Multi-messenger observations with cosmic rays, gamma-rays and neutrinos, present status and future perspectives

D. Semikoz
APC, Université Paris Diderot, CNRS/IN2P3, CEA/IRFU, Observatoire de Paris, Sorbonne Paris Cité, France
E-mail: dmitri.semikoz@apc.univ-paris7.fr

Abstract. In lectures presented at the ISAPP-Baikal summer school I summarised the status and expectations of the multi-messenger astroparticle physics observations using astrophysical neutrinos, cosmic rays and gamma-rays. In this lectures I presented a summary of existing observations as well as an interpretation of the results.

1. Introduction
The development of optical astronomy over last 400 years has lead to many discoveries. However significant progress in understanding of the nature of astrophysical objects and phenomena was done when astrophysical observations from the relatively narrow optical band were extended to the wide range of wavelength from the radio to X-rays in the second half of 20th century. This became possible using satellites to overcome absorption in Earth atmosphere in all wave bands except for optical and radio.

The next challenge came with gamma-rays observations. First, one cannot use antennas to detect high energy photons with GeV energies or, equivalently, with a wavelength of the nucleus size. Instead one can use particle physics detectors to study secondaries from gamma-ray interactions with target material. In particular, at energies $E > 100$ GeV one can detect Cherenkov light produced by secondary electrons and positrons in atmosphere.

Development of this field led to detection of the first gamma-ray source Crab pulsar in 1987. With this discovery, the high energy gamma-ray astrophysics, one of the major fields in astroparticle physics, was born. At high energies $E > 100$ GeV, the gamma rays cannot travel freely through the Universe due to the absorption on photon background. Thus, the Universe is not transparent to photons in the TeV energy range, and one has to find other messengers to study the Universe at high energy.

Another source of our knowledge of astrophysical objects is charged nuclei, called cosmic rays, which come from outside of the Solar system to the Earth. They were observed in the last 100 years over an energy range from GeV to $10^{20}$ eV. Unfortunately due to their non-zero electric charge, nuclei are significantly deflected both by the Galactic and extragalactic magnetic fields. Thus, the direct information about their sources is lost, except for the highest energies $E \sim 10^{20}$ eV. However at such energies protons themselves cannot freely travel through the Universe due to their interaction with the Cosmic Microwave Background (CMB). This restricts the search
of cosmic ray sources to the nearby part of the Universe, up to 100 Mpc. Thus, cosmic rays can serve as messengers only for local extragalactic sources.

With the discovery of neutrino in 1959, a new hope was born to study the Universe with the help of those neutral weakly interacting particles. They freely propagate through the Universe without interactions, from astrophysical sites of their production to an observer on Earth. In the energy range between TeV and $10^{20}$ eV, they are the only messengers which can reach us from the high redshift objects. However due to the same weak interactions, their detection on Earth is very challenging.

Only in 2013 were the first astrophysical neutrinos discovered by IceCube experiment at the South pole. Since then, more than 100 astrophysical neutrinos were detected in all three possible channels with electron, muon and tau neutrinos. This field of the astroparticle physics has a bright future.

Multi-messenger observations with neutrinos and gamma-rays can shed light on the nature of hadronic processes in astrophysical sources. First of such observations was the famous discovery of neutrinos from the SN 1987A supernova explosion. Recently, evidence for neutrino flux was found from a distant blazar together with increased gamma-ray flux from the same object. This source challenged existing models of astrophysical neutrinos.

In the lecture notes below, we sum up the present status of astroparticle physics observations with cosmic rays and neutrinos. Detailed studies in gamma rays are overviewed in lectures of A. Neronov.

In Section 2 we discuss cosmic rays. In Section 3 we sum up the present experimental observations of astrophysical neutrinos and discuss multi-messenger observations, which shed light on the nature of neutrino sources.

2. Cosmic rays

![Figure 1](image1.png)

**Figure 1.** Cosmic ray flux of individual nuclei as a function of kinetic energy per nucleus directly measured by satellites or balloons from ref.[1].

![Figure 2](image2.png)

**Figure 2.** Cosmic ray flux measured by indirect detection at high energies from [2].

Cosmic rays are charged nuclei and electrons accelerated in astrophysical objects and propagating to the Earth in Galactic and extragalactic magnetic fields. Cosmic rays at energies
below 100 TeV are observed directly by particle detectors on satellites or balloons. Such detectors can measure both the cosmic ray particle energy and its charge. In this way the flux can be reconstructed for individual nuclei. In Fig. 1 we plot fluxes of individual nuclei as functions of kinetic energy per nucleon measured by the direct measurement experiments. Unfortunately cosmic ray flux quickly drops as a function of energy to 1 particle per year per \( m^2 \) at energies \( E > 10^{15} \text{eV} \). Thus at such very high energies typical \( m^2 \) detectors cannot collect enough statistics to register it.

Cosmic rays interacting in atmosphere produce secondaries, which in turn interact. This cascade process ends up with a large number of \( E < 100 \text{MeV} \) electrons, positrons, photons, and muons. For CR with primary energies \( E < 10^{14} \text{eV} \), most of the secondaries except muons disappear high in atmosphere, but above this energy secondaries can reach the surface, where they can be measured by a grid of detectors. From the flux of secondary particles, one can reconstruct the initial energy of a cosmic ray. From the signal front curvature detected by a network of detectors, one can get the arrival direction. At higher energies, \( E > 10^{17} \text{eV} \), the cascade process in the atmosphere can be detected by fluorescence and radio telescopes. In this case, the total measured flux directly connected with the particle energy and the cascade axis can be found by geometrical reconstruction with two or more detectors.

