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Model for the diffuse gamma-ray and neutrino emission of the Milky Way at multi-TeV energies

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We are developing new model propagation of cosmic rays in the Galaxy from their sources in three dimensional magnetic field. The model automatically takes into account anisotropic distribution of cosmic rays around their sources at all stages of their propagation in the Galaxy up to their escape. Cosmic rays are interacting with interstellar gas and produce secondary gamma-ray and neutrinos. For this interactions we use recent AAfrag model. We compare predictions of the model for individual sources and for several regions of the Galaxy with existing gamma-ray and neutrino data. We show that in the Galactic Ridge the gamma-ray spectrum measured by Fermi and the neutrino spectrum measured by IceCube and ANTARES are in perfect agreement and are consistent with hadronic origin of diffuse gamma-ray flux corresponding to $1/E^{2.5}$ cosmic ray spectrum.

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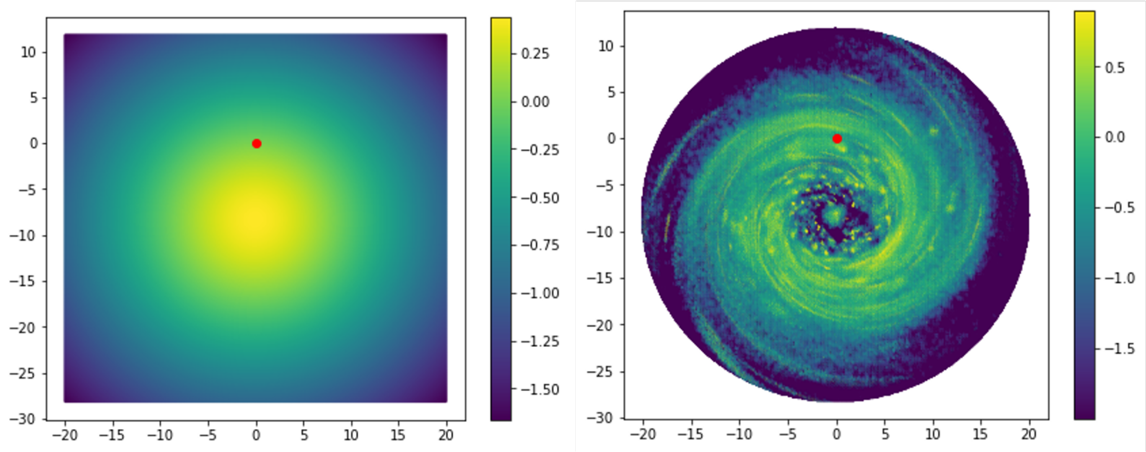

Figure 1: Left: Distribution of cosmic rays in axi-symmetric model of Vernetto-Lipari [10]. Right: distribution of cosmic rays in Galaxy in 3d model from ref.[1].

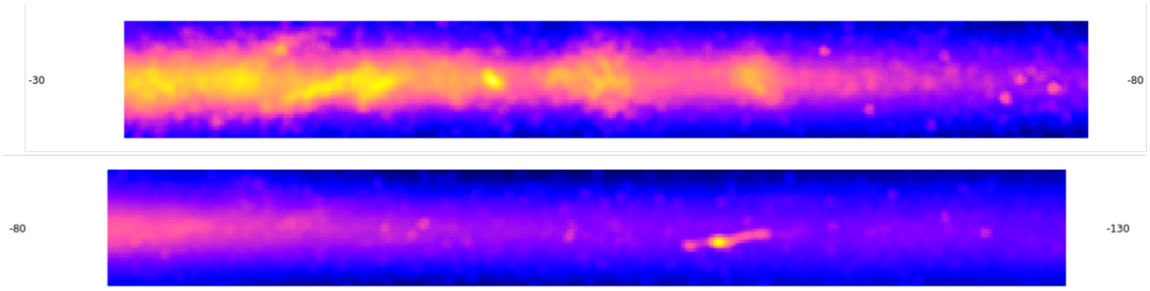

Figure 2: Examples of hadronic contribution to the gamma-ray flux from regions of Milky Way in the model of ref. [1].

