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Large Scale Anisotropy of Cosmic Rays and Directional Neutrino Signals from Galactic Sources

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Abstract. We investigate the neutrino $\leftrightharpoons$ cosmic ray connection for sources in the Galaxy in terms of two observables: the shape of the energy spectrum and the distribution of arrival directions. We also study the associated gamma ray emission from these sources.

Above about 10 GeV, cosmic ray (CR) energy spectrum observed at Earth falls roughly as a power law, with flux decreasing almost three orders of magnitude per energy decade until eventually it exhibits a strong suppression near 60 EeV [1]. Closer examination reveals several other spectral features. A steepening of the spectrum between $J(E) \propto E^{-2.67\pm0.07}$ and $E^{-3.07\pm0.11}$ has been labeled the "knee" and is prominent at $E_{\rm knee} \approx 3$ PeV [2]. A less prominent "second knee", corresponding to additional softening of the spectrum, $J(E) \propto E^{-3.52\pm0.19}$, appears above 0.3 EeV [3]. At $E_{\rm ankle} \approx 3$ EeV a pronounced hardening of the spectrum appears, the so-called "ankle" feature [4].

The Earth lies near the edge of the Galaxy, so if CR sources are concentrated in the Galactic disk one would expect to observe a dipole anisotropy in the flux, with a relative excess in the direction of the Galactic center. Hints of this anisotropy have in fact emerged. The IceCube Collaboration has reported [5] an excess of events in the 400 TeV sky-map (29° smoothing) at right ascension $\equiv \alpha = 256.6°$ and declination $\equiv \delta = -25.9°$, with a pre-trial significance of 5.3σ. The data also show a deficit at $\alpha = 73.1°$ and $\delta = -25.3°$, with a pre-trial significance value of 8.6σ (optimized smoothing of 21°). After correcting for the trials, only the deficit remains significant beyond the 5σ level, with a post-trial significance of 6.3σ.

The right ascension distribution of the flux can be characterized by the amplitudes and phases of its Fourier expansion [6]

$$J(\alpha) = J_0[1 + \mathcal{A}\cos(\alpha - \phi) + \mathcal{A}'\cos(2(\alpha - \phi')) + \dots]\,, \qquad (1)$$

where J_0 is the monopole intensity, $\mathcal{A}$ and $\mathcal{A}'$ are the first and second harmonic amplitudes and ϕ and ϕ' the associated phases. The right ascension harmonic analysis cannot reveal the component of the anisotropy vector $\vec{\delta}$ along the Earth rotation axis, $\delta_\parallel = \vec{\delta}\sin\lambda$, where λ is the latitude of the direction where the flux is maximum. The first harmonic amplitude $\mathcal{A}$ is related to the component of anisotropy in the equatorial plane, $\delta_\perp = \vec{\delta}\cos\lambda$, via $\mathcal{A} \simeq \delta_\perp\,\overline{c_\delta}$, where $\overline{c_\delta}$ is the mean value of the cosine of the event declinations [7]. The first harmonic amplitude reported by the IceCube Collaboration is $\mathcal{A} = (3.7 \pm 0.7_{\rm stat.} \pm 0.7_{\rm stat}) \times 10^{-4}$ and the associated phase is $\phi = 239 \pm 10.6_{\rm stat.} \pm 10.8_{\rm syst.}$. These results are in agreement with previous observations by EAS-TOP Collaboration which, for 370 TeV, reported $\mathcal{A} = (6.4 \pm 2.5) \times 10^{-4}$ with $\phi = 204.0 \pm 22.5$ [8].