However the information on the charge of the original particle is lost in all cases. Instead, one can try to reconstruct contributions of nuclei groups in the total flux on average, comparing measurements of several observables with simulations of the cosmic ray shower development in atmosphere. In Fig. 2, we present as example the flux and mass composition measurement by KASCADE-Grande and Tunka experiments in the energy region \( 10^{16} \text{eV} - 10^{18} \text{eV} \) from ref. [2]. One can see that the total flux measured by both experiments is practically consistent. Measurements of heavy nuclei are also consistent, but measurements of light nuclei are not. The main difference lies in \( 10^{17} \text{eV} - 10^{18} \text{eV} \) energy range, where Tunka sees an increase of light composition contrary to KASCADE-Grande. This figure illustrate the relatively good agreement in the total flux measurements and systematic-dependent results on the mass composition between two experiments. It also illustrate the difficulty of mass composition measurement by ground experiments.

The power-law cosmic ray fluxes of Fig. 1 were explained within a simple leaky-box model, in which the galaxy was presented as a cylinder of height \( H \), within which cosmic rays diffuse in time-independent regime with space-and-time-independent diffusion coefficient \( D(t, \bar{x}, E) = D(E) \). The energy dependence of this diffusion coefficient in diffusion regime can be derived from the ratio of primary nuclei produced at sources to secondary nuclei created in interaction of the primary nuclei with the interstellar gas. The primary nuclei with higher energies diffuse faster and spend less time in galactic disk, thus in diffusion theory one expects that secondary to primary flux ratio drops as a function of energy. For diffusion in an ideal random magnetic field, this ratio drops as \( 1/E^{\delta} \), where \( \delta \) is the power law index of magnetic turbulence, which is \( \delta = 1/3 \) in the case of Kolmogorov turbulence.

The example of Boron to Carbon flux ratio is presented in Fig. 3 from the data of the AMS-02, CREAM, and NUCLEON experiments. One can see that data can be fitted by the \( 1/E^{1/3} \) power law, which is in agreement with expectations when the random magnetic field has the power law spectrum consistent with Kolmogorov turbulence. This is also consistent with observations of synchrotron emission of electrons in the Galaxy.

In the diffusion picture, one can model the propagation of CRs as a random walk with an energy dependent effective step size. For a pure isotropic random field, one expects therefore as functional dependence of the diffusion coefficient

\[
D = \frac{cL_0}{3} \left[ (R_L/L_0)^{2-\gamma} + (R_L/L_0)^2 \right],
\]

where the condition \( R_L(E_{cr}) = L_0 \) determines the transition from small-angle scattering with
**Figure 3.** Boron to Carbon flux ratio from AMS-02, CREAM and NUCLEON measurements compared to the Kolmogorov turbulence prediction, from review ref. [3]

**Figure 4.** Diffusion in case of Kolmogorov turbulence, from ref. [4]

**Figure 5.** Diffusion coefficients as functions of energy for several ratios of turbulent to ordered magnetic field $\eta$ Eq. (2) from ref. [4]. Solid and dashed lines correspond to diffusion parallel and perpendicular to the regular field.

**Figure 6.** Dependence of the parameter $\eta$ Eq. (2) on the angle $\theta$ between the regular field direction and the galactic plane. Adapted from ref. [4].

$D(E) \propto E^2$ to large-angle scattering with $D(E) \propto E^{2-\gamma}$, where $\gamma = 5/3$ in the case of Kolmogorov turbulence. Here $L_0 = L_c/(2\pi)$ is a characteristic scale, connected with the coherence scale of magnetic field $L_c$, see details in review [3].

In Fig. 4 we show the energy dependence of the diffusion coefficient from Eq. (1) for several values of the pure turbulent magnetic field value $B_{\text{rms}}$ in galaxy. Note that the measured magnetic field in Galaxy is few $\mu G$. The measured Boron to Carbon ratio defines how much grammage of target material is traversed by cosmic rays in the Galaxy before escape. A value consistent with the measurements presented in Fig. 3 is shown in Fig. 4 with green band. The
required value of the diffusion coefficient at 100 TeV is around $D(100 \text{TeV}) = 10^{30} \text{ cm}^2/\text{s}$, which corresponds to the magnetic field value $B_{\text{rms}} = 2 \cdot 10^{-11} \text{ G}$. Thus, the pure turbulent field model is inconsistent with magnetic field measurements in the Galaxy $B_{\text{gal}} \sim 10^{-6} \text{ G}$.

The main problem of the pure turbulent field model is that, according to the $B/C$ ratio, cosmic rays escape much faster from the Galaxy as compared to diffusion. To solve this problem, one has to remember that the galactic magnetic field has a non-zero regular component. Let us introduce a ratio of turbulent to regular magnetic field in the following way:

$$\eta \equiv B_{\text{rms}}/B_0,$$

where $B_0$ denotes the strength of the regular field and $B_{\text{rms}}$ is the turbulent one.

With the addition of a uniform magnetic field along the $z$ direction to the isotropic turbulent field, the diffusion tensor becomes anisotropic with $D_{ij} = \text{diag}(D_\perp, D_\perp, D_\parallel)$ and $D_\parallel > D_\perp$. In Fig. 5, we show $D_\parallel$ (solid lines) and $D_\perp$ (dashed lines) for different values of the turbulence level Eq. (2). The total magnetic field strength is chosen as $B_{\text{tot}} = \sqrt{B_{\text{rms}}^2 + B_0^2} = 1 \mu\text{G}$, and the outer scale of turbulence is set to $L_{\text{max}} = 100 \text{ pc}$. With decreasing $\eta$, the difference between $D_\parallel$ and $D_\perp$ increases, while keeping the order $D_\parallel > D_\perp$ intact, where $D_\parallel(E)$ denotes the diffusion coefficient for pure isotropic turbulence. As seen from Fig. 5, for this choice of parameters of magnetic field, $\eta = 0.5$ provides a correct $B/C$ ratio.