1. Gamma-ray flux from new three-dimensional cosmic ray model of Milky Way

We are developing a new model of cosmic ray propagation of TeV-PeV cosmic rays in the Galaxy. Three dimensional space-dependent and time-dependent structure of cosmic ray flux in this model was recently reported in ref. [1], see also contribution of G. Giacinti in the Proceedings of this conference [2].

In this model, cosmic rays injected by isolated sources follow propagation in the Galactic magnetic field in Jansson-Farrar model [3, 4]. In order to obey the measured B/C ratio and allow cosmic rays to escape from the Galaxy the turbulent component of the Galactic magnetic field needs to be reduced, compared to the original Jansson-Farrar model [5–7]. Note that standard assumption of the diffusion coefficient in turbulent field, required to cosmic ray escape from the Galaxy, corresponds to the magnetic field which is five orders of magnitude below the measured μG values [7]. Taking into account the regular magnetic field of the Galaxy reconciles cosmic ray escape and μG values of the magnetic field [7].

We use statistical distribution of Super-Nova (SN) in the Galaxy to simulate distribution of cosmic ray sources in space and time. Not all sources can accelerate cosmic rays up to highest energies of the galactic cosmic rays, around the knee of the cosmic ray spectrum. We assume that

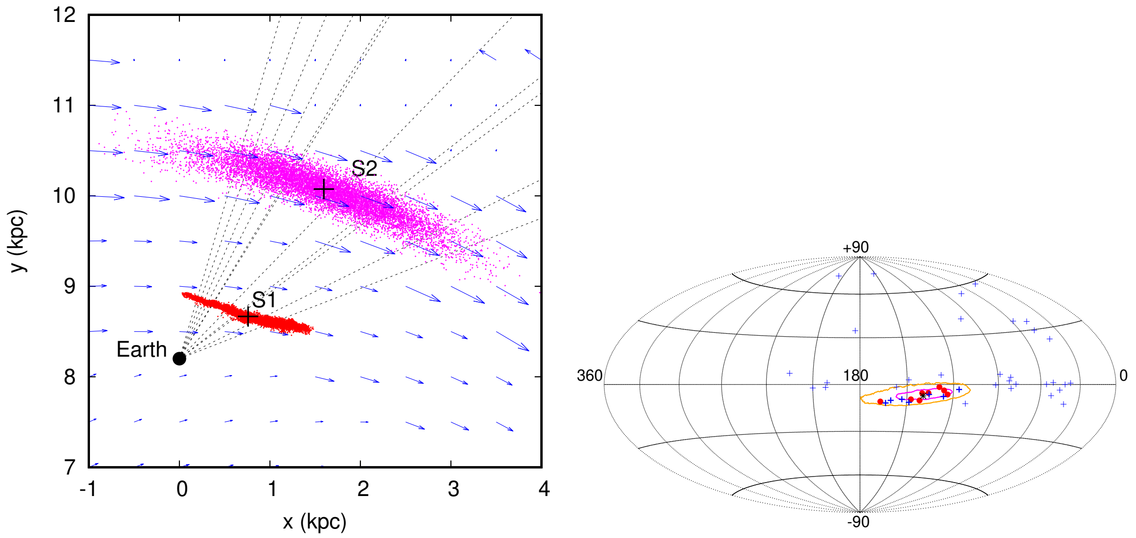

Figure 3: Left: cosmic ray distribution from nearby source in outer Galaxy from ref. [12]. Right: Gamma-rays with $E > 400$ TeV in Tibet ASγ and simulated contribution of source from left panel from ref.[12].

every source produces 10^{50} erg in cosmic rays with power law spectrum $1/E^{2.2}$ up to maximal energy $E_{max} = 10^{17}$ eV. For such parameters we find that only about 1.6% of all SN need to be able to accelerate cosmic rays up to PeV to explain the observed cosmic ray flux around the knee.