Recently, the Pierre Auger Collaboration reported an analysis of the first harmonic modulation in the right ascension distribution of the events recorded from 1/1/2004 to 12/31/2010 with the surface detector (SD) array, and from 9/12/2007 to 4/11/2011 with the infill array [9]. This analysis takes advantage of the wide range of energy (10 PeV – 100 EeV) that the Pierre Auger Observatory is able to scan thanks to the infill array. While no clear evidence for anisotropy has been found, yet it is interesting to note that in the range above 1 EeV, 3 out of the 4 energy bins are above the 99% C.L. expectation from isotropy, *i.e.* only one percent of isotropic samples would show equal or larger amplitudes. The phase evolution in this wide energy range has an interesting behavior, with a smooth transition from a common phase of $\phi = 270^\circ$ in the bins below 1 EeV to a phase $\phi = 90^\circ$ above 5 EeV. The phase at lower energies is compatible with the right ascension of the Galactic center, $\alpha_{\rm GC} \simeq 268.4^\circ$. To test the hypothesis that the phase is undergoing a smooth transition, the Pierre Auger Collaboration began to independently analyze data obtained after April 2011. After 18 months the new and independent data set is showing a similar trend [9]. Another 18 months of data collection to reach an aperture of $21{,}000\,{\rm km}^2\,{\rm sr}$ with the independent data set is needed before the trend can be confirmed. It is interesting to note that despite the possible hints for cosmic ray anisotropy discussed above, any such anisotropy would be remarkably small (at the % level). The existing limits on the equatorial amplitude $\delta_\perp$ and the reported phases by the various experiments are shown in Fig. 1.

To quantify the spectral features characteristic of Galactic CR models we adopt the "leaky box" picture, in which CRs propagate freely in the Galaxy, contained by the magnetic field but with some probability to escape which is constant in time. The local energy density is given by

$$n_{\rm CR}(E) \equiv \frac{4\pi}{c} J(E) \approx Q(E)\ \tau(E/Z), \tag{2}$$

where $Q(E) \propto E^{-\alpha}$ is the generation rate of primary CRs and $\tau(E/Z) \propto E^{-\delta}$ is the rigidity-dependent confinement time (for details, see e.g. [13]). Fits to the energy dependence of secondary to primary ratios yield $\delta = 0.6$ [14]. For a source index $\alpha \simeq 2.07$, which is close to the prediction of Fermi shock acceleration, inclusion of propagation effects reproduces the observed spectrum. However, $\delta = 0.6$ results in an excessively large anisotropy which is inconsistent with the upper limits shown in Fig. 1 [15]. Consistency with anisotropy can be achieved by adopting a Kolmogorov index, $\delta = 1/3$ [16, 17]. The apparent conflict with the secondary to primary composition analyses can be alleviated through small variations of the energy dependence of the spallation cross sections, or variation in the matter distribution in the Galaxy [16]. This hypothesis implies a steeper source spectrum, $\alpha \simeq 2.34$.

It is helpful to envision the CR engines as machines where protons are accelerated and (possibly) permanently confined by the magnetic fields of the acceleration region. The production of neutrons and pions and subsequent decay produces neutrinos, γ-rays, and CRs. If the CR source also produces high energy neutrinos, then pion production must be the principal agent for the high energy cutoff on the proton spectrum. Conversely, since the protons must undergo sufficient acceleration, inelastic pion production needs to be small below the cutoff energy; consequently, the plasma must be optically thin. Since the interaction time for protons is greatly increased over that of neutrons due to magnetic confinement, the neutrons escape before interacting, and on decay give rise to the observed CR flux. The foregoing can be summarized as three conditions on the characteristic nucleon interaction time scale $\tau_{\rm int}$; the neutron decay

