Implications of the detection of sub-PeV diffuse $\gamma$ rays from the Galactic disk apart from discrete sources

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Very recently, the Tibet-AS$\gamma$ collaboration reported the detection of $\gamma$ rays from the galactic disk in the energy range of 100 TeV – 1 PeV. Remarkably, many of these $\gamma$ rays were observed apart from known very high energy ($E > 100$ GeV) $\gamma$-ray sources. These results are best understood if these diffuse $\gamma$ rays: 1) were produced by a conventional rather than an exotic (i.e. dark matter decay or annihilation) process, 2) have a hadronic rather than a leptonic origin, 3) were produced in impulsive rather than stable sources or, alternatively, in optically thick sources. In addition to that, the detection of the sub-PeV diffuse $\gamma$ rays implies a limit on the flux of neutrinos from the Galactic disk and a lower limit on the rigidity of the cutoff in the Galactic cosmic ray spectrum.

I. INTRODUCTION

Galactic cosmic rays interact with gas and radiation fields inside the sources and in the Galactic volume, producing $\gamma$ rays, electrons, positrons, and neutrinos. $\gamma$ rays and neutrinos travel in straight lines, allowing the observer to discern their source(s). Arrival directions of high energy ($E > 100$ MeV) $\gamma$ rays from Galactic sources are concentrated towards the Galactic plane. A part of Galactic $\gamma$ rays is “diffuse”, i.e. these particles are observed apart from “discrete” (point-like or slightly extended) sources.

$\gamma$ rays of very high ($E > 100$ GeV) and super high energy ($E > 100$ TeV) may be detected with ground-based installations such as imaging atmospheric Cherenkov telescopes (IACT) and air shower arrays (e.g. Tibet-AS$\gamma$). Very recently, the Tibet-AS$\gamma$ collaboration reported the discovery of diffuse $\gamma$ rays concentrating towards the Galactic plane (hereafter A21). This observation has a number of interesting and important theoretical implications, some of which are considered below.

In particular:
1. a conventional (astrophysical) production mechanism of these $\gamma$ rays is favoured over an exotic mechanism (i.e. from dark matter decay or annihilation) (Sect. II)
2. the hadronic production mechanism is more likely than the leptonic one (Sect. III)
3. the high fraction of $\gamma$ rays detected apart from discrete sources implies that the cosmic ray acceleration sites are either optically thick to these $\gamma$ rays or that these accelerators were more active in the past than now (Sect. IV)
4. galactic cosmic ray models with a very low energy of the proton “knee” are excluded if the change in the spectral index of elemental spectra is large enough (Sect. V).

In addition, we note that diffuse Galactic $\gamma$-rays may help constraining the Galactic component of IceCube neutrinos (e.g. [21]).

II. CONVENTIONAL OR EXOTIC PRODUCTION MECHANISM?

Using the model of [22] (hereafter LV18) assuming the production of diffuse $\gamma$ rays by cosmic rays in hadronuclear interactions, A21 show that their data are reasonably well approximated with the LV18 model. However, one could speculate that the flux of $\gamma$ rays reported in A21 could be produced by decay or annihilation of dark matter particles. In this section we assume that the large-scale distribution of Galactic dark matter follows the Navarro-Frenk-White (NFW) density distribution [23].

LV18 proposed a test of dark matter origin for Galactic diffuse $\gamma$ rays using their distribution on the Galactic latitude (see Fig. 17 of LV18 and associated text). Following the approach of LV18, we calculated the angular distributions for the case of dark matter annihilation and decay and compare these with data presented in A21 for the 158–398 TeV energy bin (Fig. 1). Here, for simplicity, the effects of non-uniform sky exposure of the Tibet-AS$\gamma$ array and $\gamma$-ray absorption in the Galaxy [24, 20] were neglected. Estimates show that the proper account of the exposure non-uniformity and the $\gamma$-ray absorption result in a broadening of the latitude distribution.

The decay model poorly fits the data: the resulting latitude distribution is far too broad. Even for annihilating dark matter, this distribution does not provide a good fit to the data. Moreover, the annihilation model is less attractive in view of the unitarity limit on the mass of dark matter particle [25]. Detailed constraints on dark matter decay time / annihilation cross section are in preparation and will be published elsewhere.
III. HADRONIC OR LEPTONIC $\gamma$ RAYS?

