sov. J. Nucl. Phys. **29** (1979) 816 ,
V.S. Berezinsky, A.G., Sov. J. Nucl. Phys. **33** (1981) 120 ,

including the possibility of searching for W-boson propagator effect in giant underwater detectors.

M. Kowalski
Ch. Spiering

These cross-sections were partially included in the c++ *MC* code *ANIS*: High energy neutrino generator for neutrino telescopes, *A.G., M. Kowalski,* Comput. Phys. Commun. **172** (2005) 203-213

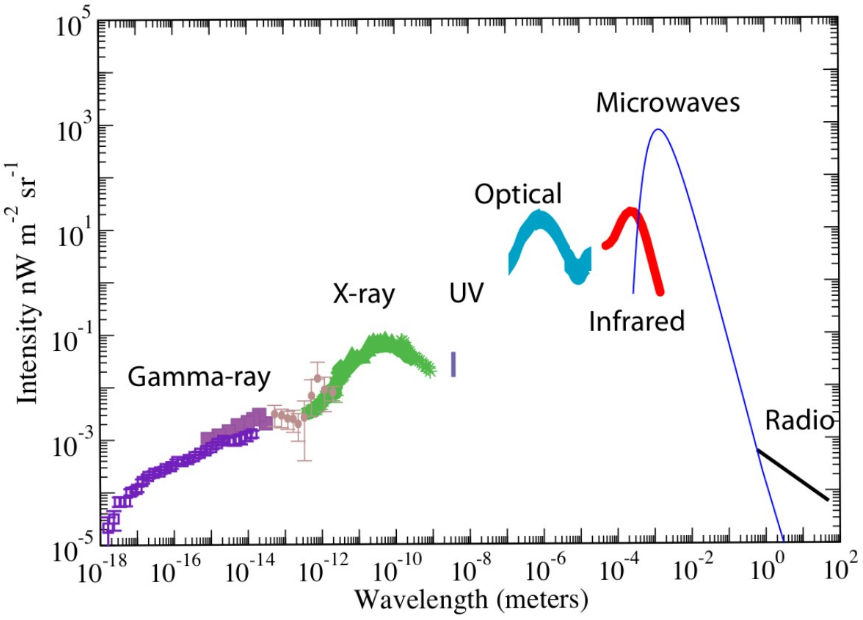
F. Halzen

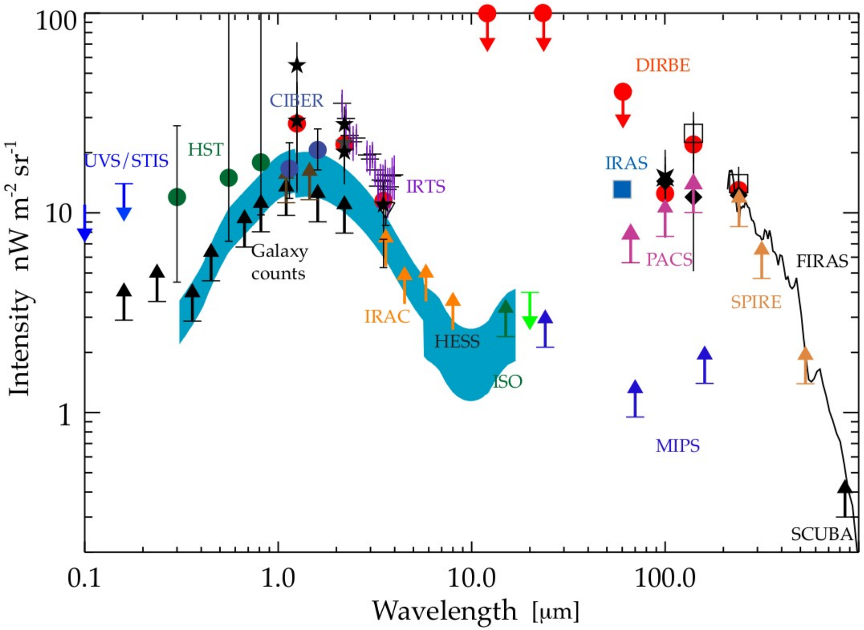
The resonance event was discovered by the *IceCube collaboration*, Detection of a particle shower at the Glashow resonance with IceCube, Nature **591**, 220-224 (2021)
The cascade had energy $(E = 6.05 \pm 0.72$ PeV); hadronic decay of $W-$boson confirmed the astrophysical origin of the source and the presence of $\bar{\nu}_e$ in the total neutrino flux.

Origin of UHECR

- *UHECR* are either protons or nuclei (up to Iron) with $E \gtrsim 10^{18}$ *eV* = *1 EeV*.
- Observations suggest that *UHECR* are extragalactic: the isotropy, light composition at *E ~ (1-3) EeV*, lack of sources accelerating to such high energies (e.g. *Hillas* plot).
- Transition from Galactic to extragalactic *CR* seems to occur at *E < 1 EeV*. Maximum acceleration energy of protons in the Galaxy $E_p \approx 4$ *PeV*; for *Fe* we expect $E_{Fe} \sim Z \times E_p \approx 0.1$ *EeV*.
- According to data of *KASCADE-Grande*, the rise of (light) extragalactic component begins at *E < 1 EeV*: the growing *p* and *He* components appear in the energy spectrum.
- If sources emit power-law decreasing *CR* spectra, all features at the Earth are owing to interactions of *CR* on their way. Adiabatic energy loss does not change the spectrum shape.
- *UHECR* interact mostly with photons: *CMB* and *EBL*. Turbulent intergalactic magnetic fields also may modify the observed energy spectrum.

CMB & EBL





SAS-2, EGRET, Fermi-LAT
COMPTEL, HEAO1 A2 and A4,
INTEGRAL, SWIFT/BAT,
ASCA, RXTE

A. Cooray, arXiv:1602.03512

$$\gamma = \gamma^{EBL}_{CMB}$$

pair-production: $p + \gamma \rightarrow e^+ + e^- + p$

π-photoproduction: $p + \gamma \rightarrow \pi + X$

photo-disintegration: $A + \gamma \rightarrow (A-1)\ \ (A-2)$

Nuclei photo-disintegration

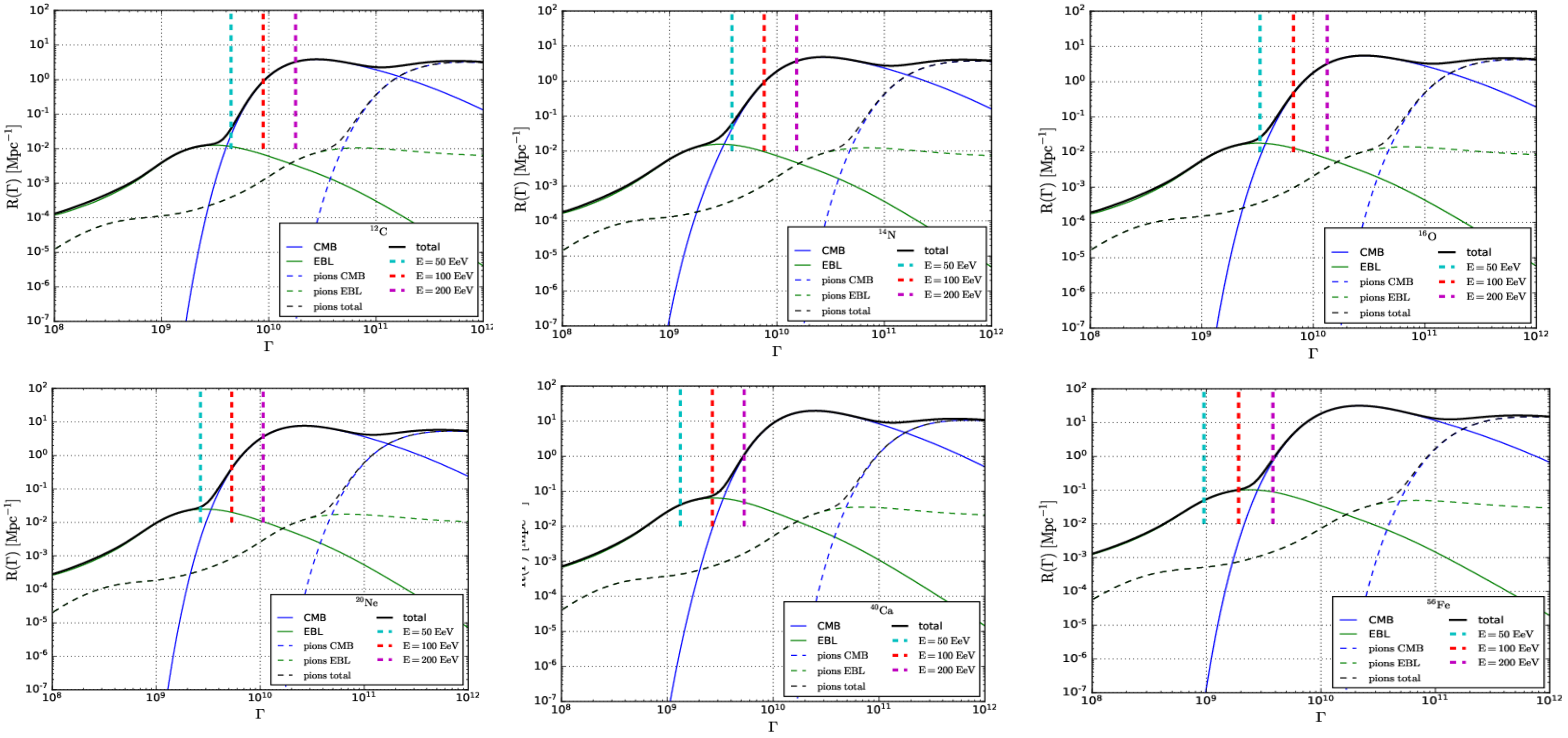
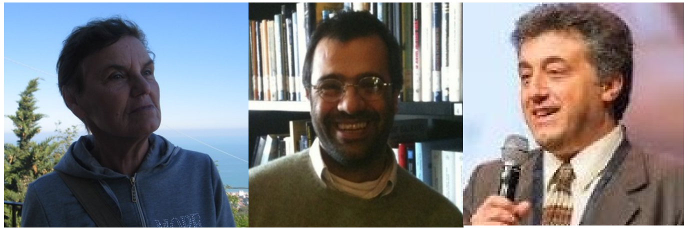


Photo-disintegration of high-energy *He* and other nuclei was first discussed in *N.M. Gerasimova, I.L. Rozental*, JTEP, **41** (1961) 488 (*in Russian*).
Prediction: no such nuclei in the spectrum at *E > 10^{19} eV*. This paper prompted the idea of *GZK*-cutoff after the *CMB was* discovered.



S.Grigorieva R.Aloisio P.Blasi

Dip model

Since protons are the most abundant nuclei in the Universe, it was natural to assume that *UHECR* are pure *p's*.
It was supported by the *HiRes* data.