Because only the $z$ component of the magnetic field is responsible for escape from the Galaxy, for regular component tilted with respect to the $z$ direction escape is more difficult. As result, one needs smaller values of $\eta$ from Eq. (2) to obey the $B/C$ ratio. In Fig. 6 we plot $\eta$ consistent with $B/C$ ratio as function of the angle $\theta$ between the regular field direction and the galactic plane. One can see that for smaller angle $\theta$, one needs smaller $\eta$, or larger difference between the regular and turbulent fields.

For state-of-the-art models of the Galactic magnetic field, for example, the Jansson-Farrar model \[5, 6\], an effective local value of $\eta = 0.25$ \[7\], or the effective tilt angle is about $\theta = 20^\circ$. A major difference between the anisotropic diffusion model and the isotropic diffusion model with large diffusion coefficient is in the number of sources that contribute locally at a given place in the Galaxy. For the above example of the Jansson-Farrar model, the diffusion coefficients satisfy $D_\parallel \geq 5D_{\text{iso}}$ and $D_\perp \geq D_{\text{iso}}/500$, where $D_{\text{iso}}$ denotes the isotropic diffusion coefficient satisfying the $B/C$ constraints. In the regime, where the CRs emitted by a single source fill a Gaussian with the volume $V(t) = \pi^{3/2}D(t)^{1/2}t^{3/2}$, the CR density is increased by factor of $500/\sqrt{5} \approx 200$ in the case of anisotropic diffusion. Thus one expects that the contribution of a few local sources is much more important for anisotropic diffusion model. We will come to this point later.

The isotropic model of cosmic ray diffusion with static time and space independent distribution of cosmic rays in Galaxy was used for many years as an effective model with large isotropic diffusion coefficient. This model has several predictions, which can be tested against data. The first of them is the dependence of dipole anisotropy on energy. This model predicts that the dipole amplitude is a growing function of energy $A(E) = A_0 \cdot E^{1/3}$ in the case of Kolmogorov turbulence. Also due to the large number of sources contributing in any point in the Galaxy, it predict a dipole phase in direction of Galactic center.

For a given density of cosmic rays $n$, the magnitude of the dipole anisotropy $\tilde{A}$ of the CR intensity $I = c/(4\pi)n$ is defined by

$$\delta \equiv \frac{I_{\text{max}} - I_{\text{min}}}{I_{\text{max}} + I_{\text{min}}}.$$

In most cases, CR experiments measure only the projection of the dipole vector on the equatorial plane. This implies in particular that the measured magnitude is smaller than the true one,
Figure 7. The dipole component of the CR anisotropy as a function of energy as measured by ARGO [8], Tibet [9, 10], HAWC [11], IceCube [12], combining HAWC and IceCube [13], Kascade-GRANDE [14] and the PAO [15]: the phase (left panel) and the amplitude (right panel) as functions of energy. Figures adopted from review [3].

except when \( \vec{A} \) lies in the equatorial plane. Moreover, at high energies \( E > 10^{16} \) eV, only the phase, i.e. the right ascension of the projected dipole vector, is experimentally determined, except for Auger measurement. The (projected) dipole anisotropy \( \delta \) measured by seven experiments is shown in Fig. 7 as a function of energy. The phase of the anisotropy shown in the left panel is close to constant up to 200 TeV, then flips by approximately 180°, and stays again constant up to 100 PeV. At even higher energies, the phase changes smoothly. The amplitude of the dipole anisotropy shown in the right panel changes rather smoothly at low energies, being first approximately constant followed by a decrease in the range between 10–200 TeV. This decrease stops abruptly at 200 TeV, i.e. at the same energy where the phase flips by 180°. At higher energies, only limits by Kascade-Grande and PAO exists up to the energy \( E > 8 \) EeV, where the dipole is again detected.

Note that such a behaviour of the dipole amplitude is not consistent with the isotropic model, which predicts a gradual increase of the amplitude shown in Fig. 7 with \( E^{1/3} \) for the case of Kolmogorov turbulence. Also for this model, one expects that the phase points to the direction of the Galactic centre, where the majority of sources are located. As one can see in Fig. 7, the dipole phase disagrees with the isotropic model. In the anisotropic model, the dipole is dominated by contributions of several nearby sources. If cosmic rays for a given source did not have time to escape from the Galaxy, their contribution to dipole amplitude in general will be energy independent for all energies, for which cosmic rays are able to reach Earth from the source. If a source is not connected to Earth by a magnetic field line, at low energies flux cannot reach observer. High energy cosmic rays escape from the Galaxy, which produces an exponential cutoff at the energy corresponding to the escape time equal to the age of the source. Thus, the contribution of a single source is expected to be energy independent in the energy range where it gives a maximum contribution to the observed flux and to decrease for both low and high energies. Data in Fig. 7 is consistent with the contribution of two sources, which are equal at the energy of 200 TeV.

The next prediction of the isotropic diffusion model is that all fluxes of nuclei as functions of rigidity should follow each other as a simple power law with the same power. This is the result of acceleration by shocks at the sources plus propagation in a turbulent magnetic field. In Fig. 7 we present the flux of protons, helium and carbon measured by AMS-02 and CREAM-III as
function of energy/nucleon. One can see that it is impossible to fit them as a single power law, and also the fluxes of different nuclei do not repeat each other. A minimal model which explains nuclei fluxes is presented in Fig. 7 with contribution of two classes of sources. At low energies, old sources give the main contribution, while above 200 GeV, the main contribution is given by the most recent nearby SN, which exploded 2-3 million years ago at a distance of about 100 pc from the Earth. This SN is seen in the data of $^{56}$Fe nuclei, which can be produced only in SN.