We use the escape model to explain knee in the cosmic ray spectrum. In this model [5, 6], the regime of propagation of cosmic rays changes from diffusive to small angle scattering at the energy corresponding to the maximum length scale of the turbulent magnetic field (around 20 pc in the Galactic disk). The sharp knee feature is guaranteed due to such change of the propagation regime. In Fig. 1 we show the spatial distribution of PeV cosmic rays. Left panel shows an example of an axi-symmetric model of ref. [10], while the right panel shows the model of ref. [1]. The position of the Sun is shown by the red dot. Cosmic ray flux is normalized to the value measured at Earth. Colorbar presents variation of cosmic ray flux in logarithmic scale.

We calculate the γ-ray and neutrino fluxes from cosmic ray interactions with interstellar gas using the AAFrag code [8, 9]. Assuming global gas distribution in disk described in ref. [10], we calculate three dimensional volume luminosity and integrate it along the line of sight. In Fig. 2 we show examples of γ-ray fluxes in from the inner and outer Galaxy. The total flux is a combination of fluxes from diffuse component generated older sources and fluxes of individual young sources. Details of the modelling of flux will be discussed in a publication [11] in preparation.

2. Gamma-ray flux from cosmic rays from single source in the outer Galaxy

We compare predictions of our model with existing γ-ray and neutrino data. In a first example, we have simulated a contribution of a single nearby source in the outer Galaxy to the Tibet ASγ PeV band signal [13]. There is set of 7 events around 7-10 degrees below the Galactic plane in the outer Galaxy (Fig. 3). We consider the possibility that this part of emission from the outer Galactic Plane is produced by cosmic rays spreading from a single SN source either in the Local or Perseus arm of the Milky Way. We show that the anisotropic diffusion of multi-PeV cosmic rays along the

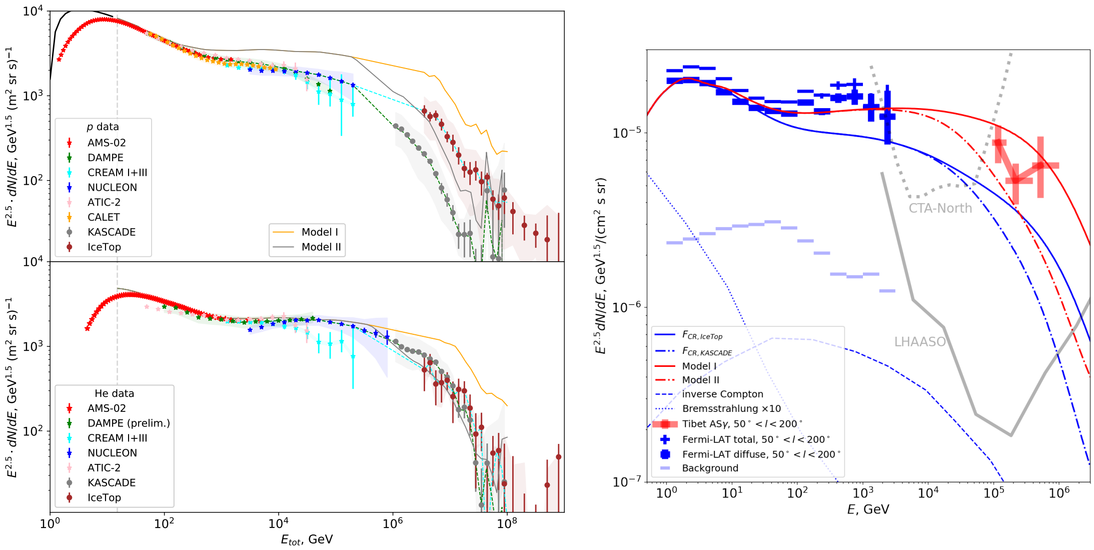

Figure 4: Left: cosmic ray models, which fit local proton and He data with power law flux indexes around 2.7 for protons and 2.5 for He. Right: gamma-ray flux from models presented on left and Fermi and Tibet ASγ gamma-ray measurements from ref. [14].