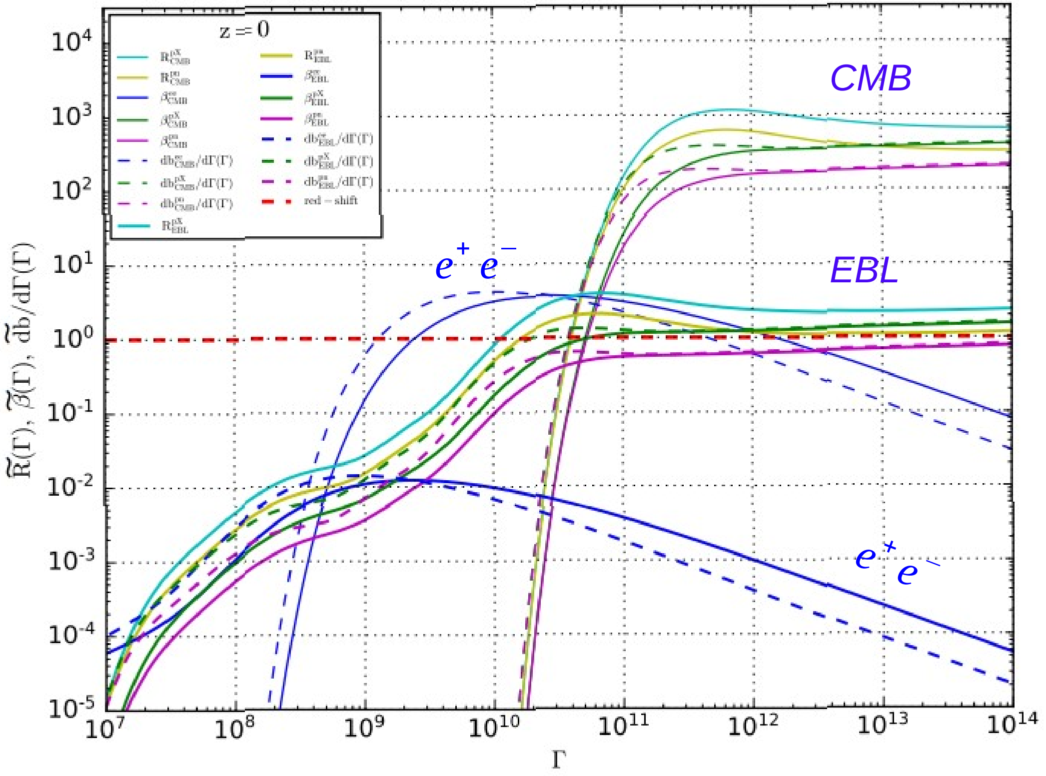
Assumptions:

1) all *UHECR* are protons,
2) similar sources are isotropically distributed in any comoving volume of the Universe,
3) the generation function of *p's* is power-law decreasing: $Q(E,z) = A(z) \times E^{-\gamma}$.

Purpose: fitting of the observed *UHECR* energy spectrum with a *'dip'* feature at $E \sim 3$ EeV.
The *GZK* cutoff was to appear at $E \sim (5\text{-}6)$ EeV, confirming the $p\gamma$-π production.
HE cosmogenic ν-fluxes were expected as a byproduct of the pion decays.

V.Berezinsky & S.Grigorieva, Astron. Astrophys. **199** (1988), 1
V.Berezinsky, A.G. & S.Grigorieva, Phys. Rev. **D74** (2006), 043005 ; astro-ph/0210095
R.Aloisio, V.Berezinsky, P.Blasi, A.G., S.Grigorieva, B.Hnatyk, Astropart. Phys. **27** (2007), 76-91.

Probability of interaction & energy losses



Functions averaged over *pγ*-interaction energies and over photon energy spectra.

$\Gamma = E_p / m_p$ – *Lorentz factor of proton*

$R(\Gamma, t) = \frac{dP}{dt}(\Gamma, t)$ – *rate of interactions*

$b(\Gamma, t) = \frac{dE}{dt}(\Gamma, t),$ – *energy loss*

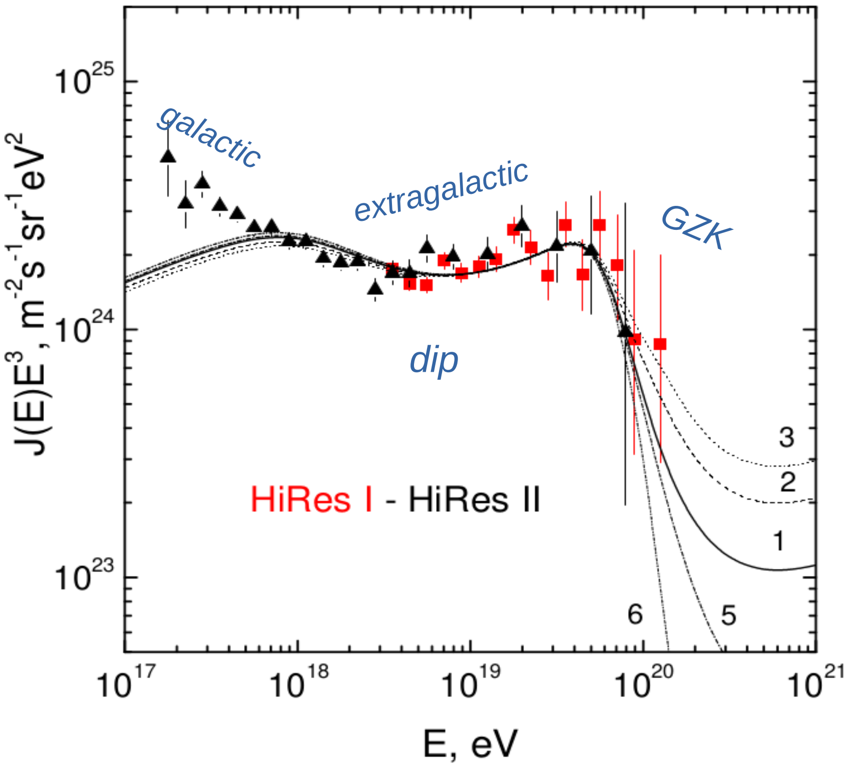
$\beta(\Gamma, t) = \frac{dE}{E\,dt}(\Gamma, t)$ – *relative energy loss*

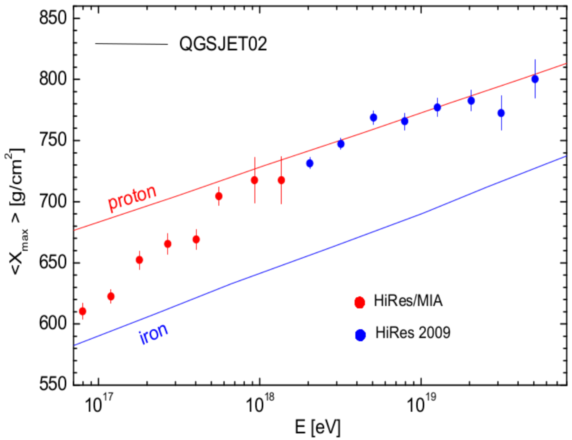
$$R(\Gamma, t) = \frac{c}{2\Gamma} \int_{\varepsilon_{th}}^{\infty} d\varepsilon_r \, \sigma(\varepsilon_r) \varepsilon_r \int_{\varepsilon_r/2\Gamma}^{\infty} d\omega \frac{n_\gamma(\omega)}{\omega^2}$$

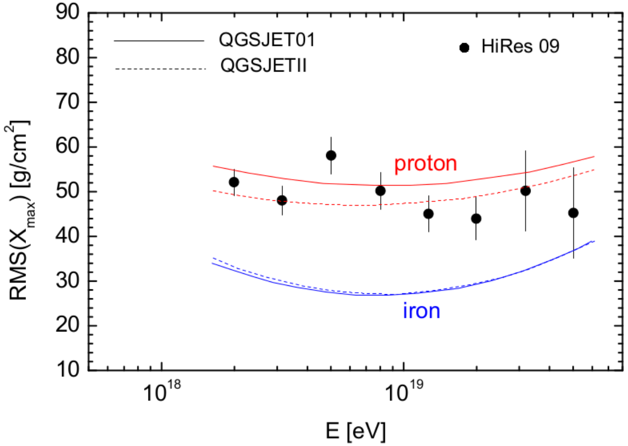
$$\beta(\Gamma, t) = \frac{c}{2\Gamma} \int_{\varepsilon_{th}}^{\infty} d\varepsilon_r \, \sigma(\varepsilon_r) f(\varepsilon_r) \varepsilon_r \int_{\varepsilon_r/2\Gamma}^{\infty} d\omega \frac{n_\gamma(\omega)}{\omega^2}$$

$$\widetilde{R}(\Gamma, t) = \frac{R(\Gamma, t)}{H(t)}, \quad \widetilde{b}(\Gamma, t) = \frac{b(\Gamma, t)}{H(t)}, \quad \widetilde{\beta}(\Gamma, t) = \frac{\beta(\Gamma, t)}{H(t)}$$

UHECR spectrum







The *HiRes* energy spectrum showed the '*dip'* and the G*ZK* cutoff features. Measurements of X_{max} *were* in agreement with light chemical composition, i.e. with a mixture of mostly protons + some *He* (< 10%).
So, data were in agreement with the '*dip'* model.

An alternative was the *'ankle'* model, assuming the dominance of Galactic contribution up to *E ~ 3 EeV*.

Continuous Energy Losses

Let $\varphi(E,t)=dn(E,t)/dE$ be the comoving volume density of protons. On their way from a source they lose energy due to red-shift $E(z)=E_0\times(1+z)$ and in collisions with *CMB+EBL* photons. In each *pγ*-interaction just a small fraction of proton's energy is lost.
This allows the use of the continuous energy loss approximation, and continuity equation reads:

$$\frac{\partial}{\partial t}\varphi(E,t)-\frac{\partial}{\partial E}\left[b(E,t)\varphi(E,t)\right]=Q(E,t),$$

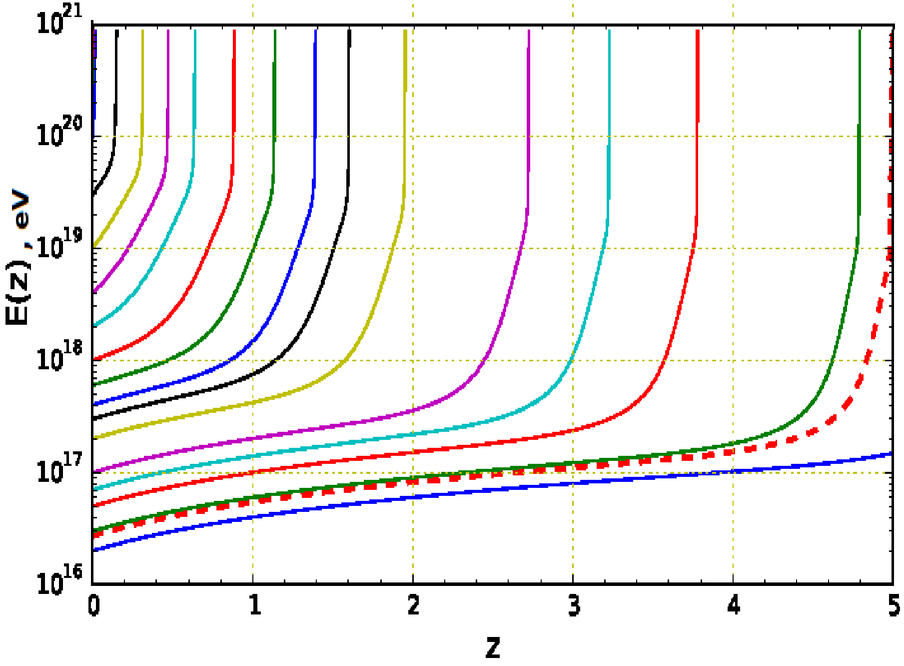
where *Q(E,t)* describes the source generation function in a comoving volume. Using the method of characteristics, the solution reduces to double integral