The anomaly which attracts most attention of the physics community is the unexpected behaviour of the positron flux, discovered by PAMELA experiment in 2008 and recently investigated by the AMS-02 experiment in great detail. For the leaky box model in steady state regime, one expect that any secondary flux, including the positron flux, would be suppressed as compared to one of protons as $E^{-1/3}$ for Kolmogorov turbulence.

In Fig. 9 we present the recent positron data from the AMS-02 experiment [16] as a function of energy with red error bars. The proton flux presented with boxes from the measurements of AMS-02 [16] and CREAM [18]. In order to compare the secondary positron flux to the primary proton one, we rescaled the proton flux by 20 in energy, since the typical secondary positron energy is $\langle E_{e^+}\rangle = E_p/20$. One can see that in the energy range $7-30$ GeV the secondary positron flux is indeed falling as compared to the original proton flux, as is expected in the leaky-box model. However at $E_{e^+} > 30$ GeV, it is not so anymore.

Additionally, we show in the left panel with black error bars the antiproton flux measured by AMS-02 [17], which we multiplied by 2. As it was noted in Refs. [19, 17, 20], the positron-to-antiproton flux ratio close to 2 is consistent with expectations that both are produced in hadronic interactions. If so, this challenge other interpretations of the positron and antiproton data. For example, if positrons are produced together with electrons in pulsars, they are not connected to the production of anti-protons, and the ratio 2 in their fluxes is just a coincidence.

To summarize, I would like to outline the following experimental anomalies, which show that a simplified isrotropic diffusion model of cosmic rays in Galaxy does not work:

- The Boron to Carbon ration measured by AMS-02 is consistent with Kolmogorov turbulence

Figure 8. The flux of CR protons, helium and carbon measured by AMS-02 and CREAM-III as function of energy/nucleon shown together with a two-component model consisting of an average CR spectrum (dotted lines) and a local source contribution (solid red lines).
Figure 9. The positron and antiproton spectra from the AMS-02 experiment Ref. [16, 17]. The antiproton flux is multiplied by factor 2. For comparison, the proton spectrum from the AMS-02 [16] and CREAM [18] experiments are shown with amplitude divided by $10^3$ and rescaled as $E/20$ in energy.

Figure 10. The energy-loss horizon $\lambda$ of UHECR protons as function of energy. Figure adopted from review [3].
and large diffusion coefficient. For isotropic diffusion this requires tiny galactic magnetic field, many orders of magnitude below measurements. Only for anisotropic diffusion in presence of regular field magnetic field value is consistent with observations.

- The fluxes of all nuclei have breaks at 200 GeV/n, which is inconsistent with a single population of sources.
- The proton to He ratio is not constant as a function of rigidity. This is again a sign of changes in the source populations.
- The dipole anisotropy amplitude and phase are inconsistent with the isotropic model. They rather show signs of contributions from individual sources, which is only possible in an anisotropic model.
- The positron to anti-proton ratio by factor 2 is consistent with the possibility that both are secondaries from the protons.

All those facts can be explained in an anisotropic model with contribution of several nearby sources, dominated by a 2-3 Myr SN at 1-100 TeV energies and Vela in the knee region.

Interactions of the Ultra-High Energy (UHE) protons with the cosmic microwave background
(CMB) leave their imprint on the Ultra-High Energy Cosmic Rays (UHECR) energy spectrum in the form of the Greisen-Zatsepin-Kuzmin (GZK) cutoff [23, 24], a bump and a dip [25, 26, 27, 28]. The GZK cutoff is a very pronounced steepening of the proton spectrum at the energy \( E_{\text{GZK}} \simeq (4-5) \times 10^{19} \text{eV} \), caused by the photo-pion production due to the interaction of UHE protons with CMB photons. This effect was predicted one year after the discovery of the CMB in 1966 by Greisen and independently by Zatsepin and Kuzmin. It implies that, at the highest energies, only local sources within \( \sim 100 \text{Mpc} \) can contribute to the observed UHECR flux.

In Fig. 11, the energy-loss horizon

\[
\lambda_{\text{hor}}(E, z = 0) = \left( \frac{1}{E \frac{dE}{c dt}} \right)^{-1}
\]

for protons as function of energy is shown. The losses are caused by three processes which dominate in different energy ranges: pion production at highest energies, \( e^\pm \) pair production in the intermediate energy range \( 3 \times 10^{18} \text{eV} < E < 5 \times 10^{19} \text{eV} \), and redshift losses due to the expansion of the Universe.

In Fig. 11 we plot the UHECR spectrum measured by the two main experiments: the Pierre Auger Observatory, or Auger, located in the Southern hemisphere, and the Telescope Array (TA), in the Northern hemisphere. One can see that spectra are consistent with each other after an overall energy shift. This shift by 10% in energy is well within experimental systematic errors. Thus, the data of both experiments on total energy spectrum are consistent with each other up to \( E = 6 \cdot 10^{19} \text{eV} \). Above this energy, the data of TA are systematically higher. At those highest energies, the difference can come from the local Large Scale Structure, since mostly the sources within 200 Mpc contribute at such energies.

In Fig. 12 we plot the mass composition measured by Auger and TA experiments, as presented in Ref. [22]. One can see that the mass composition is consistent in the data of both experiments. It is consistent with a light composition at \( 10^{18} \text{eV} \) and a heavier one at higher energies.

Finally, in Fig. 13 we present a sky map of the UHECRs with \( E > 7 \cdot 10^{19} \text{eV} \) from the combined date of the Auger and TA experiments. One can see in the North TA hot spot, which is the most significant anisotropy in the sky, with 4 \( \sigma \) significance above background. At present, TA is upgraded in 4 times in area, which will allow to study this anomaly in details in near future.
Figure 14. Total neutrino flux measured by the IceCube experiment for events starting inside the detector, from Ref. [30].

