Neutrinos from Extra-Large Hadron Collider in the Milky Way

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Neutrino telescope IceCube has recently discovered astrophysical neutrinos with energies in the TeV – PeV range. We use the data of Fermi gamma-ray telescope to demonstrate that the neutrino signal is dominated by emission from the Milky Way galaxy. Matching gamma-ray and neutrino spectra we find that TeV-PeV Galactic cosmic rays form a powerlaw spectrum with the slope $p \gtrsim 2.5$. This spectral slope is harder than previously thought, but it is compatible with that of the locally observed spectrum of cosmic ray nuclei in the same energy range. It is also consistent with the theoretical model of cosmic ray injection by diffusive shock acceleration followed by escape through the Galactic magnetic field with Kolmogorov turbulence. The locally observed TeV – PeV cosmic ray proton spectrum is softer than the average Galactic cosmic ray spectrum. This could be explained by variability of injection of cosmic rays in the local interstellar medium over $10^7$ yr.

Cosmic rays are charged particles with energies in the range from $\lesssim 1$ GeV to $10^{20}$ eV, penetrating into the Solar system and the Earth atmosphere from outer space\textsuperscript{1,2}. Hundred years after the initial discovery\textsuperscript{2}, the origin of cosmic rays remains unknown. The main difficulty for the identification of the sources of cosmic rays is non-zero electric charge of the cosmic ray particles. Deflections of cosmic rays by turbulent component of Galactic magnetic field forces them into a random walk through the interstellar medium (ISM)\textsuperscript{1}. As a result, cosmic rays arrive from random directions on the sky. The information on the sources is encoded in the cosmic ray spectrum, mass composition and global anisotropy (see Ref.\textsuperscript{2} for a review). However, it is not clear how the spectral slope $p$ and the break energies of the locally measured piecewise powerlaw cosmic ray spectrum $dN/dE \propto E^{-p}$ are related to the properties of source population(s). The diffusion through the ISM and escape from the Galactic Disk modify the cosmic ray spectrum, in a model-dependent way. It is also not clear if the locally measured properties of the spectrum are representative for those of all Galactic cosmic rays, or they are determined by the peculiarities of recent injection of particles in the local ISM\textsuperscript{4,5}.

An illustration of these uncertainties could be found in the model of modification of the cosmic ray spectrum by the propagation effects encoded in an energy-dependent diffusion coefficient $D(E) \sim E^\delta$\textsuperscript{1}. The slope of the interstellar cosmic ray spectrum is determined by $\delta$ and by the slope $p_s$ of the injection spectrum, $p = p_s + \delta$. The most commonly considered acceleration mechanism is diffusive shock acceleration (DSA)\textsuperscript{6–8}, which is expected to give a slope $p_s \simeq 2.0...2.2$. Comparison with the slope of the locally measured cosmic ray spectrum, $p \simeq 2.7$, points to a value of $\delta \simeq 0.5...0.7$. This is, however, in tension with the measurements of the ratio of abundances of primary and secondary nuclei which give $\delta \simeq 1/3$\textsuperscript{9} and with the measurements of anisotropy of the cosmic ray flux\textsuperscript{10}. The value $\delta = 1/3$ is also favoured by theoretical considerations of cosmic ray diffusion\textsuperscript{11} through the ISM with Kolmogorov turbulence spectrum\textsuperscript{11}.

Complementary information on the cosmic ray source and propagation parameters is provided by secondary $\gamma$-rays and neutrinos from cosmic ray interactions. Contrary to the charged cosmic ray particles, electrically neutral $\gamma$-rays and neutrinos go straight from their production point to the Earth. $\gamma$-ray and neutrino signal from individual sources could provide information on the injection spectrum of cosmic rays, while diffuse $\gamma$-ray and neutrino emission from the ISM could provide the data on the propagation of cosmic rays in the Galaxy.

IceCube collaboration has recently reported the detection of astrophysical neutrino signal in the energy range from 10 TeV to 2 PeV\textsuperscript{12,13}. The signal forms a powerlaw spectrum $dN_\nu/dE \propto [E/100 \text{ TeV}]^{-p_\nu}$, with $p_\nu = 2.46 \pm 0.12$\textsuperscript{13}. The statistics of the signal is currently insufficient for a judgement if the observed flux originates from sources in the Galaxy or from outside it. Several explanations for the signal might be considered.