Galactic magnetic field can produce an extended source spanning ten(s) of degrees on the sky, with a flux-per-unit-solid-angle consistent with the Tibet ASγ measurements. Observations of this new type of very extended sources, and measurements of their morphology can be used to characterize the anisotropic diffusion of PeV cosmic rays in the Galactic magnetic field.

In Fig. 3 left we show a sketch of a 5 kpc × 5 kpc region of interest of the Galactic plane, seen from above. The black dot represents the Earth's location, and the two black crosses are those of "S1"(source in the local –Orion– arm) and "S2"(source in the Perseus arm). The red and magenta dots represent the locations, projected onto the Galactic plane, of the 10^4 simulated cosmic rays that have escaped respectively from S1 and S2. The blue arrows show the directions of the regular Galactic magnetic field in the Jansson-Farrar model [3, 4]. and their lengths are proportional to the field strength. The thin black dotted lines represent the directions (projected onto the Galactic plane) of the 11 Tibet ASγ events at $100° < l < 170°$ and $|b| < 15°$. The right panel shows the 398–1000 TeV sky map in the Galactic coordinates The black star shows the location of the source S1 on the sky. The magenta and orange contours encircle the regions with the largest surface brightness, containing respectively 50% and 95% of the total γ-ray emission. The red dots show simulated random sets of gamma-ray events that would be detected in the 398–1000 TeV energy range by a detector with Tibet ASγ's exposure. The blue crosses represent the 38 Tibet ASγ events in the 398–1000 TeV energy range from Ref. [13].. The 7 Tibet ASγ events represented with thicker lines show the events falling within the source extension.

3. Diffuse γ-ray and neutrino flux from the inner and outer Galaxy

In ref. [14] we considered two phenomenological models for cosmic ray spectra, one which follows the local proton measurements above a few hundred GeV with the spectrum $1/E^{2.7}$ and

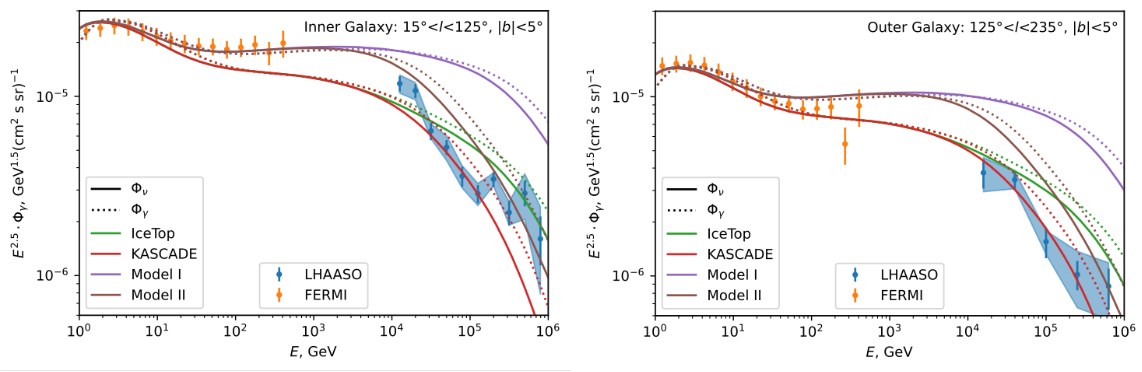

Figure 5: Same models which used in Fig.4 for combined gamma-ray data of LHAASO [16] and Fermi LAT [17] in inner and outer Galaxy.

another one, which follows the local He spectrum with the slope $1/E^{2.5}$ above a few hundred GeV. Considering that both acceleration and propagation in the Galaxy can not make difference between the slopes of the proton and He spectra, those measurements either signal that several source populations are present or point to a contribution from a local source with ratio of p to He different from the average one [15]. For each of two models we assumes a cutoff in the spectrum following either KASCADE or IceTop observations, see Fig. 4 left.