3. Neutrino astronomy and multi-messenger observations

At energies above TeV, the Universe is not transparent to photons anymore. They interact with infrared and optical background created by star light and dust in Galaxies. As a result, our information about sources of particles at $E > 1$ TeV is limited. Long attempts to find sources of UHECR failed so far due to deflection of charged UHECR by inter-galactic and galactic magnetic fields. On the other hand, the presence of UHECR up to $E = 10^{20}$ eV guarantees that such sources exist.

For more than 50 years, a hope to find sources of UHECR was connected with direct searches of their arrival directions. However indirect searches with neutrinos are also possible. Neutrinos are produced in hadronic interactions mainly from charged pions

$$\pi^\pm \rightarrow \mu^\pm + \nu_\mu \rightarrow e^\pm + \bar{\nu}_e + \nu_\mu$$

Thus, after averaging of muon and tau neutrinos after oscillations on cosmological scales, one can expect that all neutrinos arrive at detector in the $1:1:1$ ratio.

Astrophysical neutrinos were first detected by the IceCube experiment at the South pole in 2013 at PeV energies. Double challenge to detect such neutrinos is to build a detector big enough to overcome the tiny neutrino cross section and to fight huge background of atmospheric neutrinos and muons, both produced as secondaries from interaction of cosmic rays in atmosphere.

The neutrino cross section at $E = 100$ TeV is

$$\sigma_\nu(100 \text{ TeV}) = 3 \cdot 10^{-34} \text{ cm}^2.$$  \hspace{1cm} (4)

The density of protons in ice is

$$n_{\text{ice}} = 0.9 \frac{g/m_p}{\text{cm}^3} = 3 \cdot 10^{23} / \text{cm}^3.$$  \hspace{1cm} (5)

Thus, for a detector with size of $R_d = 1 \text{ km} = 10^5 \text{ cm}$, one expects that the following fraction of neutrinos interact in detector

$$\tau = \sigma_\nu(100 \text{ TeV}) n_{\text{ice}} R_d \sim 10^{-5}.$$  \hspace{1cm} (6)
This means that most of neutrinos just go through the detector without any interactions.

A typical flux of neutrinos can be estimated from gamma-ray flux of the Fermi extragalactic sources, with a typical energy flux

$$E^2 F_{\nu}(E) = 10^{-12} \text{erg/}(\text{cm}^2 \text{s}).$$

(7)

Then one expects, from a typical bright neutrino source, to detect the following number of events

$$N_{\nu} = \tau E F_{\nu}(E) = 10^{-5} \times 10^{-14} \times 10^7 / (\text{km}^2 \text{yr}) = 0.03 / (\text{km}^2 \text{yr}).$$

(8)

One can see from Eq. (8) that detection of neutrino sources is a challenge even for km$^3$ detectors. Contrary to point sources, the diffuse astrophysical neutrino flux can be detected. Indeed, for $E^2 F_{\nu}(E) = 30 \text{eV/cm}^2 / \text{s/sr}$ one expects one event per year per sr of detection, which means about 5-10 events per year in a km$^3$ detector.

The diffuse astrophysical neutrino flux was detected by the IceCube experiment in 2013. Recent data from the ICRC-2017 conference are presented in Figs. 14–15. In Fig. 14 the total neutrino flux multiplied by energy squared is shown as a function of energy. With such normalisation, the flux shows total energy in neutrinos in a given energy bin. This is the flux of High Energy Starting Events (HESE), i.e. neutrino events which start inside the IceCube detector. This flux is dominated by cascade events, which come from charged interactions of electron neutrinos and from neutral interactions of all types of neutrinos. The total energy of neutrinos is deposited inside the detector in this case. Thus, one can recover neutrino energy with a good precision. On the other side, cascade events produce almost spherically symmetric signal in the detector. Indeed, electron neutrino or hadronic cascade length is several meters, which is much less than the distance between strings of photomultipliers in the detector (70 meters). As a result, knowledge of the arrival direction of HESE events is very limited. The total normalisation of flux in HESE events is

$$E^2 F_{\nu}(E) = 4.8 \left( \frac{E}{100 \text{TeV}} \right)^{-2.5} \times 10^{-7} \text{GeV/cm}^2 \text{s sr}.$$ 

(9)

At $E > 100$ TeV, the measurement of cascade events is background free. Atmospheric neutrino and muon background are negligible in this case. At lower energies, the background can be
significantly reduced using the outer part of the detector as veto. This allows IceCube to measure HESE events well for energies above 10 TeV and, with limited statistics, above 1 TeV, see Fig. 14. At \( E > 100 \text{ TeV} \), the Earth is not transparent to neutrinos anymore, so starting from this energy one begins to lose information from neutrinos coming through the Earth centre.

In Fig. 15 we present the muon neutrino flux. Contrary to electron neutrinos, muon neutrinos produce long lived muons, which lose their energy over distances of several up to tens of kilometres. As a result, the secondary muons produced outside of the IceCube detector produce muon tracks in the detector. Those tracks allow to define the original neutrino direction up to 0.5 degree precision. In the contrast, information on the original neutrino energy is very limited in this case. Only a lower limit on the neutrino energy can be reconstructed from the energy deposited in the detector. Since information on neutrino energy is limited, atmospheric background propagates to higher energies. In Fig. 15 it is presented with the blue line. Additionally, contribution of the poorly known neutrino flux from charm decay leptons limited with the green line to value still above the Standard Model prediction. The red line shows the measured astrophysical muon neutrino flux with 8 years of the IceCube data. This flux is consistent with a power law with index between \( 1/E^{2.0} \) and \( 1/E^{2.2} \). Note that this measurement does not contradict the one in Fig. 14, as seen from a direct comparison with the HESE data in Fig. 15. Combination of the two data shows that at higher energies \( E > 100 \text{ TeV} \) the spectrum of neutrinos is hard, with \( 1/E^{2-2.2} \), while at lower energies \( E < 100 \text{ TeV} \) it has excess above this slope.