The signal might originate from extragalactic sources like Active Galactic Nuclei (AGN) or Gamma-Ray Bursts (GRB). However, typical AGN\textsuperscript{16,17} or GRB\textsuperscript{18} neutrino model calculations result in a hard neutrino spectrum in the TeV – PeV energy range, which is largely inconsistent with the observed slope of the neutrino spectrum, see Fig.\textsuperscript{11}.

Alternatively, cosmic ray interactions in normal and starburst galaxies might be responsible for the observed neutrino flux\textsuperscript{19,20}. In this case the GeV-PeV neutrino flux should be accompanied by a flux of $\gamma$-rays with energies below $E \sim 100$ GeV, with comparable spectrum. The neutrino flux is, therefore, constrained by the measurements of extragalactic $\gamma$-ray background (EGB)\textsuperscript{21,22}. The normalisation of neutrino and $\gamma$-ray flux in the GeV energy range is fixed by the known relation between the far infrared and $\gamma$-ray luminosity of galaxies, $L_\gamma \simeq 10^{-4}L_{FIR}$\textsuperscript{23}, and by the known level of extra-
Here we demonstrate that this is the case. Our produced by interactions of cosmic rays in the Galaxy for details of the model calculation). The slope of the γ-ray and neutrino spectra \( p_{\nu,\gamma} \approx 2.4 \) is slightly harder than that of the parent cosmic ray spectrum because of the logarithmic growth of the interaction cross-section with energy (see e.g. \[28\]).

Consistency of the model with the γ-ray and neutrino data suggests that the spectrum of Galactic cosmic rays is harder than the locally observed cosmic ray spectrum which has an average slope \( p \approx 2.7 \). At the same time, the hard spectrum of Galactic cosmic rays is consistent with the local measurements of the spectra of atomic nuclei component of the cosmic ray flux in the TeV – PeV energy range \[4, 33–35\]. Matching the CREAM data at the energies below 100 TeV \[33\] with the KASCADE-Grande measurements in the PeV energy range \[34\] we find that the slopes of the locally observed spectra of atomic nuclei are consistent with \( p = 2.5 \) \[35\] for nuclear species in the energy range above 1 TeV, up to the knee energy (different for different nuclei). The only exception is the spectrum of protons, which has a softer slope in this energy range.

A consistency check of the Galactic origin of the bulk of astrophysical neutrino signal is provided by the analysis of spatial distribution of the signal on the sky. The neutrino signal shows a hint of anisotropy in the direction of the Galactic Plane \[15\], which is consistent with the γ-ray – neutrino signal correlation. Moreover, distribution of neutrino events along the Galactic Plane is consistent with the distribution of the γ-rays, with higher event statistics observed around the region of Galactic Ridge \[15, 30\].

The model of the γ-ray and neutrino data shown in Fig. 2 ignores additional contributions to the all-sky γ-ray flux coming from resolved point sources and from the inverse Compton emission by cosmic ray electrons.

The flux of resolved sources outside the Galactic Plane is at the level of 10% of the overall sky flux \[22\]. Most of the sources outside the Galactic Plane are AGN or pulsars \[36\]. For both source types the γ-ray emission is produced by high-energy electrons / positrons and is not directly associated to the neutrino emission. To the contrary, brightest Galactic Plane sources in the energy band above 10–30 GeV are extended sources which might be the powered by interactions of freshly injected cos-

\[\gamma \rightarrow \nu + p \rightarrow \nu + n\]

1 Note, that for spectrum with \( p \approx 2.7 \) the neutrino flux is below IceCube observations, see ref. \[31\].

**FIG. 1:** Astrophysical neutrino spectrum measured by IceCube, compared to the extragalactic model predictions. Dark grey shading corresponds to the 68% confidence range for the measurement of the slope and normalisation of the neutrino spectrum \[13\], light grey shading is for the 90% confidence range. Thick red solid curve marked “galaxies” shows an estimate of the flux from cosmic ray interactions in star forming galaxies \[20\]. Green dashed and orange solid curves marked “AGN1, AGN2” show the spectrum of emission from AGN models from Refs. \[16, 17\], normalised on the maximal possible IceCube neutrino flux at 1 PeV. Blue dotted curve shows the spectrum of emission from GRB model from Ref. \[18\], also normalised at 1 PeV.

