Updated constraints on WIMP dark matter by radio observations of M31 – other annihilation channels

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This brief paper generalizes dark matter (DM) constraints recently derived in [A.E.Egorov, Phys. Rev. D 106, 023023 (2022)] by radio observations of M31 to all possible annihilation channels (except the cases of neutrinos and photons as primary annihilation products). All the methodology here exactly repeats that in the mentioned paper, where only two representative and popular annihilation channels – $\chi\chi \to b\bar{b}$ and $\chi\chi \to \tau^+\tau^-$ – were considered. It is confirmed here, that in the case of light primary annihilation products $\chi\chi \to \tau^+\tau^-, \mu^+\mu^-, gg, u\bar{u}, d\bar{d}, s\bar{s}, e^+e^-, b\bar{b}$ (and an arbitrary combination of them) the fiducial (averaged over uncertainties) lower mass limit for the thermal weakly interacting massive particle (WIMP) is confined in the range $\approx(40–70)$ GeV, which is bounded by $\chi\chi \to b\bar{b}, \tau^+\tau^-$ cases. Heavier WIMP, which can annihilate to $W^+W^-, Z^0Z^0, t\bar{t}, hh$; can not be probed at the level of thermal cross section, unless one assumes the optimistic cases of DM density and magnetic field distributions in M31. In conclusion, $m_\chi \gtrsim 40$ GeV represents the fiducial channel-independent mass limit for the thermal WIMP with the full uncertainty range estimated to be $\approx(20–90)$ GeV.

I. INTRODUCTION AND MOTIVATION

This paper continues the topic of weakly interacting massive particle (WIMP) dark matter (DM) indirect searches by radio observations of Andromeda galaxy (M31). In general, the idea of WIMP indirect searches is based on the opportunity of WIMP pair annihilation, which produces various highly energetic stable particles, whose signatures can be potentially detected or constrained astrophysically. WIMPs may annihilate in a galactic dark halo producing relativistic $e^\pm$. The latter would generate the synchrotron emission at radio frequencies in the galactic magnetic field (MF). Hence, radio observational data are able to provide certain constraints for WIMP properties. Meanwhile, historically, the first attempt (known to the author) to constrain DM particle properties by radio observations was made in [1]. Specifically our work on M31 began from the approximate model [2], which was recently refined and updated in [3].

The inherent free parameter in the whole field of indirect searches is the primary annihilation products or annihilation channel, which depends on the properties of the specific particle assumed to be WIMP and supersymmetry model in general (see e.g. [4]). DM constraints, which we aim to derive, are phenomenological in the sense that they are not related to any specific DM particle model. Hence, all possible annihilation channels must be treated on an equal basis. Various channels yield different spectra of $e^\pm$ at the injection and, therefore, would have different constraints on the cross section vs. mass. So far we managed to compute only two popular and representative channels for M31 – $\chi\chi \to b\bar{b}$ and $\chi\chi \to \tau^+\tau^-$. This paper adds other possible annihilation channels for the purpose of generality and to obtain channel-independent constraints, thus eliminating this free parameter. All the methodology and radio observational data used are exactly similar to those in [3]. The whole algorithm of [3] was just repeated here for other annihilation channels.

Thus all the details about the algorithm and model are supposed to be seen there.

II. CONSTRAINTS FOR ALL ANNIHILATION CHANNELS

In brief, GALPROP code [5] (v56) was employed together with our DM addition for it [6] in order to model the maps and spectra of the synchrotron emission due to WIMP annihilation in M31. The transport equation for DM $e^\pm$ was solved in 2D including the effect of spatial diffusion. Then the obtained DM emission maps were compared with the observed radio images of M31 over the wide frequency range $\approx(0.1–10)$ GHz. DM constraints were derived employing the central (bulge, i.e. $R \lesssim 3$ kpc) region of M31, where the anticipated intensity of the emission due to DM annihilation is significant. In order to estimate the whole uncertainty range for the constraints, three (MIN, MED and MAX) various possible DM density distributions and three (MIN, MED and MAX) MF/propagation (MF/prop.) configurations (thus yielding nine setups in total) were tested for each WIMP mass and annihilation channel. All together 14 following annihilation channels have been explored:

$$\chi\chi \to \tau^+\tau^-, \mu^+\mu^-, gg, u\bar{u}, d\bar{d}, s\bar{s}, e^+e^-, b\bar{b},$$

$$W^+W^-, Z^0Z^0, t\bar{t}, hh, \gamma\gamma \quad (1)$$

(with $h$ meaning Higgs boson). This required 1161 separate GALPROP runs in total. The particle physics input

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for GALPROP, i.e. DM $e^\pm$ spectra at the injection for various channels, were initially taken from [7–9]. The obtained constraints are shown in Fig. 1. I did not replicate here $\chi\chi \rightarrow b\bar{b}, \tau^+\tau^-$ cases – they can be seen at [3], Fig. 8. The exclusions for $\chi\chi \rightarrow u\bar{u}, d\bar{d}, s\bar{s}, g\bar{g}, c\bar{c}$ lie very close to each other – they differ by few percents, hence they were merged into the single plot. The exclusion lines for heavy primary products start from the points corresponding to the rest mass of the products.