![Figure 16.](image) Secondary photons and neutrinos from UHECR sources. Diffuse photons have a universal shape and contributions at least from UHECR sources, neutrino sources and unresolved gamma-ray sources. Neutrino flux example is from Ref. [31]. The difference in proton and neutrino fluxes indicates proton optical depth in sources at zone of neutrino production. The blue band represents 8 years astrophysical muon neutrino flux multiplied by 3 and red points are 4 years cascade neutrinos from IceCube Ref. [30]. Figure adopted from review [3].

Before going to interpretation of the neutrino data, let us look at the global multi-messenger picture. In Fig. 16 we plot the total cosmic ray flux (magenta data with error bars) and the proton contribution to this flux (green data with error bars) measured by the Auger and KASCADE-Grande experiments. One can see that the proton contribution is maximal at \( 10^{18} \text{ eV} \) and is subdominant both at high and low energies. Spectral hardening is seen in the proton
data above $10^{16}$ eV, with a knee-like feature above $10^{18}$ eV. The green band represents muon neutrino flux and the red points with error bars are the HESE neutrino data. At GeV energies, the diffuse photon background is shown with orange points with error bars.

Diffuse extragalactic neutrinos are mainly produced by proton primaries through the pion production mechanism. The global difference between the proton flux and neutrino flux is shown by red arrow with the label $y\tau$. Here $y = 0.2$ is a typical energy fraction transferred to neutrinos in one interaction, while $\tau = \sigma n_B L$ is the optical depth for protons in the sources, where they produce neutrinos in collisions with gas of protons and nuclei with density $n_B$ at length scale $L$ with hadronic cross section $\sigma$. Taking into account that the global difference between the proton and neutrino fluxes is of the order of $5 - 10$, we conclude that the optical depth of protons in sources, which produce neutrinos, is large $\tau \sim 1$.

Neutrinos are produced in sources together with gamma-rays, which are secondaries from the $\pi^0 \rightarrow 2\gamma$ decay. However, contrary to neutrinos, gamma-rays cascade down in energy in a chain of reactions $\gamma + \gamma_B \rightarrow e^+ + e^-$, $e^\pm \gamma_{CMB} \rightarrow e^\pm + \gamma$ and so on. As a result, all high energy gamma-rays end up in the GeV energy band where they can not produce electron-positron pairs anymore. This band is shown by the blue band in Fig. 16. Note that the shape of the photon flux above 100 GeV is universal, as it depends on properties of the electromagnetic cascade and the energy shape of the background photons and not on the original high energy photon spectrum.

Another important point is that the total energy deposited in photons in pion production process is of the same order as the total energy deposited in neutrinos. Thus all possible sources of high energy photons contribute to same diffuse photon background. This includes unresolved point sources which produce direct photon emission from electrons in sources (the inverse Compton process), cascades from neutrinos sources and cascades from UHECR, including both $e^\pm$ by protons and pion production. All those processes can give dominant production to diffuse gamma-ray background. As one can see from Fig. 16, the contribution of muon neutrino sources is easy to accomodate in diffuse gamma-ray background, while the contribution corresponding to the HESE red data is in tension with it.

Moreover, the situation is much worse for non-blazar sources. The reason is that blazars are the main resolved sources of Fermi at highest energies. Since only a small fraction of blazars was resolved by Fermi so far, unresolved blazars give major contribution to the diffuse gamma-ray background. The Fermi collaboration concluded that up to $85\% \pm 15\%$ of the diffuse gamma-ray background comes from unresolved blazars. In turn, that means that non-blazar sources can give only up to $30\%$ contribution to the diffuse gamma-ray background. This value is already in contradiction with the HESE neutrino flux and in tension with the muon neutrino flux, and it can be easily saturated by UHECR contribution.

This makes blazars special candidates for neutrino sources. A minimal model for extragalactic sources of UHECR, IceCube neutrinos and diffuse gamma-rays was developed in refs. [32, 31]. Correlation of bright Fermi blazars with IceCube muon neutrino events was studied in refs. [33, 34]. However the result is negative, and the resolved Fermi blazars do not correlate with the IceCube muon neutrino data.

An additional constraint on extragalactic objects as sources of neutrino data comes from studies of point neutrino sources. Point sources can be looked in the IceCube muon data due to a good angular resolution of 0.5 degree. In 2017, the first neutrino source candidate was found by IceCube: TXS 0506+056 blazar correlated with one of neutrino events [36]. At the same time, this blazar was in high gamma-ray flux state, as was measured by the Fermi and MAGIC telescopes [36]. TXS 0506+056 blazar also made neutrino flare in 2015 with a flux much higher than photon flux at the same time [37].

An interpretation of this data can be given in the framework of hadronic blazar models, in which gamma-rays spread in bigger angle due to electron and positron deflections in the
magnetic field [38]. Then from nearby sources only gamma-rays can be seen, while for more distant sources neutrino flux can be seen face-on.

An additional constraint on density and luminosity of neutrino sources comes from the absence of doublets in muon neutrino data [39]. This constraint forbids high-luminosity high-density population of neutrino sources, see “no doublets” condition in Fig. 17. Additionally, the constraint that the first visible source TXS 0506+056 has a relatively high redshift $z = 0.3$ removes low luminosity high density sources, see Fig. 17. As a result, in order to explain the IceCube data (between the red lines in Fig. 17), one needs to have a very strongly evolving source population, which is consistent with FSRQ blazars, if the neutrino luminosity is an order of magnitude lower than the gamma-ray luminosity. This is a conservative condition, since it allows both the leptonic and hadronic processes in the sources, see details in ref. [35].