The observed astrophysical neutrinos could also be produced by interactions of cosmic rays in the Galaxy \[20, 31\]. Here we demonstrate that this is the case. Our argument is based on comparison of neutrino and γ-ray fluxes for the entire sky, shown in Fig. 2 (see Supplementary Materials (SM) for details of γ-ray data analysis). From this figure one could see that the IceCube measurement of neutrino spectrum above 100 TeV lies at the extrapolation of the all-sky \( E \gtrsim 1 \) TeV γ-ray spectrum measured by Large Area Telescope (LAT) \[32\] on board of Fermi satellite.

galactic far infrared background, \( F_{\text{FIR}} \approx 10^{-5} \) erg/(cm\(^2\) s sr) \[24\]. Fig. 1 shows the most recent calculation of the cumulative γ-ray and neutrino flux from star forming galaxies, which takes into account the cosmological evolution different types of galaxies \[20\]. This calculation adopts an (arbitrary) assumption that the spectra of cosmic rays in the non-starburst galaxies are the same as the measured cosmic ray spectrum in the local ISM. Hardening of the spectrum above 10 GeV is due to a contribution from starburst galaxies which are assumed to have harder emission spectra with \( p_{\gamma,\nu} = 2.2 \) \[25\].

The slope of the γ-ray and neutrino spectra above 100 TeV lies at the extrapolation of the all-sky E \( \gtrsim 1 \) TeV γ-ray spectrum measured by Large Area Telescope (LAT) \[32\] on board of Fermi satellite.

This is expected if both neutrinos an γ-rays are produced in interactions of Galactic cosmic rays. Red and blue thin solid curves in Fig. 2 show a model of the neutrino and γ-ray data in the 10 GeV – 2 PeV energy range with neutrino and γ-ray spectra from interactions of cosmic rays with a powerlaw spectrum with the slope \( p = 2.5 \) (see SM for details of the model calculation). The cumulative \( \gamma \)-ray and neutrino spectrum \( p_{\nu,\gamma} \approx 2.4 \) is slightly harder than that of the parent cosmic ray spectrum because of the logarithmic growth of the interaction cross-section with energy (see e.g. \[28\]).
mic rays diffusing away from their production region \[37\]. Taking this into account, our analysis includes sources in the Galactic Plane as possible sources of neutrino signal, along with the overall diffuse emission from the ISM.

The spectrum of inverse Compton emission from cosmic ray electrons is expected to be soft in the energy band above 100 GeV, because of the onset of Klein-Nishina regime for scattering of photons of the interstellar radiation field. Modelling of the inverse Compton spectrum \[22\] shows that its slope is \(p_{\gamma,IC} \simeq 3\) in this energy band. Taking into account that the observed slope of the all-sky spectrum is \(p_{\gamma} \simeq 2.4\) one could find that the inverse Compton contribution in the all-sky \(\gamma\)-ray flux is small above 100 GeV.

Detection of neutrino and \(\gamma\)-ray emission from Galactic cosmic rays with \(p = 2.5\) powerlaw index provides an important clue for understanding of formation of Galactic cosmic ray spectrum. It is consistent with the possibility that the cosmic rays are injected with the powerlaw spectrum with the slope \(p = 2.1...2.2\) predicted by the DSA models \[4,8\], with the energy dependence of the diffusion coefficient \(D(E) \sim E^{1/3}\) as expected for the Kolmogorov turbulence spectrum of the ISM \[11\] and with the anisotropy of the cosmic ray flux \[10\].