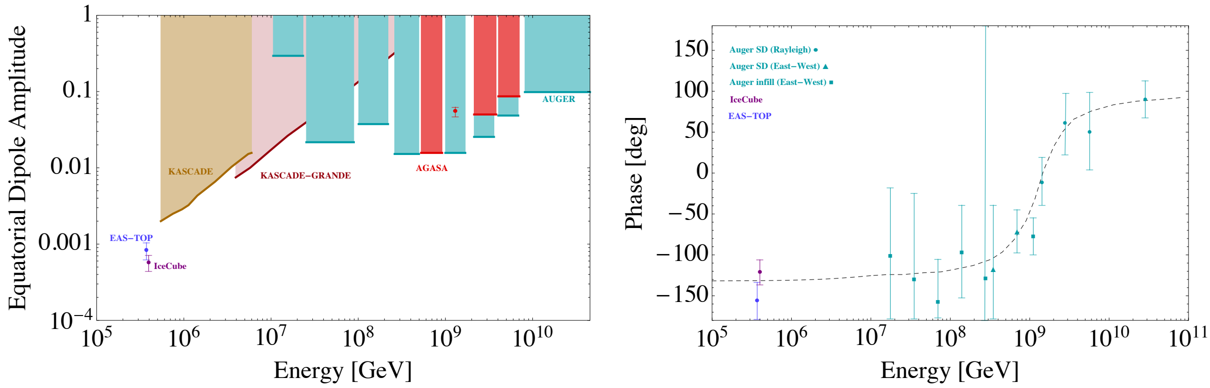

Figure 1. Left: Measurements of the first harmonic amplitude (corrected by the mean value of the cosine of the event declinations) by IceCube [5], EAS-TOP [8], and AGASA [10]. The shaded regions are excluded by null results of searches by KASCADE (@ 95% C.L.) [11] and KASCADE-Grande (@ 95% C.L.) [12], Auger (@ 99% C.L.) [9], and AGASA collaborations [10]. **Right:** Phase of the first harmonic as a function of energy as reported by the IceCube [5], the EAS-TOP [8], and the Pierre Auger [9] collaborations. The phase shows a smooth evolution from the Galactic center towards the Galactic anti-center region.

lifetime τ_n; the characteristic cycle time of confinement $\tau_{\rm cycle}$; and the total proton confinement time $\tau_{\rm conf}$: (i) $\tau_{\rm int} \gg \tau_{\rm cycle}$; (ii) $\tau_n > \tau_{\rm cycle}$; (iii) $\tau_{\rm int} \ll \tau_{\rm conf}$. The first condition ensures that the protons attain sufficient energy. Conditions (i) and (ii) allow the neutrons to escape the source before decaying. Condition (iii) permits sufficient interaction to produce neutrons and neutrinos. These three conditions together define an optically thin source [18].

If CR sources in the Galaxy are optically thin, then one would expect a flux of neutrinos with a spectrum $\propto E^{-2.34}$. If the maximum attainable energy of cosmic rays in the Galaxy is $E_{\rm max} \sim 1 - 3$ EeV, by Hillas criterion [19] we would expect protons to be accelerated to $E^p_{\rm max} = E_{\rm max}/26 \sim 40$ PeV and therefore secondary neutrinos to be be produced with energies of up to 2 to 3 PeV.

Quite recently the IceCube Collaboration has reported a preliminary observation of 26 neutrino candidates [20], in addition to but at lower energies than the two ~ 1 PeV neutrinos reported earlier in 2013 [21]. Taken together, these 28 events constitute a 4.1σ excess compared to expectations from background. Interpretation of these results, however, does not appear to be entirely straightforward. For instance, if one makes the common assumption of an unbroken E_ν^{-2} neutrino energy spectrum, then one expects to observe about 8-9 events with higher energies than the two highest energy events observed thus far. Recently, we have investigated the compatibility between the IceCube observations and the hypothesis of an unbroken power-law spectrum arising from optically thin Galactic neutrino sources, finding that a cosmic neutrino flux per flavor, averaged over all three flavors,

$$\frac{dF_\nu}{d\Omega dA dt dE_\nu} = 6.62 \times 10^{-7} \left(\frac{E_\nu}{1~{\rm GeV}}\right)^{-2.3} ({\rm GeV} \cdot {\rm cm}^2 \cdot {\rm s} \cdot {\rm sr})^{-1}\,, \qquad (3)$$

is consistent with the data reported thus far [22].

The assumption underlying the leaky box model is that the energy density in CRs observed locally is typical of other regions of the Galactic disk. If so, the total power required to maintain the cosmic radiation in equilibrium can be obtained by integrating the generation rate of primary

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CRs over energy and space. Using (2), we obtain

$$\frac{d\epsilon_{\rm CR}}{dt} = \int d^3x \int Q(E)\, dE = V_G \frac{4\pi}{c} \int \frac{J(E)}{\tau(E/Z)} dE\,, \tag{4}$$

where $V_G \sim 10^{67}$ cm^3 is the Galactic disk volume [24]. For $E_{\rm knee} < E < E_{\rm ankle}$, we conservatively assume that the trapping time in the Galaxy scales with energy as $\tau = 2 \times 10^7 (E_{\rm GeV}/Z)^{-1/3}$ yr [25]. In this case the power budget required to fill in the spectrum from the knee to the ankle is found to be $d\epsilon_{\rm CR}/dt \simeq 2 \times 10^{39}$ erg/s [25]. From this, we deduced elsewhere [22] the energy transfer fraction from the parent protons to the pions which ultimately produce the observed neutrinos, demonstrating that pp collisions are more likely to produce the neutrino flux than are $p\gamma$ collisions, and indeed that the power budget is enough to reproduce the neutrino flux in (3).