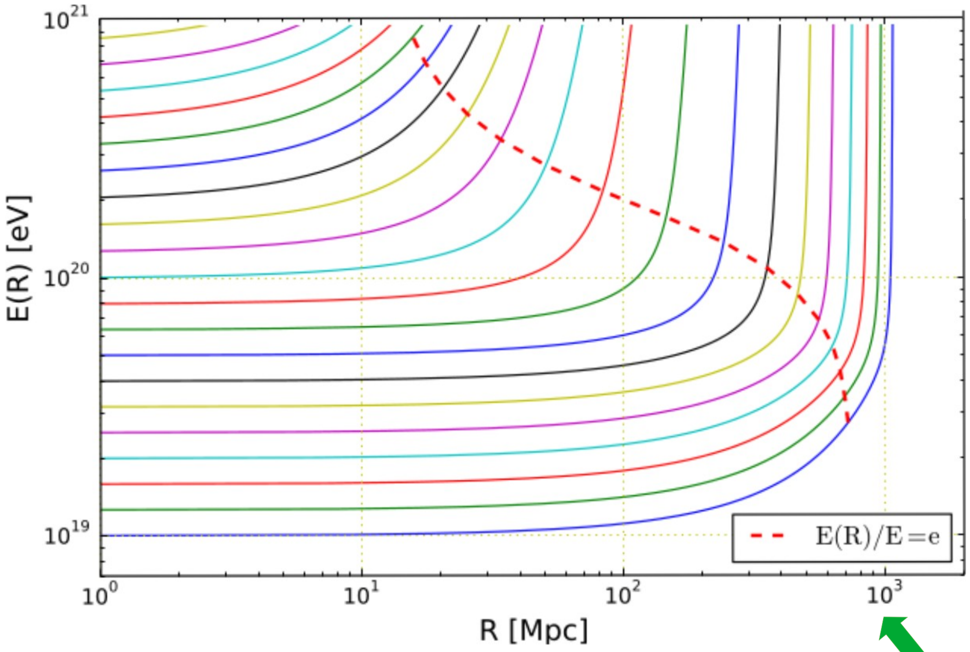
$$\varphi(E,t)=\int_{t_{min}}^{t}dt'Q[\mathcal{E}(t')]\exp\left[\int_{t'}^{t}dt''\frac{\partial}{\partial\mathcal{E}}b(\mathcal{E}(t''),t'')\right],$$

where characteristics $\mathcal{E}(t,E_0,t_0)$ are solutions of an ordinary differential equation with an initial energy E_0 at our epoch:

$$\frac{dE}{dt}(t)=-b(E,t),\qquad E(t_0)=E_0$$

Characteristics for protons

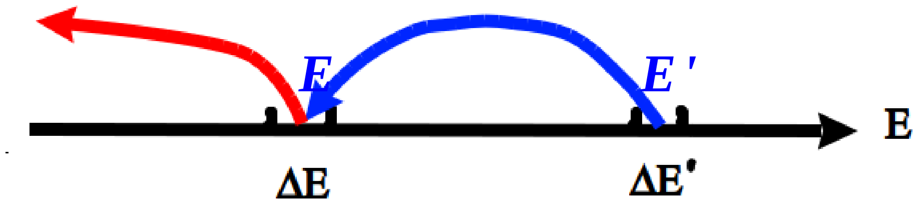




z=0.24

Adiabatic energy loss and pair-production loss with $\Delta E/E_p \sim 10^{-3}$ may be well described in continuous energy loss approximation. But in case of pion photo-production, $\Delta E/E_p \sim 0.2$ and the *CEL* approximation becomes less reliable.

Integro-differential and *FP* equations



$$R(E',E,t)=\frac{dP}{dt}(E',E,t)$$

$$E'=E+\varepsilon$$

$$\frac{d\varphi}{dt}(E,t)=-[\int_0^E d\varepsilon\, R(E,\varepsilon)]\times\varphi(E,t)+\int_E^\infty d\varepsilon\, R(E+\varepsilon,\varepsilon)\varphi(E+\varepsilon,t)+Q(E,t)$$

Using Taylor series expansion in powers of ε

$$R(E+\varepsilon,\varepsilon)\varphi(E+\varepsilon,t)\approx R(E,\varepsilon)\varphi(E,t)+\varepsilon\frac{\partial}{\partial E}R(E,\varepsilon)\varphi(E,t)+\frac{1}{2}\varepsilon^2\frac{\partial^2}{\partial E^2}R(E,\varepsilon)\varphi(E,t)$$

and permutation of integration and differentiation, we arrive at the *Fokker-Plank* equation

$$\frac{\partial}{\partial t}\varphi(E,t)-\frac{\partial}{\partial E}\left[b(E)\varphi(E,t)+\frac{\partial}{\partial E}\left(d(E,t)\varphi(E,t)\right)\right]=Q(E,t)$$

where

$$b(E,t)=\frac{dE}{dt}(E,t)=\int d\varepsilon\,\varepsilon R(E,\varepsilon),\quad d(E,t)=\frac{1}{2}\int d\varepsilon\,\varepsilon^2 R(E,\varepsilon)$$

M.Kachelrieß

V.Berezinsky, A.G., M.Kachelriess, Phys. Rev. Lett. **97** (2006) 231101,
Fokker-Plank approach was compared with *CEL* and *MC* calculations.

Diffusion in IMF

- *IMF* – intergalactic turbulent magnetic fields. $B \sim (10^{-16} - 10^{-8})$ G, $l_c \sim (0.1 - 1)$ Mpc.
- Propagation: rectilinear in a weak, ballistic and diffusive in a strong fields.
- Some information about *B* comes from *Faraday* rotations of the polarized radio emission in the extragalactic magnetic fields (clusters, radiolobes, filaments).
- If sources separation $d \ll (l_{diff}, l_{att})$, the spectrum has a universal shape.
- Anti-GZK effect – the steepening of the CR spectrum at $E \lesssim 2$ EeV.

R. Aloisio, V. Berezinsky, Astrophys. J. **612** (2004) 900-913 (propagation theorem)
R. Aloisio, V. Berezinsky, Astrophys. J. **625** (2005) 249-255 (Anti-*GZK*)

Diffusion in the expanding Universe

$$n(E,r)=\frac{1}{b(E)}\int_E^{\infty} dE_g\, Q(E_g)\times\frac{\exp\left[-\frac{r^2}{4\lambda(E,E_g)}\right]}{[4\pi\lambda(E,E_g)]^{3/2}};$$

r is distance from the source

$$\lambda(E,E_g)=\int_E^{E_g} d\varepsilon\frac{D(\varepsilon)}{b(\varepsilon)};\qquad \tau(E,E_g)=\int_E^{E_g}\frac{d\varepsilon}{b(\varepsilon)};$$

S.I. Syrovatskii, Sov. Astron. J., **3**, (1959) 22

$$\frac{\partial n}{\partial t}-b(E,t)\frac{\partial n}{\partial E}+3H(t)\,n-\frac{\partial b(E,t)}{\partial E}\,n-\frac{D(E,t)}{a^2(t)}\nabla_x^2 n=\frac{Q(E,t)}{a^3(t)}\,\delta^3(\vec{x}-\vec{x}_g),$$

Diffusive solution for a single source in the expanding Universe with an account for energy losses

$$n(\vec{x},E)=\int_0^{z_g}\frac{dz}{H(z)}Q(\mathcal{E}_g,z)\,\exp\left[\int_0^{z}\frac{dz'}{(1+z')H(z')}\frac{\partial b(\mathcal{E}',z')}{\partial\mathcal{E}'}\right]\times\frac{\exp[-(\vec{x}-\vec{x}_g)^2/4\lambda(E,z)]}{[4\pi\lambda(E,z)]^3/2}$$

$$\lambda(E,t,t')=\int_t^{t'} dt''\frac{D(\mathcal{E}'',t'')}{a^2(t'')};\qquad \mathcal{E}'=\mathcal{E}(t',E,t)\quad -\textit{the characteristic line}$$

V. Berezinsky, A.G., Astrophys. J. **643** (2006) 8
V. Berezinsky, A.G., Astrophys. J. **669** (2007) 684
R. Aloisio, V. Berezinsky, A.G., Astrophys. J. **693** (2009) 1275

UHECR spectra with diffusion

Let sources are located in vertices of cubic grid with separation d = (20 - 100) Mpc. Magnetic field is described by (B_c, l_c); l_c is the basic scale of the turbulence and B_c is the coherent magnetic field on this scale. The measured flux is a sum of contributions from all sources

$$J(E)=\frac{c}{4\pi}\sum_{i,j,k} n(x_{i,j,k},E), \quad with \quad x_{i,j,k}=d\sqrt{\left(i+\frac{1}{2}\right)^2+\left(j+\frac{1}{2}\right)^2+\left(k+\frac{1}{2}\right)^2}$$

The critical energy E_c may be defined from the Larmor radius in this field, i.e. when $r_L(E_c) = l_c$.
For protons $E_c = 0.93\times(B_c/1\ nG)\ EeV$.

At $E \gg E_c$ the diffusion coefficient rapidly grows and the spectrum becomes 'universal' $D(E)=\frac{1}{3}\frac{c\,r_L^2(E)}{l_c}$.