Dominance of the Galactic component of the astrophysical neutrino flux also implies a significant extragalactic \(\gamma\)-ray and neutrino flux from star forming galaxies. Indeed, the straightforward theoretical interpretation of the \(p \simeq 2.5\) slope, introduced above, suggests that this slope should be generically found in all star forming galaxies, with a possible exception of starburst galaxies in which cosmic rays lose energy before escaping. A consequence of this fact is that the entire population of the star forming (non-starburst) galaxies produces neutrino and \(\gamma\)-ray spectra with the slope \(p_{\gamma,\nu} \simeq 2.4\). Correcting the estimates of the \(\gamma\)-ray and neutrino flux from the star forming galaxies from Fig. \[4,19,20\] for the harder slope of the cosmic ray spectrum we find that the cumulative \(\gamma\)-ray flux from sources of this type should provide significant contribution to the EGB, see Fig. \[2\]. The expected neutrino flux from star forming galaxies is at the level of 10-50% of the all-sky neutrino signal. The upper estimate stems from an assumption that the slope of the neutrino and \(\gamma\)-ray spectra of the starburst galaxies is \(p_{\gamma,\nu} = 2.2\) (as in the Ref. \[20,25\]), the lower estimate assumes that starburst galaxies have on average the same slope of the \(\gamma\)-ray and neutrino spectra as normal galaxies, \(p_{\gamma,\nu} = 2.4\).

Although the slope and normalisation of the Galactic neutrino spectrum are fixed by the \(\gamma\)-ray data at lower energies, there is no certainty about its high-energy end. The Galactic cosmic ray spectrum should have a knee like suppression at high energies produced by the escape from the Galactic Disk and / or high-energy cut-off due to the absence of sources capable of particle acceleration beyond certain energy range \[1\]. This opens a possibility of negligible contribution of other extragalactic sources, like AGN and / or GRBs \[16,18\] to the neutrino flux in the PeV energy range.

The locally observed TeV – PeV cosmic ray proton spectrum appears ”peculiar” in the sense that its slope is different from the slope of the average Galactic cosmic ray spectrum. This peculiarity could not be related to the specific of the propagation process in the local ISM, because in this case also the spectra of atomic nuclei would be affected. It could also hardly be related to the process of injection from the Galactic cosmic ray sources in general, because in this case the proton spectrum would be systematically softer than the nuclei spectrum everywhere in the Galaxy and this would be visible in the softer \(\gamma\)-ray / neutrino spectrum of the Galaxy.

The most probable reason for the peculiarity of the locally observed proton spectrum is in the change of the cosmic ray injection rate over the last \(T \sim 10^7\) yr. Massive injection of cosmic rays in the local ISM some \(10^7\) yr ago could have resulted in an increase of the cosmic ray energy density at all energies. Faster diffusion of higher energy particles should have led to faster ”wash out” of the excess density at high-energies and, as a consequence, to a temporary softening of the local cosmic ray spectrum. The dynamics of the energy dependent ”wash out” of the excess density of cosmic rays is different for protons and atomic nuclei, because the nuclei are also affected by spallation. Typical spallation time scale is shorter of comparable to \(10^7\) yr \[1\], so that after \(T \sim 10^7\) yr the softening of the spectrum could still be present in the proton component of the cosmic ray flux, but is already (almost) not observed in the heavier nuclei components. Several candidate past events in the local Galaxy, like e.g. the event which produced an expanding ring of molecular clouds, the Gould Belt \[38\], could be considered. Further improvement of the quality of neutrino, \(\gamma\)-ray and cosmic ray data should provide an identification of the event(s) responsible for the variability of the local cosmic ray injection rate.

To summarise, we have used a multi-messenger (\(\gamma\)-ray, neutrino and cosmic ray) data to show that the IceCube astrophysical neutrino signal is dominated by the flux from the Milky Way. These new data also suggest that the Galactic cosmic ray spectrum is harder than previously thought, with the slope \(p \simeq 2.5\) in the TeV – PeV energy range. These facts provide a new understanding of the mechanisms of injection and propagation of cosmic rays and have far reaching implications for the problem of identification of Galactic cosmic ray sources.