Cosmic rays excite turbulence in the interstellar medium, inhibiting the cosmic ray transport outside of their sources [28]. Assuming the diffusion coefficient according to eq. (3) of [29] with $r_s = 10$ pc, $r_t = 100$ pc, $\beta = 1, \delta = 0.35, R_0 = 4$ GV, $D_0 = 4.0 \times 10^{28}$ cm$^2$/s, $D_z = D_0/100$, we estimate the typical time needed to travel the central 20 pc as $\sim 100$ years (this time is somewhat greater for the greater radius of 100 pc, $\sim 200$ years). The typical synchrotron cooling time for electrons is $\approx 2(B/100 \mu G)^{-2}(E_e/500 TeV)^{-1}$ years (e.g. [30]), i.e. about 100 years for $E_e = 500$ TeV and $B = 15 \mu G$. We conclude that for the typical distance to the source in excess of 1 kpc these electrons would be confined inside a 1$^\circ$ circle as seen by a distant observer, resulting in a very sharp concentration of $\gamma$-rays near discrete sources, in stark contradiction to the results of A21 [31]. We note that a similar qualitative argument was put forward in A21, without, however, quantitative estimates. Additional constraints could be obtained from the balance of energy gain and losses during the acceleration process.

IV. THE NATURE OF COSMIC RAY SOURCES

Now consider the escape of protons and nuclei from the sources. The typical escape time is $\sim 100$ years (see the previous section). The typical acceleration time up to the knee [32,33] $t_{acc} \sim D/v_s^2 = (cE)/(3eBv_s^2)$ ($v_s$ is the shock front velocity). For stable Galactic hadronic PeVatrons such as star forming regions [37,41] is $t_{acc} \sim 10^3$ years or even more.

The typical lifetime of 3 PeV cosmic rays in the Galactic volume is $\sim 5 \times 10^4$ years (e.g. [42]). The typical contrast of gas densities between the sources and the Galactic volume is about $10^2 - 10^3$. The number of produced $\gamma$ rays is proportional to the concentration of the gas and the time spent inside particular regions (i.e. inside the discrete sources and inside the Galactic disc, but outside the discrete sources). We conclude that the time spent in sources should be less than several hundred years in order to not overproduce $\gamma$-rays near the discrete sources, in stark contrast to the above estimates. We conclude that the sources are likely to be impulsive or optically thick for $> 100$ TeV $\gamma$ rays.

V. COSMIC-RAY KNEE CONstrained with $\gamma$ RAYS

The spectrum of $\gamma$-rays measured with the Tibet-AS$\gamma$ array together with several model curves is shown in Fig. 2. For model curves, the primary proton spectrum was assumed to follow eq. (2) of [43]. Only primary protons were considered. Black curve corresponds to the proton spectral index below the knee $\gamma_1 = 2.7, \Delta \gamma = 2$, the energy of the knee $E_{br} = 1$ PeV and $\epsilon_c = 10$. Blue curve is for the same parameters, except $E_{br} = 3$ PeV, magnet curve is for the same parameters as black curve, except $\Delta \gamma = 1$. Remarkably, results for smaller $\epsilon_c$ down to 1 are similar to those presented in the graph. We conclude that relatively small values of $E_{br} < 1$ PeV are excluded for sufficiently large values of $\Delta \gamma$. We note that much better constraints could likely be achieved using the data of the LHAASO experiment [44].

VI. CONCLUSIONS

The discovery of diffuse superhigh energy $\gamma$-rays with Tibet-AS$\gamma$ opened a new area of study in $\gamma$-ray as-
tronomy, capable of constraining dark matter properties, probing the Galactic neutrino component, and unveiling the nature of cosmic ray sources. New data are expected from the LHAASO experiment shortly \textsuperscript{15}. Directions around $\gamma$ rays registered with Tibet-AS$\gamma$ (and, hopefully, LHAASO) could be studied with existing IACT arrays H.E.S.S., MAGIC, VERITAS, as well as with the forthcoming CTA array \textsuperscript{16, 46} in order to put further constrain on the possible contribution from discrete sources to the diffuse $\gamma$-ray flux.

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