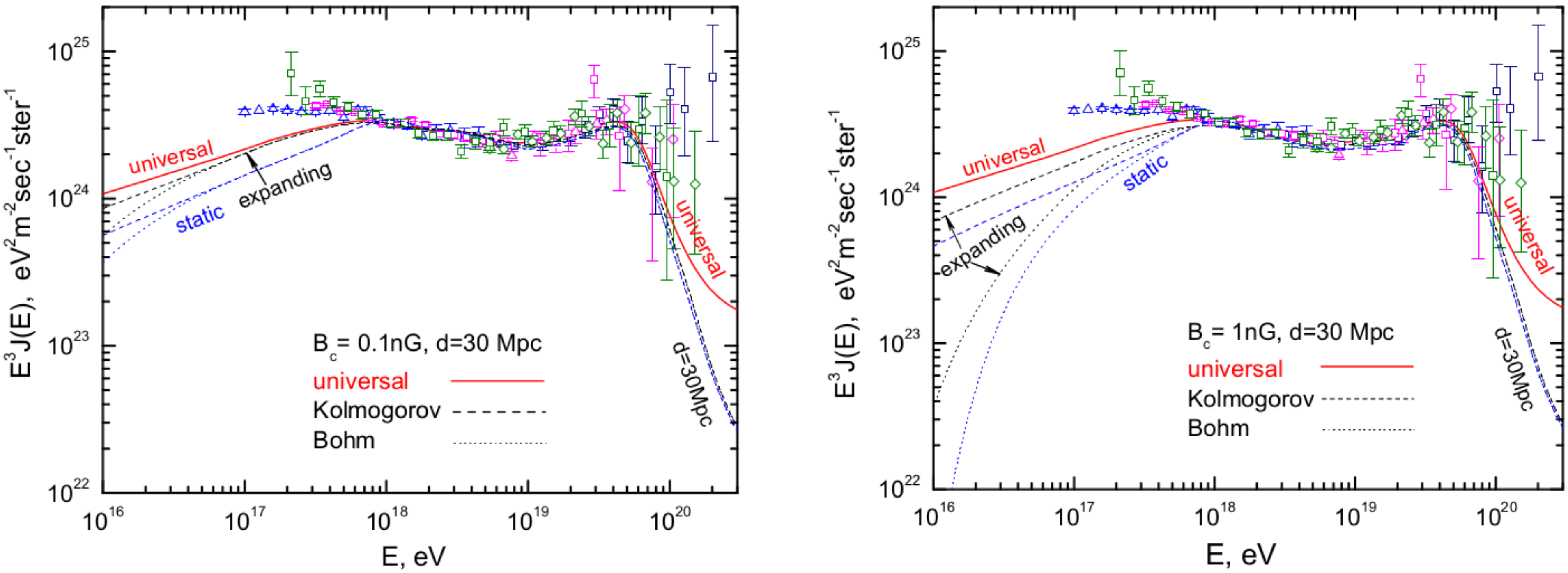
At "low" energies, when $r_L \lesssim l_c$, 3 types of diffusion coefficients were considered:

1) energy-independent diffusion coefficient $D=\frac{1}{3}c\,l_c$,

2) the *Bohm* diffusion coefficient $D_B(E)=\frac{1}{3}c\,r_L(E)$,

3) the *Kolmogorov* diffusion coefficient $D_K(E)=\frac{1}{3}c\,l_c\left(\frac{r_L(E)}{l_c}\right)^{1/3}$.

Comparison with static solutions



Best fit: $\gamma_g = 2.7$, $L_0 = 2.4 \times 10^{45}$ $erg/Mpc^3\ yr$ for expanding universe,
$\gamma_g = 2.65$, $L_0 = 5.7 \times 10^{44}$ $erg/Mpc^3\ yr$ for static universe

Superluminal propagation

Diffusion is described by *non-covariant* second order partial differential equation.
Its solutions comprise a superluminal signal. The density of particles should not change immediately at large distances from the source when there some changes occur.

The similar problem in *QM* for *Schrödinger* equation was discussed in

J. Dunkel, P. Talkner, P. Hänggi, Phys. Rev. D**75** (2007) 043001.

For relativization authors used the approach of *Ferencz Jüttner*

F. Jüttner, Ann. Phys. (Leipzig), **34** (1911) 856,

who derived the relativization of *Maxwell-Boltzmann* distribution for $k_B T >> mc^2$.

Generalization of this approach in application to diffusion of *UHECR* in the expanding Universe was proposed in

R. Aloisio, V. Berezinsky, A.G., Astrophys. J. **693** (2009) 1275.

Venya valued this approach highly and believed that it would be important in the future.

Superluminal propagation, cont.

In terms of new variables, generalizing the static Jüttner solution to time-dependent form

$$\zeta(t)=\int_{t}^{t_0}\frac{c\,dt}{a(t)},\qquad \lambda(E,t,t')=\int_{t'}^{t}dt''\,\frac{D(\mathscr{E}'',t'')}{a^2(t'')},\qquad \alpha(E,t)=\frac{\zeta^2(t)}{2\lambda(E,t)},\qquad \xi(t)=\frac{x_s}{\zeta(t)},$$

and using the propagator

$$P_{gJ}(E,t,x_s)=\theta(1-\xi)\,\frac{\xi^3}{x_s^3(1-\xi^2)^2}\times\frac{\alpha(E,\xi)}{4\pi K_1[\alpha(E,\xi)]}\times\exp\left[-\frac{\alpha(E,\xi)}{\sqrt{1-\xi^2}}\right]$$

the solution becomes

$$n(E,x_s)=\frac{1}{4\pi c x_s^2}\int_{\xi_{min}}^{1}d\xi\,\frac{\xi}{1+z(\xi)}\times\frac{Q[\mathscr{E}_g(E,t)]}{(1-\xi^2)^2}\times\frac{\alpha}{K_1[\alpha]}\times\exp\left(-\frac{\alpha}{\sqrt{1-\xi^2}}\right)\times\frac{dE_g}{dE}$$

Here $K_1(\alpha)$ is the modified *Bessel* function, dE_g/dE factor is the same as in the *CEL* approach. For $\xi\approx 1$ and $\alpha \ll 1$ we have the rectilinear case, and for $\xi < 1$ and $\alpha \gg 1$ the diffusive propagation is described. The generalized Jüttner solution interpolates between these regimes.

Spectrum with the *Jüttner* solution

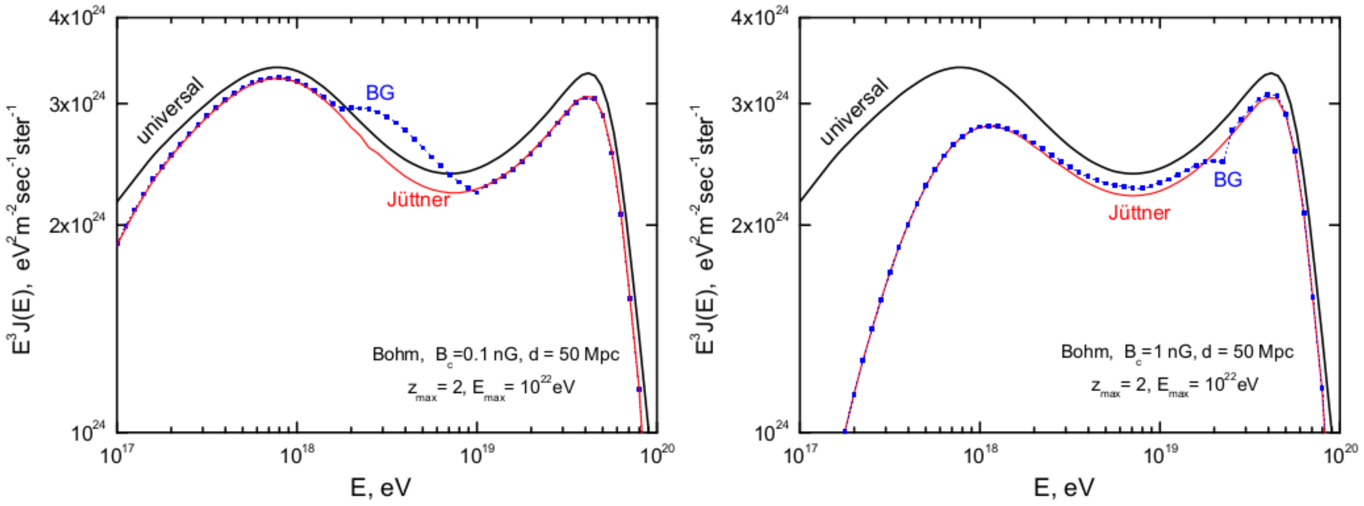
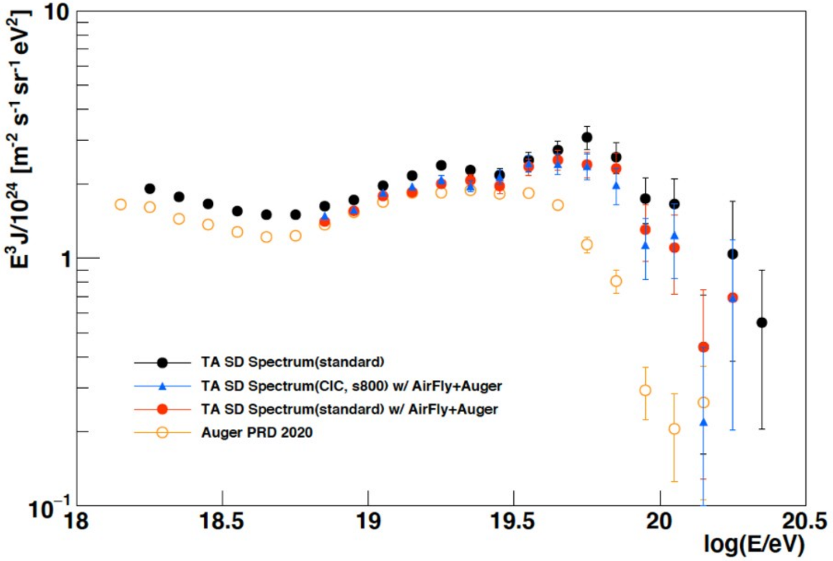
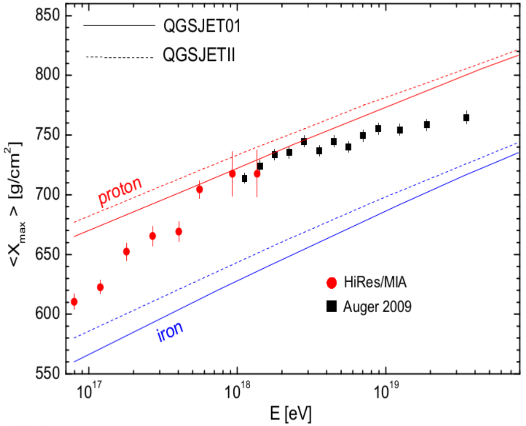


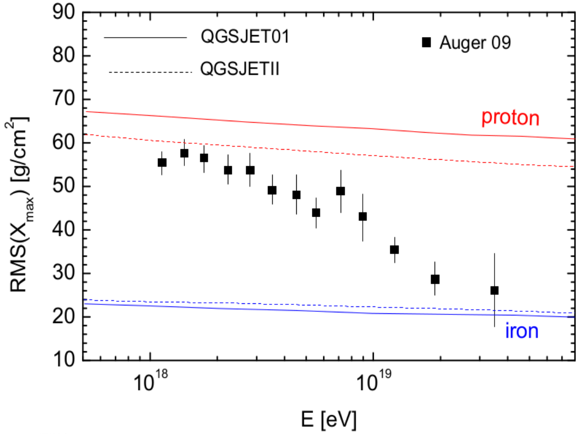
Fig. 2.— Comparison of the Jüttner solution with the combined diffusive and rectilinear solution (BG dotted curves) from work (Berezinsky & Gazizov 2007). The left panel shows the case $B_c = 0.1$ nG, and the right panel $B_c = 1$ nG, the distance between sources $d =$ 50 Mpc in both cases and $\gamma_g = 2.7$. The universal spectrum is also presented for $\gamma_g = 2.7$. The features seen in the BG spectra are artifacts produced by assumption about transition from diffusive to rectilinear propagation (see text). These features are small: note the large scale on the ordinate axis.