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\[1\] Berezinskii V.S., Bulanov S.V., Dogiel V.S., Ginzburg V.L., Ptuskin V. S., The Astrophysics of Cosmic Rays, Nothr-Holland, Amsterdam (1990).
FIG. 2: Gamma-ray and neutrino spectra of the full sky. Neutrino data and the EGB spectrum (grey hatched range) are the same as in Fig. 1. Black data points show Fermi/LAT all sky spectrum. Thick errorbars are for statistical error, thin errorbars are the systematic error. Red and blue thick solid curves show the spectrum of neutrino and γ-ray emission generated by interactions of protons with the powerlaw spectrum with the slope $p = 2.5$. The curves are dashed above $E = 100$ TeV to highlight an uncertainty of the high-energy extrapolation of the model. Thin solid blue and dashed red curves show the estimates of the γ-ray and neutrino fluxes from star forming galaxies. The red hatched range shows the uncertainty of the estimate of neutrino flux due to the uncertainty of the contribution of starburst galaxies.

SUPPLEMENTAL MATERIAL

Fermi/LAT data analysis

Our analysis uses all publicly available Fermi / Large Area Telescope (LAT) data collected over the period from August 2008 till June 2014. We have processed the data using the Fermi Science Tools v9r32p5, a standard software package, provided by the Fermi collaboration to reduce the data, obtained by the Fermi/LAT. We have used the Pass 7 "reprocessed" event selection.

We have filtered the event lists using the gtselect tool with parameter evclass=3, which leaves the γ-ray events and rejects most of the cosmic ray background events. To produce the all-sky spectrum shown in Fig. 2, we have used the aperture photometry method, applied to the full sky. An estimate of the exposure in each energy bin was done using the gtexposure tool with the option apcorr=no (there is no need to correct the exposure for the point spread function for the full sky). We have

2 http://fermi.gsfc.nasa.gov/ssc/data/analysis/
3 http://fermi.gsfc.nasa.gov/ssc/data/analysis/scitools/aperture_photometry.html

[17] Mannheim K., Protheroe R.J., Rachen J.P. Phys. Rev. D63, 023003 (2001).
[18] Waxman E., Bahcall, J., Phys. Rev. Lett., 78, 2292 (1997).
[19] Loeb A., Waxman E., JCAP, 05, 003 (2006).
[20] Tambora I., Ando S., Murase K., JCAP, 09, 043 (2014).
[21] Abdo A.A., et al., Phys. Rev. Lett., 104, 101101 (2010).
[22] The Fermi LAT collab., arXiv:1410.3696 (accepted to Ap.J.) (2014).
[23] Ackermann M. et al., Ap.J., 755, 164 (2012).
[24] Hauser M.G., Dwek E., ARA&A, 39, 249 (2001).
[25] Abdo A.A., et al., Ap.J., 709, L152 (2010).
[26] Stecker F.W., Ap.J., 228, 919 (1979).
[27] Berezinskii V.S., Gaissier T.K., Halzen F., Stanev T., Astropart.Phys., 1, 281 (1993).
[28] Kappes A., Hinton J., Stegmann C., Aharonian F.A., Ap.J., 656, 870 (2007).
[29] Tchernin C., Aguilar J.A., Neronov A., Montaruli T., A&A, 560, A67 (2013).
[30] Neronov A., Semikoz D., Tchernin C., Phys.Rev., D89, 103002 (2014).
[31] M. Kachelriess and S. Ostapchenko, Phys. Rev. D 90, 083002 (2014) [arXiv:1405.3797 [astro-ph.HE]].
[32] Atwood W.B., et al., Ap.J., 697, 1071 (2009).
[33] Ahn H.S., et al., Ap.J., 707, 593 (2009).
[34] Neronov A., Semikoz D., Phys. Rev., D89, 041302 (2014).
[35] Nolans L., et al., Ap.J., 755, 229 (2012).
[36] Neronov A., Semikoz D., Phys. Rev., D85, 083008 (2012).
[37] Gehlers N., et al., Nature, 404, 363 (2000).
verified that such an approach gives the result which is consistent with the results obtained using the likelihood analysis. In particular, the spectrum of the $|b| > 20^\circ$ part of the sky, calculated using the aperture photometry method is identical to that reported by Fermi collaboration in the Ref. [22] over the entire energy range from 100 MeV up to 1 TeV.