The Tibet ASγ experiment measured diffuse γ-ray flux over a large fraction of the Galaxy $50° < l < 200°$ [13]. In ref. [14] we have taken the Fermi LAT measurements from the same region of sky and used the AAFrag code [8, 9] for calculation of the γ-ray flux from cosmic rays in this region. Right panel of Fig. 4 shows that models based on the local proton spectrum underpredict both Fermi LAT and and Tibet-ASγ measurements in this part of sky. To the contrary, in the model which follows the local He spectrum the γ-ray spectra for both KASCADE-based and IceTop-based composition models provide a satisfactory description of the joint Fermi/LAT + Tibet-ASγ γ-ray spectrum.

Recently LHAASO collaboration has reported analysis of diffuse γ-ray emission in two regions of Galaxy [16]. The main difference between LHAASO and Tibet ASγ measurements is that LHAASO has masked not only point but also extended sources in their diffuse flux analysis. The γ-ray flux measured with Fermi LAT data exactly for same regions of sky was calculated in ref.[17]. In Fig. 5 we compare those data for inner (left) and outer (right) Galaxy with models of ref. [14].

Combined gamma-ray data for inner Galaxy $25° < l < 125°$, $|b| < 5°$ are consistent with the local He models with cosmic ray flux with power law index $\Gamma = 2.5$, however, change of slope of in gamma-ray flux in inner Galaxy related to knee in cosmic ray spectrum happens at lower energy compared to the local measurements. To the contrary, the flux in the outer Galaxy is well fitted with proton-like local spectrum with the slope $\Gamma = 2.7$ and cutoff similar to the one derived from the KASCADE data. Fits to the spectra of diffuse gamma-ray emission from the inner Galactic disk indicate that in this part of the Galaxy the data are consistent with the cosmic ray spectrum slope 2.5 all over the GeV-PeV energy range. This is not the case locally and it seems to be not the case for the cosmic ray spectrum in the outer Galactic disk.

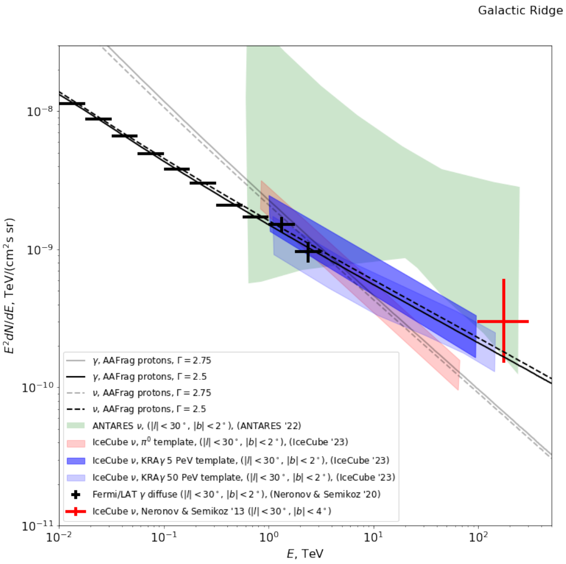

Figure 6: Multi-messenger spectrum of the diffuse emission from the Galactic Ridge. Fermi-LAT γ-ray data are from [23]. IceCube neutrino flux estimate shown by the red data point is from [22]. ANTARES hint of the signal from the Galactic Ridge is from [21]. Lighter and darker blue shaded regions show the estimates of the IceCube signal from the direction of the Ridge done following the method of Ref. [19] assuming the KRAγ all-sky model templates with cut-offs at 5 PeV and 50 PeV. Red shaded region shows the estimate of the Galactic Ridge flux derived using the π^0 all-sky model template of [19]. Black (grey) curves show the γ-ray (solid) and neutrino (dashed) pion decay spectra calculated for power-law distributions of protons with slope $\Gamma = 2.5$ ($\Gamma = 2.75$), calculated using AAFrag code [8, 9]. All neutrino fluxes correspond to the all-flavor $\nu + \bar{\nu}$ emission with 1σ uncertainty bands.