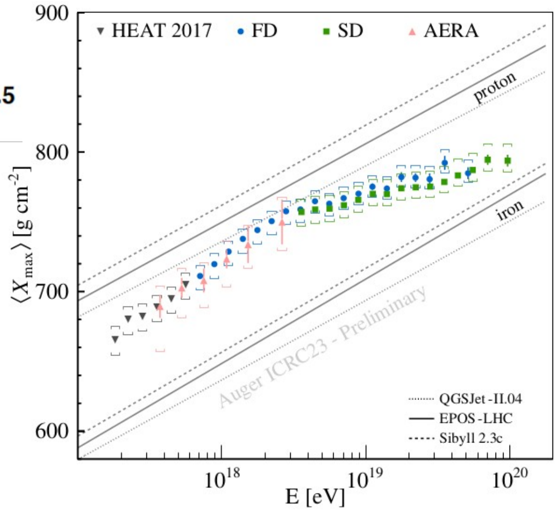
From *R. Aloisio, V. Berezinsky, A.G.*, Astrophys. J. **693** (2009) 1275

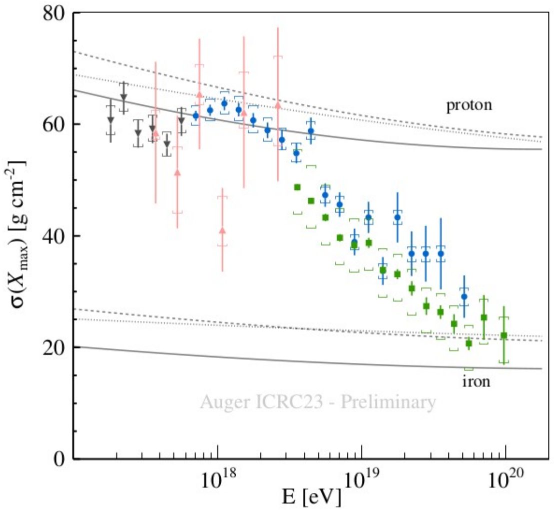
Tension with PAO data











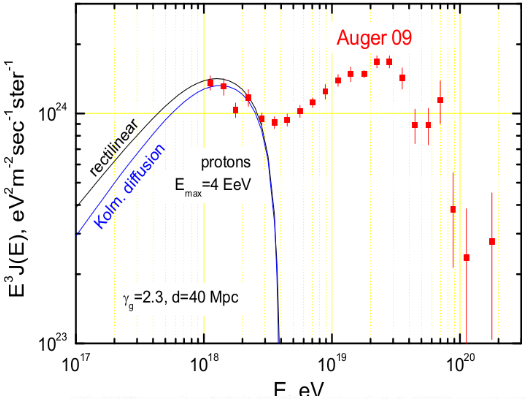
After rescaling the *PAO* and *TA* spectra coincide below GZK cutoff, but still differ at highest energies. The $\langle X_{max} \rangle$ and $\sigma(X_{max})$ indicate the ever heavier composition at *E > 3 EeV*.

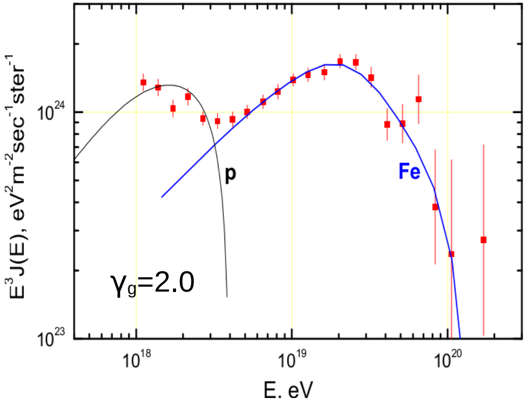
A.Watson

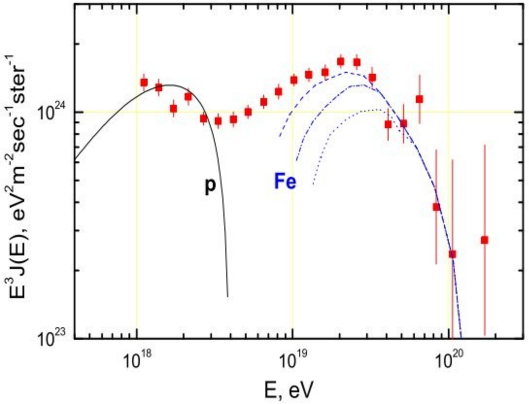
Disappointing model

R. Aloisio, V. Berezinsky, A.G., Ultra High Energy Cosmic Rays: The disappointing model, Astropart. Phys. **34** (2011) 620-626.

Assumptions: extragalactic protons at $E \sim (1\text{-}3)$ EeV, $E^p_{max} = (4 - 10)$ EeV; rigidity-dependent acceleration of nuclei $A(Z)$ in sources up to $E^A_{max} = Z \times E^p_{max}$; $E^{Fe}_{max} = (100 - 200)$ EeV.







with '*diffusion cutoff*' for 3 different sets of $\{B_c, l_c, d\}$

- Energy of nucleons in nuclei is small → hence no π's → no ν-fluxes.
- No *GZK*-cutoff on protons. The nuclei *GDR* photo-disintegration feature in the spectrum is similar to *GZK* on *p*'s.
- In case of strong intergalactic magnetic fields, the arrival correlation with sources will be lost.

$$E_{cut} \sim 24 \times \frac{Z}{26} \times \frac{B_c}{1\ nG} \times \frac{l_c}{1\ Mpc}\ EeV$$

Thanks to *Alan Watson* for encouraging us to write this paper and for valuable advices.

Spectra of UHE nuclei

- A method of analytic calculations of UHE nuclei spectra was proposed in

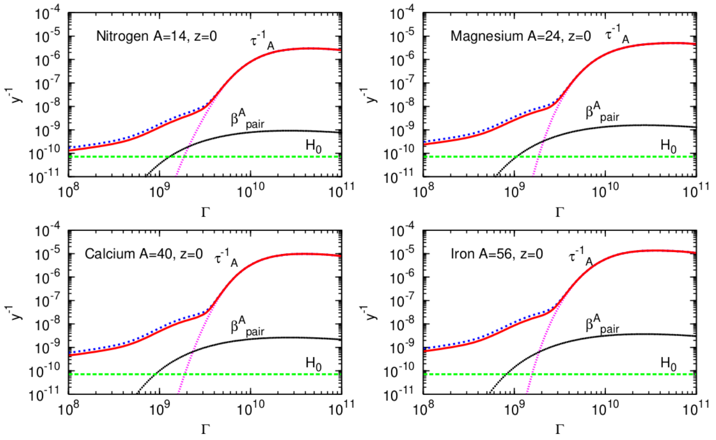
  R.Aloisio, V.Berezinsky, S.Grigorieva,
  Astropart.Phys. 41 (2013) 73, (I) the case of *CMB*
  Astropart.Phys. 41 (2013) 94, (II) the general case of *CMB&EBL*

- Photo-disintegration practically does not change the Lorentz-factor of nuclei; only red-shift and e^+e^--production energy loss change it:

$$\left(\frac{1}{\Gamma}\frac{d\Gamma}{dt}\right) \equiv \beta^A_{pair}(\Gamma,t) = \frac{Z^2}{A}\beta^p_{pair}(\Gamma,t)$$

- The rate of photo-disintegration is given by where $\sigma(\epsilon_r,A)$ and $\nu(\epsilon_r)$ are cross-section and multiplicity of secondary nuclei.

$$\frac{dA}{dt} = \frac{c}{2\Gamma^2}\int_{\epsilon_0(A)}^{\infty} d\epsilon_r\, \epsilon_r\, \sigma(\epsilon_r, A)\, \nu(\epsilon_r) \int_{\epsilon_r/2\Gamma}^{\infty} d\omega\, \frac{n_\gamma(\omega)}{\omega^2},$$



The basic kinetic equation for space density of A-nuclei $n_A(\Gamma, t)$:

$$\frac{\partial n_A(\Gamma,t)}{\partial t} - \frac{\partial}{\partial \Gamma}\left[n_A(\Gamma,t)\, b_A(\Gamma,t)\right] + \frac{n_A(\Gamma,t)}{\tau_A^{tot}(\Gamma,t)} = Q_A(\Gamma,t)$$

τ_A is the photo-disintegration life-time.

MC simulations

MC codes for simulating the propagation of high-energy particles in the Universe.

- *R. Aloisio, D. Boncioli, A.F. Grillo, S. Petrera, F. Salamida,* **SimProp**, JCAP **1210** (2012) 007

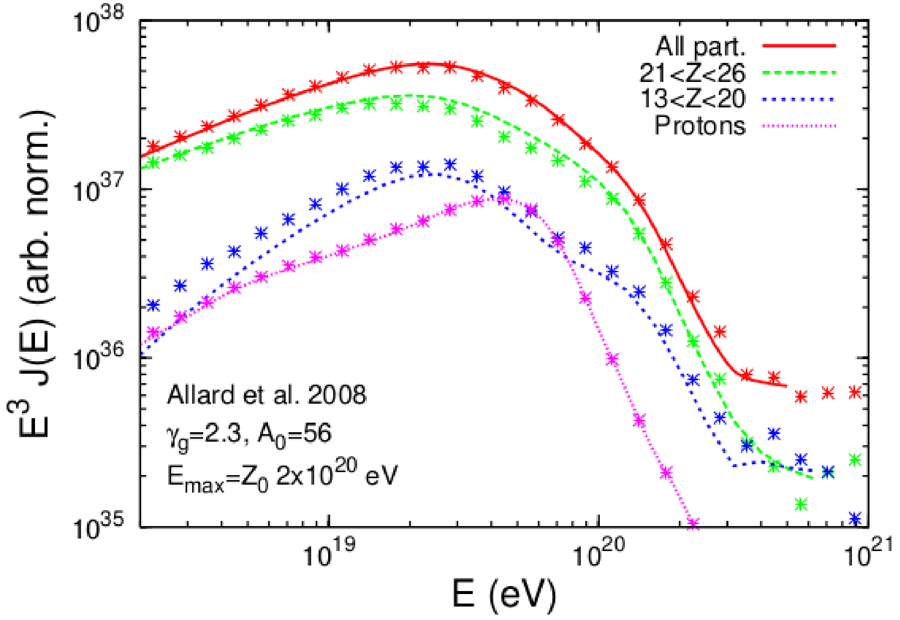
  Results of simulations were tested by comparison with those obtained by direct solving of the kinetic equations for propagation of UHECR.