Model spectra of neutrinos and $\gamma$-rays from cosmic ray interactions

For the model calculation of the $\gamma$-ray and neutrino spectra shown in Fig. 2 we have used the parameterisations of the pion production and decay cross-sections in $pp$ interactions proposed in the Ref. [23]. We did not include separately the calculations of $\gamma$-ray and neutrino production in interactions of the cosmic ray nuclei and instead assumed that the nuclear contribution to the $\gamma$-ray and neutrino spectrum is identical (in shape) to the proton contribution. Account of the nuclei only changes the overall normalisation of the $\gamma$-ray and neutrino spectra. We suppose that such an approach is sufficient for our purposes. A more advanced calculation should take into account the inevitable differences in the spectra of protons and nuclei which occur in the knee energy range of the cosmic ray spectrum. However, the knee energy in different parts of the Galactic Disk (and Halo) generally depends on the structure of turbulent magnetic fields, which is already uncertain in the local Galaxy and is largely uncertain in different components of the Galaxy on larger scales. Thus, we consider the precision of our modelling sufficient for the purposes of the paper.

Previous modelling if the spectra of diffuse $\gamma$-ray emission by Fermi collaboration [24] has invoked the possibility of significant inverse Compton contribution to the flux from different parts of the sky in the energy band 10-100 GeV [4]. The necessity of high level of inverse Compton flux appeared because the characteristic slope of the spectrum of Galactic cosmic rays was assumed to be $p = 2.7$, rather than $p = 2.5$ (as derived here). This has resulted in a steep slope of the pion decay $\gamma$-ray emission and, as a consequence, in a low pion decay flux in the energy band above 10 GeV. Our results suggest that instead, the typical (averaged over the sky) slope of the neutral pion decay emission spectrum is harder and the pion decay flux is significant (or even dominant) in the energy band above 10 GeV, up to the $\sim 1$ TeV energy range.

PeV-TeV spectra of atomic nuclei

Measurement of the slopes of the spectra of the cosmic ray atomic nuclei in the TeV-PeV energy range have to combine the data collected using two different observational techniques.

Direct measurements of the spectra of individual atomic nuclei are done by detectors operating in space or on high-altitude balloons in the energy range below $\approx 100$ TeV. In our analysis we use the data of Cosmic Ray Energetics And Mass (CREAM) balloon borne detector [5].

At higher energies, only indirect measurements are possible using the Extensive Air Shower (EAS) arrays like KArlsruhe Shower Core and Array DEtector (KASCADE) and its extension KASCADE-Grande [8]. Extraction of the spectra different components of the cosmic ray flux with such a technique suffers from uncertainties of the modelling of the EAS. In the energy band around 1 PeV, these uncertainties were, up to recently, dominated by the uncertainties of hadronic interactions. Recent measurements of these interactions in the relevant energy range at the Large Hadron Collider (LHC) have led to a significant reduction of this type of uncertainties. Account of the new LHC data has allowed a measurement of the spectra of groups of atomic nuclei: $p$, He, CNO, Mg-Si and Fe in the PeV-EeV energy range by KASCADE-Grande experiment [8].

An additional difficulty of the measurement of the slope of the spectra of atomic nuclei lies in the presence of the "knee" feature in the 1-100 PeV energy range [9]. Soon after the discovery of the knee in 1960th, Ginzburg and Sirovatsky have proposed an explanation of the knee by a change of the regime of diffusion / scattering of cosmic rays in the ISM [8]. One of predictions of this model was that the knee energy should scale with the charge $Z$ of the nucleus. In a recent work [10], detailed numerical modelling of propagation of cosmic rays in the regular and turbulent Galactic magnetic field has demonstrated that the change of regime of propagation of cosmic rays through the ISM indeed takes place in the knee energy range and that the model spectra of all groups of nuclei reproduce the KASCADE and KASCADE-Grande measurements of the shapes of the knees for different elements [8]. The numerical model of the Ref. [10] was found to reproduce also the recovery of the spectra above the knee and the observed energy-dependent levels of anisotropy of the cosmic ray spectrum. An illustration of the application of the escape model of the knee [8] is shown in Fig. 8.