It is interesting to employ existing limits on high energy photons to check the plausibility of our hypothesis that the IceCube excess is of Galactic origin. γ rays are produced by π^0 decays at the same optically thin sources where neutrinos are produced by $\pi^\pm$ decay. As described in [13], one can predict a differential γ ray flux based the best-fit single power law ν flux discussed in this paper, and compare to measurements. The CASA-MIA 90% C.L. upper limits on the integral diffuse γ ray flux, I_γ for energy bins,

$$\frac{E_\gamma^{\rm min}}{\rm GeV} = 3.30 \times 10^5,\ 7.75 \times 10^5,\ 2.450 \times 10^6\,, \tag{5}$$

are

$$\frac{I_\gamma}{\rm cm^{-2}\ s^{-1}\ sr^{-1}} < 1.0 \times 10^{-13},\ 2.6 \times 10^{-14}, 2.1 \times 10^{-15}\,, \tag{6}$$

respectively [26]. A more rigorous comparison would involve measurements on the diffuse γ fay flux within about 15° of the Galactic plane. The CASA-MIA Collaboration has in fact studied γ ray emission from the direction of the Galactic plane, reporting the flux limits as a fraction of the CR flux [27] rather than an integral bound. Comparing the relative fractions from the all-sky analysis to the Galactic plane analysis indicates that constraining the observation to the Galactic plane region does indeed lead to tighter constraints:

$$\frac{I_\gamma}{\rm cm^{-2}\ s^{-1}\ sr^{-1}} \lesssim 5.0 \times 10^{-14},\ 1.3 \times 10^{-14},\ 2.1 \times 10^{-15}\,, \tag{7}$$

at the 90% C.L. Under the simplifying assumption that there is no photon absorption, the integral photon fluxes we predict based on our single power law hypothesis (in units of photons cm^{-2} s^{-1} sr^{-1}), above the energies specified in (5), are

$$\int_{E_\gamma^{\rm min}} \frac{dF_\gamma}{d\Omega dA dt dE_\gamma} dE_\gamma = 4.2 \times 10^{-14},\ 1.4 \times 10^{-14},\ 3.1 \times 10^{-15}\,. \tag{8}$$

For the first two energy bins, the predicted fluxes saturate the 90% C.L. measurements of CASA-MIA, while the last bin slightly exceeds the 90% C.L. bound. This does not, however, imply that the Galactic origin hypothesis is ruled out at 90% C.L. First of all, one must keep in mind that sources which are optically thin up to $E_\gamma \sim 100$ TeV may not be optically thin at higher energies, suggesting that the importance of photon bounds in establishing the origin of the IceCube excess should be considered with some caution. Even if we ignore this caveat, we still do not know the maximum neutrino energy reached at acceleration sites, so the maximum photon energy is likewise unknown. In addition, absorption becomes important in the energy regime covered by the last bin, as mean free path of PeV photons in the CMB is about 10 kpc.

Note that $R_{\rm G} \sim 10$ kpc, leading to an interesting signature: Photons coming from "our half" of the Galaxy will be largely unattenuated, while those from the farther half will be significantly attenuated. Since both photons and neutrinos point back to the sources, coordinated comparisons of neutrino and photon data will facilitate a completely new exploration of the highest-energy Galactic sources. As described in [13], taking into account absorption of the photon flux for $E_\gamma^{\rm min} > 1$ PeV leads to about a 12% reduction in the predicted photon flux. Furthermore, varying the photon maximum energy cutoff of Eq. (8) to,

$$\frac{E_\gamma^{\rm max}}{\rm PeV} = 6,\ 7,\ 8\,, \tag{9}$$

we obtain

$$\int_{E_\gamma^{\rm min}}^{E_\gamma^{\rm max}} \frac{dF_\gamma}{d\Omega dA dt dE_\gamma} dE_\gamma = 2.1 \times 10^{-15},\ 2.3 \times 10^{-15},\ 2.4 \times 10^{-15}\,. \tag{10}$$

From the discussion above, we can see there are several ways to comply with the CASA-MIA bound. For instance, $E_\gamma^{\rm max} = 6$ PeV is already consistent with the measured bound, even without absorption. For higher energies, absorption provides enough reduction of the photon flux to retain consistency with measurements. It is also worth noting that the comparison discussed here is based on experimental bounds on the all-sky γ ray flux.