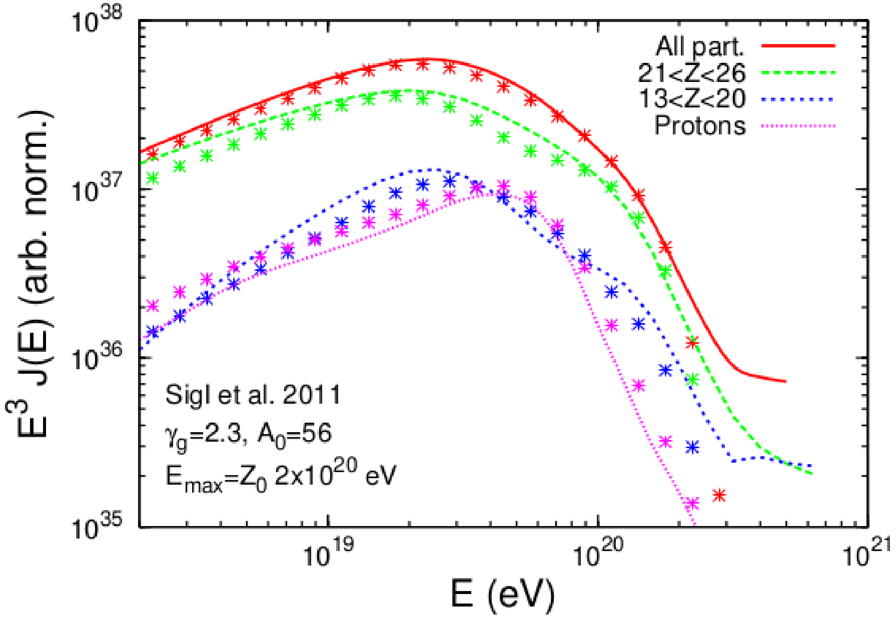
- *R. A. Batista, J. B. Tjus, J. Dörner, A. Dundovic, B. Eichmann, A. Frie, Ch. Heiter, M. R. Hoerbe, K.-H. Kampert, L. Merten, G. Müller, P. Reichherzer, A. Saveliev, L. Schlegel, G. Sigl, A. van Vliet, T. Winchen,* **CRPropa 3.2**, JCAP, **09** (2022) 035

  The propagation in diffusion-dominated domains is included with an accurate account for the development of e.-m. cascades. CRPropa handles both ballistic and diffusive propagation.

MC simulations are straightforward, but slow and time-consuming. It is difficult to study the influence of various source parameters on the observed *UHECR* spectrum. We didn't use this approach.

Comparison of analytical and MC





Pure *Fe* is injected at the source. Analytical calculations are compared with two MC simulations. An agreement is good.
Note, that our knowledge of nuclei photo-disintegration cross-sections is limited.
A better account for magnetic fields, both in sources and in intergalactic space, is needed.

The Book

Astrophysics of Cosmic Rays
V.S. Berezinskii, S.V. Bulanov,
V.A. Dogiel, V.L. Ginzburg, V.S. Ptuskin
Amsterdam: North-Holland, 1990,
edited by ***V.L. Ginzburg*****.**

Астрофизика космических лучей
В.С. Березинский, С.В. Буланов,
В.А. Догель, В.Л. Гинзбург, В.С. Птускин
Москва: "Наука", 1984.
Moscow, Izdatel'stvo Nauka, 1984, 360 p.
In Russian.

Venya valued this book highly and was proud of his participation in it. Despite the fact that it was written a long time ago, it has not lost its value even today.

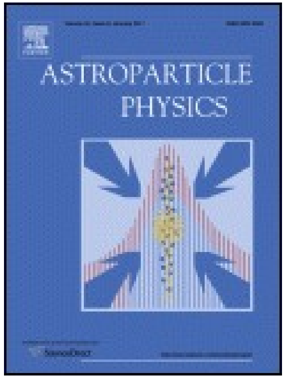
In this survey of cosmic-ray astrophysics, results of observations and experiments are summarized, and general theoretical questions (such as the selection of cosmic-ray models) are elucidated. Particular attention is given to the origin of cosmic rays observed at the earth, the propagation and acceleration of cosmic rays in interstellar space, superhigh-energy cosmic rays, the proton-nuclear component of cosmic rays in the Galaxy (including the chemical and isotopic composition), and the electron component and radio astronomy. Principles and results of gamma- and X-ray astronomy, and of high-energy neutrino astronomy are examined.

VS and ‘Astroparticle Physics’

Problem with publications: *VS* and *Hector R. Rubinstein* (Uppsala and Stockholm U.): a new place is needed to publish works at the intersection of particle physics, cosmology, radio-, *X*-ray- and gamma-astrophysics, cosmic ray physics and neutrino astrophysics.

H. Rubinstein - one of the editors of *Physics Letters B*.
VS - one of the editors of Soviet "*Letters to the Astronomical Journal*".

Today it is trivial, but at that time works "at the intersection" were published in various "physics" or "astronomical" journals. → **Astroparticle Physics**



Astroparticle Physics was established in 1992. It is published monthly by *North-Holland*, an imprint of *Elsevier*.

Both became the first editors of this journal. And for many years Venya was engaged in the difficult and time consuming editorial work.

G.T.Zatsepin

Important ideas

VS: - "In decays of *GZK-π's*, *ν's* with *E*$\gtrsim 10^{18}$ *eV* should be formed".
GT: - "Perhaps we already see them! $\sigma_{\nu N}(E) \propto E$, so these *ν's* generate the observed ultra-high energy *CRs* at $E > 3x10^{19}$ *eV*".

V.S. Berezinsky, G.T. Zatsepin,
Cosmic rays at ultra high energies (neutrino?), Phys. Lett. ***28B****, 423, 1969;*
Cosmic neutrinos of superhigh energy, Yad.Fiz. ***11*** *(1970), 200-205.*

There were authors who called them *BZ*-neutrinos. But… cosmogenic *ν's.*

A.Yu. Smirnov

Cross-sections, sources and fluxes of these *ν's*, methods of their registration:
V.S. Berezinsky and A.Yu. Smirnov,

- *Astrophysical upper bounds on neutrino-nucleon cross-section at energy* $E \geq 3x10^{17}$ *eV, Phys. Lett. B* ***48*** *(1974) 269-272;*
- *Cosmic neutrinos of ultra-high energies and detection possibility, Astrophys. Space Sci.* ***32*** *(1975) 461-482.*

The observed energy densities of the *X*- and *γ*-ray spectra constrain the expected flux of cosmogenic neutrinos. It was the beginning of *"multimessager approach"*.

Constrains from γ-ray and ν-fluxes



M.Kachelrieß S.Ostapchenko O.Kalashev

V. Berezinsky, A.G., M. Kachelrieß, and S. Ostapchenko, Restricting *UHECRs* and cosmogenic neutrinos with Fermi-LAT, *Phys. Lett. B**695** (2011) 13*

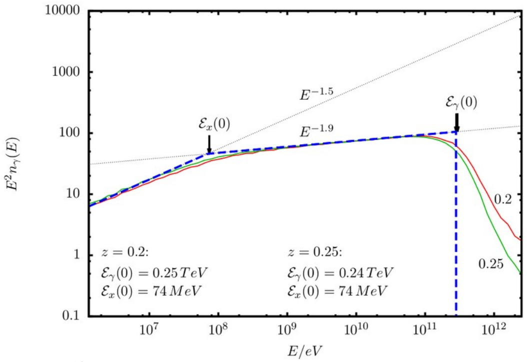
V. Berezinsky, O. Kalashev, High energy electromagnetic cascades in extragalactic space: physics and features, Phys. Rev. D**94** (2016) 023007

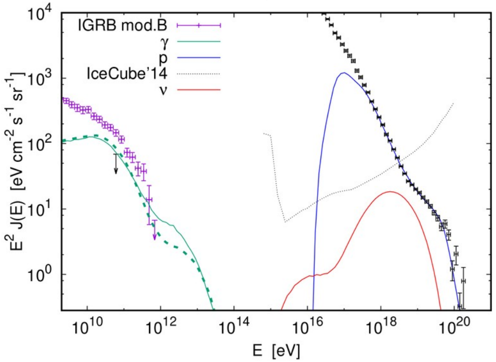
$EGBL: \omega_{cas} \leqslant 8.3\times10^{-8}\, eV/cm^3$: more stringent restriction; analytical approach vs. numerical, dependence on z.

V. Berezinsky, A.G., O. Kalashev, Cascade photons as test of protons in *UHECR*, *Astropart. Phys. **84** (2016) 52.*

Fermi-Lat EGBL constraint at *E~(580−820) GeV (HEB)*.
The γ-ray constraint is stronger than the ν one (*IceCube*).
Steeply decreasing spectrum, small z_{max}, nuclear admixture.

$EGBL: \omega_{cas}^{max} \approx 5.8\times10^{-7}\, eV/cm^3$
no dip-model with source evolution, the flux of cosmogenic ν's is strictly limited.





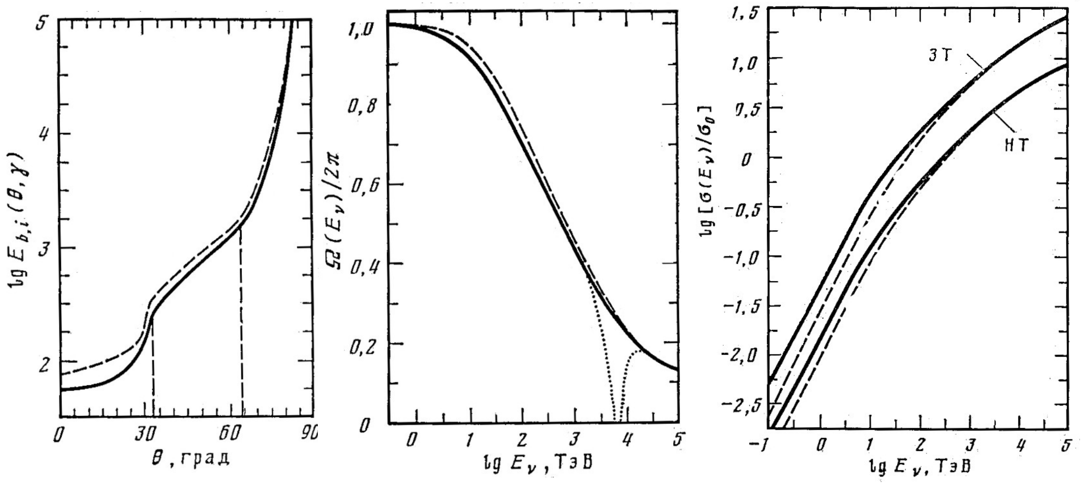
G.T.Zatsepin I.L.Rosental

Penetration of ν's through the Earth

The growth of the νN-cross-section leads to the opacity of the Earth for the fluxes of high-energy neutrinos.

V.S. Berezinsky, A.G., G.T. Zatsepin, I.L. Rozental

On Penetration of high-energy neutrinos through Earth and a possibility of their detection by means of EAS, Sov. J. Nucl. Phys. ***43*** *(1986) 406.*



Supra*horizontal and* ***sub****horizontal EAS:*
EAS from *ν's* and *EAS* from *μ's* (*ШАЛОН & ШАЛОМ*). Comparison of future giant *EAS* detectors vs. *GWD*.
Absorption *(CC)* and regeneration *(NC)* of *ν*-fluxes in the Earth, including the resonant absorption of $\bar{\nu}_e$,

$$\nu_\mu + N \to \mu(\nu_\mu) + X, \quad \bar{\nu}_e + e^- \to W^- \to X$$

as well as the density distribution in the Earth were taken into account.