The analysis of CREAM collaboration, reported in the Ref. [5] shows that the best fit value for the powerlaw model of the spectra is $p_{\text{cream}} = 2.66 \pm 0.04$, shown in the figure. From Fig. 8 one could see that the quality of the fit of the CREAM data with a powerlaw model is good for proton spectrum, but not for the CNO group spectrum. The CNO spectrum shows a hardening above several TeV ($\sim 100$ GeV energy per nucleon) energy. This hardening is detected by several experiments, see Refs. [5-7]. One more problem with the powerlaw fit CNO data is that
FIG. 3: Spectra of protons (bottom) and CNO elemental group (top) as measured by CREAM detector in the 1-100 TeV energy band [5] and by KASCADE-Grande air shower array in the 1-100 PeV energy range [8]. Spectra of individual elements measured by CREAM are shown with the respective labels (C,N,O) by blue, green and red data points. Black data points in 1-100 TeV range show the total spectrum of the three elements. Grey data points in the 1-100 PeV range show the KASCADE measurements. Black data points in the 10-100 PeV range are KASCADE-Grande measurements [6]. Grey shaded area shows the model calculations of the spectrum from the Ref. [10]. The scatter of the model calculations reflects fluctuations of the shape of the spectrum due to the discreetness of the source distribution. The slope of the model spectrum below 1 PeV is $p = 2.5$. Dashed line shows the fit to the CREAM data alone, derived in the Ref. [5].

its extrapolation to higher energies under-predicts the KASCADE flux measurement, see Fig. 3. A fit of the common CREAM and KASCADE-Grande spectrum with a simple powerlaw with the slope $p = 2.66$ is ruled out by more than $5\sigma$, while a cut-off powerlaw with a cut-off at $E_{\text{cut}} \simeq 5 \times 10^{16}$ eV (the best fit value) is inconsistent with the data at $2.5\sigma$.

Instead, a common fit to the CREAM and KASCADE data above 3 TeV with the model from Ref. [10], which has a reduced $\chi^2 < 1$, has a slope $p \simeq 2.5$. The grey shaded model in the $E > 1$ PeV energy range, shown in the upper panel of Fig. 3 shows the numerical model of the knee from Ref. [10], calculated assuming $p = 2.5$ Galactic CNO spectrum. The width of the region corresponds to the fluctuations of cosmic ray flux due to the discreetness of the source distribution (assumed to be the distribution of supernovae). One can see that overall the $p = 2.5$ model provides a satisfactory description of the CREAM + KASCADE-Grande data.

Similar modelling could be done for the nuclei of other groups, see Ref. [10]. In all cases, the numerically modelled knee structure of the spectrum, superimposed onto the $p = 2.5$ powerlaw spectrum, provides a satisfactory description of the CREAM and KASCADE-Grande data. The only exception is the spectrum of protons, shown in the bottom panel of Fig. 3. In this case, the powerlaw fit to the CREAM spectrum alone is satisfactory. The slope of the powerlaw is softer than $p = 2.5$. The extrapolation of the powerlaw over-predicts the flux measurement by the KASCADE-Grande.

[1] Atwood W.B., et al., Ap.J., 697, 1071 (2009).
[2] The Fermi LAT collab., arXiv:1410.3696 (accepted to Ap.J.) (2014).
[3] Kelner S.R., Aharonian F.A., Bugayov V.V., Phys.Rev., D74, 034018 (2006).
[4] Ackermann M., et al., Ap.J., 750, 3 (2012).
[5] Ahn H.S. et al., Ap.J., 707, 593 (2009).
[6] Ahn H.S., et al., Ap.J., 714, L89 (2010).
[7] Adriani O., et al., Science, 332, 69 (2011).
[8] Apel W.D. et al., Astropart. Phys., 47, 54 (2013).
[9] Berezinskii V.S., Bulanov S.V., Dogiel V.S., Ginzburg V.L., Ptuskin V. S., The Astrophysics of Cosmic Rays, Noth-Holland, Amsterdam (1990).
[10] Giacinti G., Kachelriess M., Semikoz D., Phys. Rev., D90, 041302 (2014).