Only the IceCube Collaboration has thus far reported constraints on γ ray emission between 1 and 10 PeV from the direction of the Galactic plane. Bounds from the IceCube 40 string configuration [30], are not restrictive enough to challenge the Galactic origin hypothesis. However, within 5 years of data taking with the complete IceCube configuration of 86 strings, enough statistics will be gathered to elucidate the $\nu - \gamma$ ray connections.

Finally we comment on the consistency between the arrival direction distribution of the IceCube excess and the hypothesis that the sources are nearby. Fourteen of the 26 reported neutrino events arrive from within about 15° of the Galactic plane, including one of the two highest energy events, which coincides with the Galactic center (within errors) [28] . The highest energy event is outside of this angular window, but (as noted in [29]) does correspond with a possible hotspot in the IceCube photon search [30]. This could reflect emission of neutrinos and γ rays from a common, nearby source, as γ rays do not survive propagation further than ~ 10 kpc. The recently discovered large reservoir of ionized gas extending over a large region around the Milky Way [31] could provide the target material required for neutrino production outside the Galactic disk in models in which proton diffusion extends to the Galactic halo [32, 33]. However, given the current statistics and the insufficient understanding of the atmospheric (in particular the prompt neutrino [34]) background, the arrival direction distribution neither favors nor disfavors a Galactic origin [29, 35]. More data are required to settle the issue.

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References

[1] R. Abbasi *et al.* [HiRes Collaboration], Phys. Rev. Lett. **100**, 101101 (2008) [arXiv:astro-ph/0703099]; J. Abraham *et al.* [Pierre Auger Collaboration], Phys. Rev. Lett. **101**, 061101 (2008) [arXiv:0806.4302].

[2] J. R. Hörandel, Astropart. Phys. **19**, 193 (2003) [arXiv:astro-ph/0210453]; P. Blasi and E. Amato, JCAP **1201**, 010 (2012) [arXiv:1105.4521].

[3] T. Abu-Zayyad *et al.*, Astrophys. J. **557**, 686 (2001) [arXiv:astro-ph/0010652].

[4] D. J. Bird *et al.* [HIRES Collaboration], Phys. Rev. Lett. **71**, 3401 (1993).