Thus, muon neutrino data can be accumulated in multi-messenger picture of extragalactic neutrino sources. First, let us note that the transition from Galactic to extragalactic cosmic rays, consistent with the mass composition measurements and with the dipole data, is at the second knee energy $3 \cdot 10^{17}$ eV. Since at highest galactic energies around this transition, the
spectrum is dominated by iron, this corresponds to a transition in the proton data at $Z = 26$ times lower energy, i.e. around $10^{16}$ eV. In turn, this should have an imprint in the secondary neutrino data at 20 times smaller energy, around $5 \cdot 10^{15}$ eV, i.e. near the energy at which the muon and HESE data start to deviate. One can see those two components in Fig. 18 together with power-law fits. As we discussed above, the low energy part of the HESE component cannot be of extra-galactic origin due to the contradiction with diffuse gamma-ray background data. Can it be Galactic?

In ref. [41] it was for the first time noticed that if one takes all sky gamma-ray data, they are well consistent with the HESE flux of IceCube neutrino data. In Fig. 19 we show the same plot with the recently updated Fermi and IceCube data. One can see that indeed the IceCube HESE data follow the Fermi $\pi^0$ decay model. This gamma-ray flux is dominated by diffuse gamma-ray emission created by cosmic rays in the Galaxy.

In ref. [44], the contribution of sources located in the Galactic plane was calculated. It was shown that this contribution gives subdominant flux in the IceCube muon data. On the other hand, in ref. [42] it was shown that a combination of the events excess in the Galactic plane with the absence of events at high galactic latitudes gives evidence of the Galactic contribution to the IceCube HESE data. As it was shown in ref. [45], this model is consistent with the muon neutrino data. An updated version of this plot with the 2017 data is shown in Fig. 20. One can see that a big contribution to neutrino data comes from events in middle galactic latitudes. A contribution from the Galactic plane was constrained by IceCube and Antares for several specific models of diffuse emission [43]. From those results one can conclude that the Galactic contribution to neutrinos should be dominated by an out-of-plane signal.

Indeed, one can divide the all sky signal from Fig. 19 into a Galactic plane part with $|b| < 10^\circ$ and an out-of-plane signal $|b| > 10^\circ$. In Fig. 22 we plot the galactic contribution to the Fermi diffuse gamma-ray background. This background is dominated by pion production by cosmic rays interacting with the interstellar gas of the Galaxy. One can see that this data are consistent with the IceCube energy-dependent limit, but lie above the model-dependent constraint from ref. [43]. Also this figure shows that some increase of sensitivity at low energies $E < 10$ TeV will allow to detect the flux from the Galactic plane.

In Fig. 23 we show the high galactic latitude signal from Fermi borrowed from ref. [40] together with the IceCube neutrino data. One can see that the excess in HESE neutrino data

**Figure 19.** All-sky gamma-ray flux by Fermi and neutrino flux by IceCube adapted from ref. [40].
Figure 20. Distribution of HESE events with $E > 100$ TeV as a function of Galactic latitude, updated version of a figure from [42].

Figure 21. Constraints on the diffuse emission models from the Galactic plane [43].

is consistent with the excess in Fermi data at TeV energies. Both data can originate from the same new component above the diffuse gamma-ray flux from the galactic disk and extragalactic muon neutrino data.

The combined excess in gamma-ray and neutrino data can be interpreted by several models. First, both neutrino and gamma-rays can come from a large-scale halo of our Galaxy [46]. Cosmic rays can be accumulated in such halo over long time scales and interact with low density gas to produce gamma-ray and neutrino excesses. The second possibility is that the excess is produced by a local cosmic ray source in cosmic ray interactions with the walls of the Local Bubble [47]. The neutrino and gamma-ray flux from this model is presented in Fig. 24. The final possibility is that both gamma-rays and neutrinos come from decaying Dark Matter with
Figure 22. The Galactic plane $|b| < 10^\circ$ gamma-ray data from Fermi [40] and the neutrino flux limits from IceCube and ANTARES ref. [43].

Figure 23. The high galactic latitude $|b| > 20^\circ$ gamma-ray data from Fermi [40] and the neutrino flux measurements by IceCube, KASCADE limit on gamma-ray flux.

mass around $M = 5 \text{ PeV}$ [40], as presented in Fig. 25. Unfortunately, the present neutrino and gamma-ray data cannot distinguish between those possibilities.

The diffuse gamma-ray flux from the above models can be looked for by experiments, which can discriminate cosmic ray flux at least up to $10^5$ factor. This was first done by the KASCADE experiment and is planned for the future CARPET-3, which is in its final construction stage at the moment. From CARPET-3 sensitivity in Fig. 26 one can see that it will be able to detect the diffuse gamma-ray flux at energies above 100 TeV.

4. Conclusions

Multi-messenger data with cosmic rays, gamma-rays, and neutrinos allow to study their origin with minimal models, which explain them at the same time. In cosmic ray data, a large number of anomalies show that the standard isotropic diffuse model cannot explain the cosmic ray data. In contrast, an anisotropic diffuse model can explain all anomalies due to an increased
Figure 24. The model of neutrino flux from cosmic rays from nearby source interacting with Local Bubble from ref. [40].

Figure 25. The model of neutrino flux from heavy Dark Matter with $M = 5$ PeV from ref. [40].