EAS-TOP and ν's upper limit

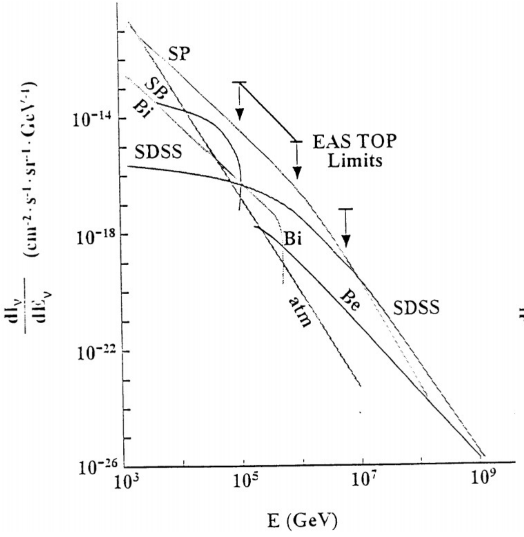
G.Navarra

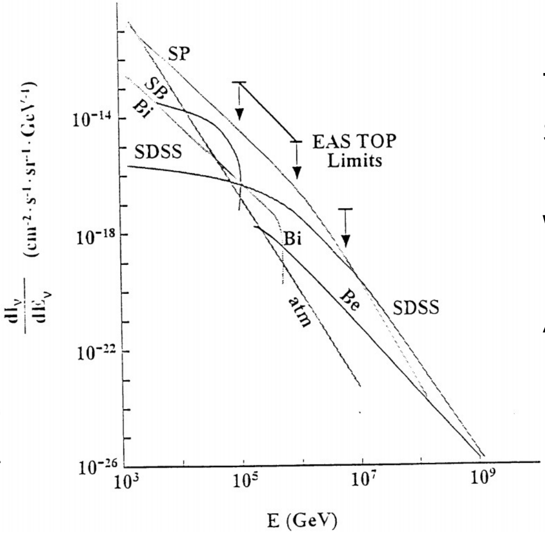
M.Aglietta,… V.Berezinsky,... ***G.Navarra*** *et al.,* The Limit to the UHE extraterrestrial neutrino flux from the observations of horizontal air showers at EAS-TOP, *Phys. Lett. B* ***333*** *(1994) 555.*

EAS-TOP: *Campo Imperatore*, *LNGS*, Italy – 2000 m a.s.l. on the slope of *Mount Aquila* ~15°.

Measurement of *CR* with $E = 10^{13} - 10^{16}$ eV; $S_{e.m.} \sim 10^5\ m^2$, $S_\mu \sim 140\ m^2$.

VS noted that it's possible to obtain a limit on the flux of horizontal events from ν's and μ's.



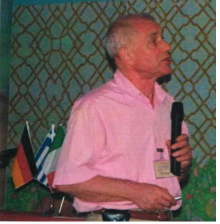


Interestingly, many underground detectors, including those that are no longer operational (e.g. FREJUS), subsequently used this idea to introduce stricter restrictions. The best was the DUMAND prototype with only 1 string of photomultipliers, which was later torn off by underwater currents in the ocean. And it measured the ν-flux for only ~8 hours!

$$I_\nu(>100\ TeV) < 1.5\times10^{-8}\ cm^{-2}s^{-1}sr^{-1}$$

$$F_\mu(>30\ TeV) = 1.15\times10^{-11}\ cm^{-2}s^{-1}sr^{-1}$$

F. W. Stecker, C. Done, M. H. Salamon, and P. Sommers
Phys. Rev. Lett. **66**, 2697, Phys. Rev. Lett. **69**, 2738 (1992)



Some interesting facts about *VS*

- Unlike many of his Soviet colleagues, he spoke English. He was even asked to back up his friends with English at conferences. His talks were clear, precise and full of jokes.

- He had an exceptional memory, recited by heart long poems and prose. At a conference banquet in Trondheim, Norway in 2009, he suddenly began to recite the great Russian poet Pushkin. Many non-Russian speaking people were simply charmed with the beauty of the sound of poems. I was surprised by his action. Well, he deeply loved Russian culture, art and the Russian language itself.

- In his youth, he was a very athletic guy. As a boy, he had to fight a lot "until the first blood". He used to come home with torn clothes, but never complained.

- He played football for the Moscow regional team "Spartak". The coach scolded him for sometimes skipping training because of preparing for exams at the Moscow State University: - "What did you come here for? To play football or to waste time!"
VS studied excellently.

Interesting facts, cont.

- Despite his non-basketball height, he played in the *MSU* basketball team, had an accurate long-range shot, was a point guard.

- Nephritis stopped his sports career, he was on the verge - but survived! Thanks to the long recovery in the former royal palace and now the resort *Bayramaly* in Turkmenistan.

- Venya's **main interest** throughout his life **was physics**. But he also had an exceptional sense of humor, a talent for writing ("Physicists continue to joke"), was an art connoisseur, collected (together with his wife Julia) paintings, including "Russian avant-garde", and loved antiques.

- He was friends with many famous soviet theater artists, writers, fashion designers, and scientists. In many ways, thanks to his wife, who was his support all his life. She briefly outlived him and they are buried next to each other in the family grave in Moscow. And thanks to our colleagues from the *INR RAS*, who visit his grave.

- He was simply a very interesting person, a storyteller. Communication with Venya was a luxury.

- For many physicists in the world he was just the friend. And the confirmation we see here today.

Physicists continue to joke

Как работает физик-теоретик

В. Березинский

Я всегда думал, хотя и опасался высказывать эти мысли вслух, что теоретик не играет никакой роли для физики. При теоретиках это говорить опасно. Они убеждены, что эксперименты нужны только для того, чтобы проверять результаты их теоретических выводов, хотя на самом деле все обстоит как раз наоборот: законы устанавливаются экспериментально, а теоретики их только потом объясняют.

А объяснить, как известно, они могут любой результат.

Однажды мы закончили важный эксперимент по определению соотношения между двумя физическими величинами *A* и *B*. Я бросился к телефону и позвонил знакомому теоретику, который занимался тем же вопросом.

– Володя! Закончили! *A* оказалось больше *B*!

– Это совершенно понятно. Вы могли и не делать вашего опыта. *A* больше *B* по следующим причинам...

– Да нет! Я разве сказал: *A* больше *B*? Я оговорился – *B* больше *A*!

– Тогда это тем более понятно. Это вот почему...* Теоретиками обычно становятся неудачники-экспериментаторы. Еще студентами они замечают, что стоит им просто на пять-десять минут остановиться около любого прибора – и его можно даже не проверять, а прямо нести на свалку. Это преследует их всю жизнь. Однажды после семинара известный немецкий теоретик Зоммерфельд сказал своим слушателям: «А теперь посмотрим, как действует прибор, построенный на разобранном нами принципе». Теоретики гуськом просочились за Зоммерфельдом в лабораторию, поснимали очки и понимающе уставились на прибор. Слегка побледневший Зоммерфельд торжественно включил рубильник... Прибор сгорел.

* О Я.И. Френкеле рассказывают, что якобы в ФТИ в 30-е годы его изловил в коридоре некий экспериментатор и показал полученную на опыте кривую. Подумав минуту, Я.И. дал объяснение хода этой кривой. Однако выяснилось, что кривая случайно была перевернута вверх ногами. Кривую водворили на место и, немного поразмыслив, Я.И. объяснил и это поведение кривой.

"Ways to the unknown" No.3, 1963, later reprinted in the "Physicists continue to joke", «Mir», Moscow, 1968

How does a theoretical physicist work

V. Berezinsky

I always thought, although I was afraid to express this thought out loud, that the theorist plays no role for physics. It is dangerous to say this in front of theorists. They are convinced that experiments are needed only to test the results of their theoretical conclusions, although in reality everything is just the opposite: laws are established experimentally, and theorists only explain them later. And, as we know, they can explain any result. … Theorists are usually unsuccessful experimenters. Even as students, they notice that if they just stop for five or ten minutes near any device, they can simply take it straight to the dump without even checking it….
Do you believe, for example, that Newton sat under a tree and waited for an apple to fall on him in order to discover the law of universal gravitation? Nothing of the sort! He simply shied away from work. And I'm not even saying that it is at least dishonest to discover the law thanks to an apple and take all the credit for it.

D.V. Skobeltsyn

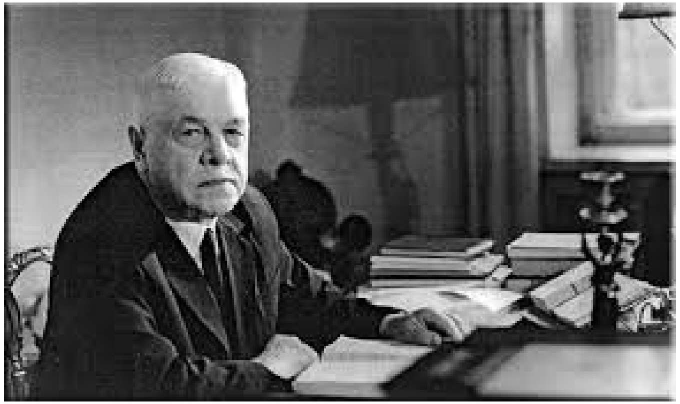
My meeting with D.V. Skobeltsyn.

For the first time I met Prof. D.V. Skobeltsyn very early, when I was a student of the Moscow University. As a student of G.T. Zatsepin, I had an access to FIAN. It had, as has it now, two entrances, the main one from the Leninsky Avenue, and another one from the Vavilov street. The entrance for private cars from the Leninsky Avenue was forbidden.

One day, entering FIAN from the Leninsky Avenue I met in the yard a big limousine ZIS-110, which could be used only by highest rank leaders of the country. The limousine stopped at the Institute building, but no one left it. Then rapidly the chauffeur appeared and opened the back door. A very unusual person exited the car. He was a tall, strong, gray-haired man, keeping of that time. He had a long elegant coat,accordingly the fashion of that time.

Seeing my bewildering, somebody behind me promptly said: "This is our Director".

In Russia it is not a custom for a student to say "hello" to the Director or to a famous professor of the Institute, unless they met and spoke before. Once, with my friend-student we met Professor Skobeltsyn at the Institute entrance and passed by without greetings.Thinking a bit I asked my colleague: why we did not say "good morning" to the Director? After a short consideration my friend answered: "Then why you don't say "hello" to the Lenin's monument at the entrance of FIAN every morning?"



Dmitriy Vladimirovich Skobeltsyn
The first to use the *Wilson* gas chamber, placed in a magnetic field, for quantitative examination of the *Compton* effect and cosmic rays. He first registered the *positrons*, although he could not prove their nature, he has been engaged in the study of wide atmospheric showers of cosmic rays. He opened together with the students the formation of electron-nuclear showers and nuclear cascade process.

D.V. Skobeltsyn #2

In my case it was the time of getting my first permanent position in FIAN. This appointment was questioned by the special service because of the imprisonment of my parents in 1937. However, formally this decision had to be taken and signed by the Director of the Institute.

As Prof. G.T. Zatsepin told me much later, Skobeltsyn in his presence read attentively the prescription concerning me, then silently took his famous Rollex fountain-pen and wrote "to enlist, Skobeltsyn". Then he cunningly glanced at Zatsepin and asked him with a smile: "Am I still the Director?"