4. Neutrino flux from the Galactic Ridge

IceCube collaboration has recently reported the detection of neutrino signal from the Milky Way [19] in the "cascade" type neutrino-induced events in the detector. Evidence for the presence of the Galactic component in the astrophysical neutrino flux in the same detection channel has been previously seen in an earlier data release of IceCube [20]. ANTARES collaboration has reported an excess of muon neutrino events from the Galactic Ridge, the central part of the Milky Way disk within Galactic longitude $|l| < 30^\circ$ [21]. This excess is consistent with the initial estimates of the neutrino flux from the Ridge derived from the IceCube data [22].

In Fig. 6 we show the estimate of the neutrino flux from the direction of the Ridge $-30^\circ < l < 30^\circ$, derived in ref. [**?**], for KRAγ and π^0 models of IceCube publication [19], as well as neutrino flux from same region measured by ANTARES [21] and estimates of the neutrino flux from the Ridge derived from first few years of IceCube data [22]. Those neutrino fluxes are in good agreement with Fermi LAT diffuse gamma-ray flux from the Galactic Ridge [23]. A model of pion decay emission from cosmic ray population with powerlaw spectrum with the slope $\Gamma = 2.5$ can explain the multi-messenger data in this region. In Fig. 6 we show gamma-ray and neutrino fluxes calculated using AAFrag code [8, 9].

The consistency of the IceCube and ANTARES neutrino flux estimates with the measurements of the diffuse γ-ray emission from the Ridge in the TeV energy range by Fermi-LAT shows that the bulk of the multi-messenger emission from this part of the sky originates from the decays of pions produced in interactions of high-energy protons and atomic nuclei, rather than from electron interactions. This is the first time when such an unambiguous distinction between "hadronic" and "leptonic" emission mechanisms can be done.

5. Conclusions

In this work we summarize the status of development of a new three-dimensional Galactic cosmic ray model and it's applications to γ-ray and neutrino data. The model cosmic ray distribution in Galaxy from ref.[1] is shown in the map in Fig. 1 right. Examples of diffuse γ-ray flux seen from the Earth in this model are shown in Fig. 2. We show a model of possible contribution of a single source in the outer Galaxy in the Tibet ASγ flux measurements in Fig. 3 [12]. The left panel shows the spatial distribution of cosmic rays around the source position and the right panel presents the distribution of the simulated γ-rays, which agrees well with the distribution of γ-rays in the Tibet ASγ data.

Diffuse γ-ray flux from different parts of the Galaxy is shown in Fig. 4 for the Tibet data [13] and in Fig. 5 for the LHAASO data, combined with the Fermi-LAT γ-ray flux in the corresponding regions. In both figures we present our modelling from ref. [14]. We conclude that the model predicts well the γ-ray flux in the inner Galaxy with the spectrum similar to the local He measurements $\Gamma = 2.5$, while the flux in the outer Galaxy can be fitted with the pion decay emission from cosmic ray distribution with the slope $\Gamma = 2.7$, similar to that of the local proton flux.

Finally we present in Fig. 6 from ref. [18] we show that recent IceCube detection of Galactic neutrinos combined with Fermi-LAT data show that diffuse gamma-ray flux from galactic Ridge has hadronic origin can be explained by cosmic rays with spectrum slope $\Gamma = 2.5$ in this region.

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