[5] R. Abbasi *et al.* [IceCube Collaboration], Astrophys. J. **746**, 33 (2012) [arXiv:1109.1017 [hep-ex]].
[6] J. Linsley, Phys. Rev. Lett. **34**, 1530 (1975).
[7] J. Aublin and E. Parizot, Astron. Astrophys. **441**, 407 (2005) [astro-ph/0504575].
[8] M. Aglietta *et al.* [EAS-TOP Collaboration], Astrophys. J. **692**, L130 (2009) [arXiv:0901.2740 [astro-ph.HE]].
[9] A. Aab *et al.* [Pierre Auger Collaboration], arXiv:1307.5059 [astro-ph.HE]. For previous analyses, see also, P. Abreu *et al.* [Pierre Auger Collaboration], Astrophys. J. Suppl. **203**, 34 (2012) [arXiv:1210.3736 [astro-ph.HE]]; P. Abreu *et al.* [Pierre Auger Collaboration], Astropart. Phys. **34**, 627 (2011) [arXiv:1103.2721 [astro-ph.HE]]. A summary of the Auger results has been preseneted in these proceedings, O. Deligny [for the Pierre Auger Collaboration], arXiv:1403.5569 [astro-ph.HE].
[10] N. Hayashida *et al.* [AGASA Collaboration], Astropart. Phys. **10**, 303 (1999) [astro-ph/9807045].
[11] T. Antoni *et al.* [KASCADE Collaboration], Astrophys. J. **604**, 687 (2004) [astro-ph/0312375].
[12] M. Stumpert, PhD Thesis, FZKA-7380.
[13] L. A. Anchordoqui, V. Barger, I. Cholis, H. Goldberg, D. Hooper, A. Kusenko, J. G. Learned, D. Marfatia, S. Pakvasa, Thomas C. Paul, and Thomas J. Weiler, JHEAp **1**, 1 (2014) [arXiv:1312.6587 [astro-ph.HE]].
[14] M. Gupta and W. R. Webber, Astrophys. J. **340**, 1124 (1989); S. P. Swordy *et al.*, Astrophys. J. **403**, 658 (1993).
[15] P. Blasi and E. Amato, JCAP **1201**, 011 (2012).
[16] P. L. Biermann Astron. Astrophys. **271**, 649 (1993); P. L. Biermann, T. K. Gaisser and T. Stanev, Phys. Rev. D **51**, 3450 (1995); A. M. Hillas, J. Phys. G **31**, R95 (2005).
[17] S. I. Syrovatskii, Comment. Astrophys. Space Phys. **3**, 155 (1971); V. S. Ptuskin *et al.*, Astron. Astrophys. **268**, 726 (1993); J. Candia, S. Mollerach and E. Roulet, JCAP **0305**, 003 (2003).
[18] M. Ahlers, L. A. Anchordoqui, H. Goldberg, F. Halzen, A. Ringwald and T. J. Weiler, Phys. Rev. D **72**, 023001 (2005) [astro-ph/0503229].
[19] The Hillas criterion states that the maximum attainable energy is limited by the fact that particles can only be accelerated in a region until their Larmor radius exceeds its size. A. M. Hillas, Ann. Rev. Astron. Astrophys. **22**, 425 (1984).
[20] M. G. Aartsen *et al.* [IceCube Collaboration], Science **342**, no. 6161, 1242856 (2013) [arXiv:1311.5238 [astro-ph.HE]]; F. Halzen, arXiv:1308.3171.
[21] M. G. Aartsen *et al.* [IceCube Collaboration], Phys. Rev. Lett. **111**, 021103 (2013) [arXiv:1304.5356].
[22] L. A. Anchordoqui, H. Goldberg, M. H. Lynch, A. V. Olinto, T. C. Paul and T. J. Weiler, Phys. Rev. D, in press [arXiv:1306.5021 [astro-ph.HE]].
[23] T. K. Gaisser, F. Halzen and T. Stanev, Phys. Rept. **258**, 173 (1995) [Erratum-ibid. **271**, 355 (1996)] [arXiv:hep-ph/9410384].
[24] T. K. Gaisser, arXiv:astro-ph/0501195.
[25] T. K. Gaisser, J. Phys. Conf. Ser. **47**, 15 (2006).
[26] M. C. Chantell *et al.* [CASA-MIA Collaboration], Phys. Rev. Lett. **79**, 1805 (1997) [astro-ph/9705246].
[27] A. Borione *et al.*, Astrophys. J. **493**, 175 (1998) [astro-ph/9703063].
[28] S. Razzaque, Phys. Rev. D **88**, 081302 (2013) [arXiv:1309.2756 [astro-ph.HE]].
[29] M. Ahlers and K. Murase, arXiv:1309.4077 [astro-ph.HE].
[30] M. G. Aartsen *et al.* [IceCube Collaboration], Phys. Rev. D **87**, no. 6, 062002 (2013) [arXiv:1210.7992 [astro-ph.HE]].
[31] A. Gupta, S. Mathur, Y. Krongold, F. Nicastro and M. Galeazzi, Astrophys. J. **756**, L8 (2012) [arXiv:1205.5037 [astro-ph.HE]].
[32] F. C. Jones, A. Lukasiak, V. Ptuskin and W. Webber, astro-ph/0007293. V. S. Ptuskin, O. N. Strelnikova and L. G. Sveshnikova, Astropart. Phys. **31**, 284 (2009). V. Ptuskin, Astropart. Phys. **39-40**, 44 (2012).
[33] Precise calculations for neutrino production in the Galactic halo have been recently carried out, A. M. Taylor, S. Gabici and F. Aharonian, arXiv:1403.3206 [astro-ph.HE].
[34] P. Lipari, arXiv:1308.2086 [astro-ph.HE].
[35] A. Neronov, D. V. Semikoz and C. Tchernin, arXiv:1307.2158 [astro-ph.HE].