My visit to D.V. Skobeltsyn.

Thanks to my age, at present I am the only alived Russian physicist who was speaking with the great Russian scientist Dmitrii Vladimirovich (here and below DV) Skobeltsyn.

In fact I met him twice, and these two meetings were separated by a few days.

The first invitation (1970?) was confusing.

I was working at home when the phone ringed and a women voice asked:

– Veniamin Sergeevich?

D.V. Skobeltsyn #3

deflected in a wrong direction. In our conversation with DV I mentioned that three positively charged electrons were found. DV corrected me, saying ”two”.
I said:
– In the journal ”Reports of the Academy of Sciences” you wrote ”three”.
He smiled and answered:
– Later I’ve made a new analysis and excluded one event as unreliable. It was published later, after my coming to Moscow.
I remember that I asked DV:
– Why you did not continue your measurements on coming back to Moscow?”
The answer was interesting:
– The cloud chambers were very complicated to run, and there were just a few persons in the world in which hands the cameras were functioning reliably.

V.L. Ginzburg

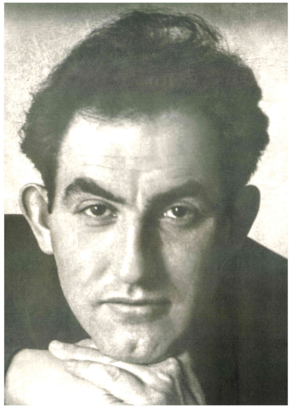
Vitaly Lazarevich, as I knew and remember him

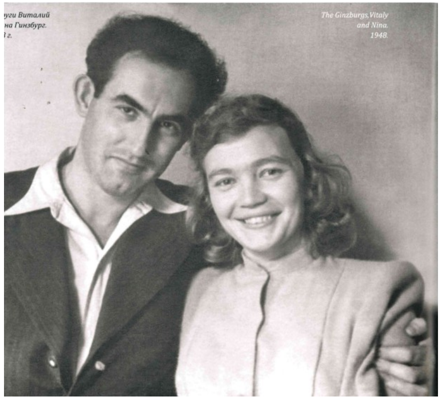
V. Berezinsky

From the book "Vitaly Ginzburg in recollections of friends and contemporaries"

P.N. Lebedev Institute of Physics 2011, p. 46 – 50

My work with Vitaly Lazarevich and my personal friendship with him (our families were tied with friendship) played a tremendous role in my life. It is not only that I belonged to one of the schools created by VL, the physics of cosmic rays, and that I worked with VL and his group in this field. The main thing is that I saw a new style, which I would call "an equationless attack of a problem." I did not even try to emulate this method; for that one would need to have, as A.S. Pushkin said, "a miracle gift of providence". VL could see a new problem or solve an existing one while listening to someone else's talk. He had a "side vision", a wide circle of associations, and all that field was open when he listened to a talk or discussed somebody's idea. This is not something one can learn, but I taught myself to hear the faint echos of new ideas or analogies while listening to other people's talks and without being embarrassed to "switch off" and think about them, securing them in my memory and consciousness. In that I see the school of VL; he himself immediately "sound-tracked" his thoughts. He used to say that for this "incontinence of thought" people secretly called him an upstart in his youth and a genius in his old age, adding "but in essence I have not changed".





Memories

FROM MOSCOW TO SIBERIA AND BACK

I was evacuated from Moscow to Lenin-Kuznetskii (Siberia) just before the temperature reached its minimum. It was the last train with children, my sisters, Julia and Vita, left earlier. My aunt Rosa said I am too small (7 years old) to travel without mother, in spite of my bitter experience at 4 years old. This time she managed to get the position of head of the train-echelon with a strong obligation to be back to job in 7 days. As I learned later, our train was fired by a German plane in spite of Red Cross signs on the roofs of the train. It stopped, all children were pushed out of the wagons with cries: "run, run!" I was running with others, when somebody pushed me down and fell on me to protect from bullets. It was my aunt. The wagon roofs had small holes from bullets.

We reached Lenin-Kuznetskii and it was as cold there as in Moscow. We easily found the big house given by the town to children from Moscow and among them I saw to my

VS began writing his memories about his difficult childhood, his family, about the Second World War, but they were not finished. Problems with his vision and health also prevented him from doing this.

War II

HITLER'S ASSAULT TO RUSSIA AND MUSSOLINI CONTRIBUTION

Plan Barbarossa assumed the beginning of the war with Russia on May 15, 1941, when ground in Russia becomes dry enough for heavy tanks. On October 27, 1940 Hitler obtained the secret information that Italy starts very soon the war with Greece. He sent a telegram to Mussolini and made the urgent appointment with him in Florence next day. He arrived there in the morning of October 28 and met Mussolini who said: "Our army entered Greece at 6 o'clock taday. Don't worry, everything will be finished in a few days". In a few days Mussolini asked Hitler to help Italian army and to enter Greece. The beginning of the war with Russia was postponed until June 22, 1941. (This story and dates are taken from the book of Raymond Cartier "Secrets of the war. By materials of the Nuremberg trials").

The consequences of this six-week delay were very dramatic for Germany, because Gud-

MOSCOW, DECEMBER 1941: GUDERIAN, KATUKOV AND MYSELF.

This part is written for a foreign, mostly Italian, reader. It is a mixture of history from reliable documents and recollections of a 7 year old child. Talking with my Italian friends during 27 years of my living in Italy I discovered that their knowledge about the Battle for Moscow with Hitler's troops in winter 1941 is very far from reality, and the name of colonel Katukov is perfectly unknown.

I was evacuated from Moscow in the beginning of December 1941 with a kindergarten which I attended, and this evacuation was organized by the Moscow administration. Connection with general Heinz Guderian and colonel Mikhail Katukov needs explanation.

My parents were mobilized in the beginning of war, the father as a retired officer (the captain) and mother as a medical doctor to serve in a military hospital. My sister Yulia and I were moved to aunt Rosa, the sister of our mother, who lived with her 11 year old daughter Victoria (Vita) in a small, 12 m^2 room, in a big municipal apartment.

The war started with the attack of German troops on June 22, 1941, without declaring the war. The German tanks moved especially fast through Ukraine. On the morning of June 22, Molotov told the population by radio about the German attack. Stalin was a few days later and very unexpectedly he addressed the audience: "Brothers and Sisters" (like priest in the church), instead of traditional "comrades".

War II

HITLER'S ASSAULT TO RUSSIA AND MUSSOLINI CONTRIBUTION

Plan Barbarossa assumed the beginning of the war with Russia on May 15, 1941, when ground in Russia becomes dry enough for heavy tanks. On October 27, 1940 Hitler obtained the secret information that Italy starts very soon the war with Greece. He sent a telegram to Mussolini and made the urgent appointment with him in Florence next day. He arrived there in the morning of October 28 and met Mussolini who said: "Our army entered Greece at 6 o'clock taday. Don't worry, everything will be finished in a few days". In a few days Mussolini asked Hitler to help Italian army and to enter Greece. The beginning of the war with Russia was postponed until June 22, 1941. (This story and dates are taken from the book of Raymond Cartier "Secrets of the war. By materials of the Nuremberg trials").

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VS with colleagues #1

VS with Alexey Smirnov, LNGS

Vjacheslav Dokuchaev, Masahiro Teshima
and VS, LNGS
(and partially Yuriy Eroshenko, sorry!)

VS with colleagues #2

Svetlana Grigorieva
Dip model etc.
Diffusion of nuclei

Yuriy Eroshenko, Svetlana Grigorieva
Aleksey Malgin, Vjacheslav Dokuchaev
Small-scale clumps of dark matter,
SUSY DM annihilation...

With Michael Kachelrieß, LNGS
Supersymmetric superheavy dark matter,
Ultrahigh energy cosmic rays spectra
in top-down models...

Photos with VS #1

Photos with VS #1

Photos with VS #2





Photos with VS #3






Thanks to the organizers
and to all the conference participants
for the memories of
Veniamin Sergeyevich Berezinsky

and thanks for attention.

VS and O.F. Prilutsky

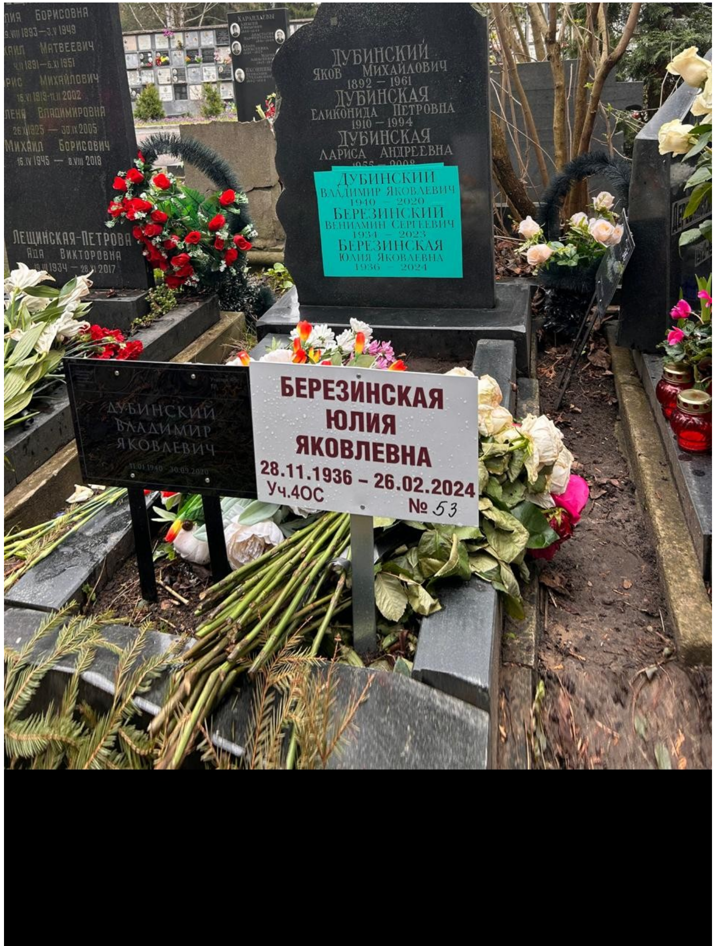
Recalling his early work with O. Prilutsky,

V. S. Berezinsky, 0.F. Prilutsky
Pisma Astron. J. (USSR) **3** (1977) 152;
Pisma Astron. J. (USSR) **3** (1977) 267;
Proc. of DUMAND Summer Workshop / Ed. A. Roberts, (1976) 229;
Pulsars and Cosmic Rays in Dense Supernova Shells
Astron. and Astrophys., **66** (1978) 325,

VS told how the idea of accelerated protons' escape from the magnetized region of young pulsars via neutrons production had arosen. It came during a joint walk in *Izmailovo*, Moscow. They talked in turn…

Also they discussed the generation of neutrinos vis $pp \to \pi's \to \nu's$ in a dense shell (cocoon) of hidden sources.

Danilovskoye Cemetery



Moscow
Danilovskoye Cemetery