Figure 26. Carpet-3 sensitivity to Galactic gamma-ray signal from ref. [48].
5. References

[1] Tanabashi M and et al (Particle Data Group) 2018 Phys. Rev. D 98(3) 030001
[2] Prosin V V et al. 2014 Nucl. Instrum. Meth. A756 94–101
[3] Kachelrieß and Semikoz D V 2019 Progress in Nuclear and Particle Physics (Preprint 1904.08160)
[4] Giacinti G, Kachelrieß M and Semikoz D V 2018 JCAP 1807 051 (Preprint 1710.08205)
[5] Jansson R and Farrar G R 2012 Astrophys.J. 757 14 (Preprint 1204.3662)
[6] Jansson R and Farrar G R 2012 Astrophys.J. 761 L11 (Preprint 1210.7820)
[7] Giacinti G, Kachelrieß M and Semikoz D V 2014 Phys. Rev. D90 041302 (Preprint 1403.3380)
[8] Bartoli B et al. (ARGO-YBJ) 2015 Astrophys. J. 809 90
[9] Amenomori M et al. (Tibet AS Gamma) 2005 Astrophys. J. 626 L29–L32 (Preprint astro-ph/0505114)
[10] Amenomori M et al. (Tibet AS-gamma) 2017 Astrophys. J. 836 153 (Preprint 1701.07144)
[11] Abeysekara A U et al. 2018 Astrophys. J. 865 57 (Preprint 1805.01847)
[12] Aartsen M G et al. (IceCube) 2016 Astrophys. J. 826 220 (Preprint 1603.01227)
[13] Velez J C D et al. (HAWC, IceCube) 2018 PoS ICRC2017 539 (Preprint 1708.03005)
[14] Chivassaa A et al. (KASCADE-Grande) 2016 PoS ICRC2015 281
[15] Aab A et al. (Pierre Auger) 2018 Astrophys. J. 868 4 (Preprint 1808.03579)
[16] Aguilar M et al. 2019 Phys. Rev. Lett. 122 041102
[17] Aguilar M et al. (AMS) 2016 Phys. Rev. Lett. 117 091103
[18] Yoon Y S et al. 2017 Astrophys. J. 839 5 (Preprint 1704.02512)
[19] Kachelrieß M, Neronov A and Semikoz D V 2015 Phys. Rev. Lett. 115 181103 (Preprint 1504.06472)
[20] Lipari P 2017 Phys. Rev. D95 063009 (Preprint 1608.02018)
[21] Ivanov D (Telescope-Array, Pierre Auger) 2018 PoS ICRC2017 498
[22] Alves Batista R et al. 2019 (Preprint 1903.06714)
[23] Greisen K 1966 Phys. Rev. Lett. 16 748–750
[24] Zatsepin G T and Kuzmin V A 1966 JETP Lett. 4 78–80 [Pisma Zh. Eksp. Teor. Fiz.4,114(1966)]
[25] Hill C T and Schramm D N 1985 Phys. Rev. D31 564
[26] Berezinsky V S and Grigor’eva S I 1986 Astron. Astrophys. 199 1–12
[27] Stanev T, Engel R, Mucke A, Protheroe R J and Rachen J P 2000 Phys. Rev. D62 093005 (Preprint astro-ph/0003484)
[28] Berezinsky V, Gazizov A Z and Grigor’eva S I 2006 Phys. Rev. D74 043005 (Preprint hep-ph/0204357)
[29] Matthews J (Telescope Array) 2018 PoS ICRC2017 1096
[30] Aartsen M G et al. (IceCube) 2017 (Preprint 1710.01191)
[31] Kachelrieß M, Kalashov O, Ostapchenko S and Semikoz D V 2017 Phys. Rev. D96 083006 (Preprint 1704.06993)
[32] Giacinti G, Kachelrieß M, Kalashov O, Neronov A and Semikoz D V 2015 Phys. Rev. D92 083016 (Preprint 1507.07534)
[33] Aartsen M G et al. (IceCube) 2017 Astrophys. J. 835 45 (Preprint 1611.03874)
[34] Neronov A, Semikoz D V and Ptitsyna K 2017 Astron. Astrophys. 603 A135 (Preprint 1611.06338)
[35] Neronov A and Semikoz D V 2018 (Preprint 1811.06356)
[36] Aartsen M G et al. (IceCube, Fermi-LAT, MAGIC, AGILE, ASAS-SN, HAWC, H.E.S.S., INTEGRAL, Kanata, Kiso, Kapteyn, Liverpool Telescope, Subaru, Swift NuSTAR, VERITAS, VLA/17B-403) 2018 Science 361 eaat1378 (Preprint 1807.08816)
[37] Aartsen M G et al. (IceCube) 2018 Science 361 147–151 (Preprint 1807.08794)
[38] Neronov A Yu and Semikoz D V 2002 Phys. Rev. D66 123003 (Preprint hep-ph/0208248)
[39] Murase K and Waxman E 2016 Phys. Rev. D94 103006 (Preprint 1607.01601)
[40] Neronov A, Kachelrieß M and Semikoz D V 2018 Phys. Rev. D98 023004 (Preprint 1802.09983)
[41] Neronov A, Semikoz D V and Tchernin C 2014 Phys. Rev. D89 103002 (Preprint 1307.2158)
[42] Neronov A and Semikoz D V 2016 Astropart. Phys. 75 60–63 (Preprint 1509.03522)
[43] Aartsen M G et al. (IceCube) 2017 Astrophys. J. 849 67 (Preprint 1707.03416)
[44] Kachelrieß M and Ostapchenko S 2014 Phys. Rev. D90 083002 (Preprint 1405.3797)
[45] Neronov A and Semikoz D V 2016 Phys. Rev. D93 123002 (Preprint 1603.06733)
[46] Taylor A M, Gabici S and Aharonian F 2014 Phys. Rev. D89 103003 (Preprint 1403.3206)
[47] Bouyahiaoui M, Kachelrieß M and Semikoz D V 2019 JCAP 1901 046 (Preprint 1812.03522)
[48] Dzhappuev D D et al. 2018 Search for astrophysical PeV gamma rays from point sources with Carpet-2 (Preprint 1812.02663)