Overall, we do not see any drastic differences between the exclusion bands for the various channels. A general trend is that the exclusion lines for the hadronic channels have smaller slope (i.e. $(\sigma v)_{\text{lim}}$ increases with the mass slower) and wider uncertainty range with respect to the leptonic channels. The wave-shaped peculiarities in the exclusions for $e^+e^-$ channels likely reflects the features of the $e^\pm$ injection spectrum dependence on WIMP mass, since these wave-shaped features repeat similarly for all nine DM density and MF/prop. models. This channel is distinct from others in the sense that $e^\pm$ are the primary annihilation products. Considering the heavier thermal WIMP annihilating to $W^+W^-, Z^0Z^0, t\bar{t}, hh$, it might manifest itself only in the case of optimistic configurations of DM density and MF/prop.

A typical width of the whole uncertainty bands in Figs. 1, [3], 8 in the vertical direction (i.e., over $(\sigma v)$) slightly exceeds one order of magnitude. We also naturally would like to have some representative constraints, which are averaged over the uncertainties. Analogously to [3], the geometric mean of all nine DM density and MF/prop. models was calculated for each channel as a fiducial or effective average constraint. The results are presented in Fig. 2 for all the channels. $\chi\chi \rightarrow b\bar{b}, \tau^+\tau^-$ cases there replicates the green thick lines from [3], Fig. 9. We see that the exclusions for all channels form a relatively narrow band – narrower than one order of magnitude over the cross section at any WIMP mass. This agrees with the results of similar study for Milky Way [10] (Fig. 9 there). Thus, overall, the dependence of constraints on the channel is not strong. The exclusions for $W^+W^-$ and $Z^0Z^0$ channels, as well as for $b\bar{b}, t\bar{t}$ and $hh$ channels, are nearly indistinguishable from each other (at least for WIMP mass range considered here). For $m_x \gtrsim 60 \text{ GeV}$ the exclusions for all channels are mainly confined between those for $b\bar{b}$ and $\tau^+\tau^-$. Table 1 lists the WIMP mass limits for the thermal cross section, which represent the masses at the intersection points of the exclusion curves with the thermal cross section curve at Figs. 1-2. Table 1 shows the fiducial (geometric mean) limits and the uncertainty ranges. The latter is provided separately for two cases: when only DM density uncertainties contribute (MF/prop. is fixed to MED configuration), and the full uncertainties. The latter reaches an order of magnitude for some channels. The ”...” symbol in the table means that the corresponding exclusion curve does not reach the thermal level at any WIMP mass; i.e. our setup is not sensitive enough to probe the respective channel, and any WIMP mass (above the threshold for production of primary products) is allowed. Hence we may divide all the channels into two categories according to the table: the ”fully” probed channels and those, which may manifest themselves only in the case of optimistic DM density / MF / prop. configuration. Let us call the ”fully” probed channels $\chi\chi \rightarrow \tau^+\tau^-, \mu^+\mu^-, g\bar{g}, c\bar{c}, u\bar{u}, d\bar{d}, s\bar{s}, e^+e^-, b\bar{b}$ by light-product channels, and the other ones $\chi\chi \rightarrow W^+W^-, Z^0Z^0, t\bar{t}, hh$ by heavy-product channels. The obtained mass limits does not change our previous conclusion stated in [3], that $m_x \gtrsim (40 – 70) \text{ GeV}$ fiducially for the thermal WIMP.

Another natural opportunity, which should be taken into account, is the annihilation through several channels simultaneously. In this case DM source function [3], Eq. (1) in the transport equation generalizes to the following form:

$$q(R, E) = \frac{1}{2} (\sigma v^2) \left( \rho(R) \right)^2 \sum_i BR_i \frac{dN_i}{dE}(E),$$

where $BR_i$ is the branching ratio to the $i$-th channel, summation goes over all channels and $\sum_i BR_i = 1$. It is easy to prove algebraically, that in the case of an arbitrary mixture of channels the limit for cross section is confined between the limits for the least and most constrained channels in the mixture, when the latter channels are considered alone. The key fact, which enables such ”theorem”, is the linear proportionality between the emission intensity due to DM annihilation and the cross section. This proportionality holds not only for the synchrotron emission, but also for the prompt gammas from DM, inverse Compton scattering emission from DM $e^\pm$ and bremsstrahlung. Thus, this simple theorem has important implications for the whole field of DM indirect searches: once all the possible annihilation channels have been constrained individually, one does not need to compute explicitly their mixtures – the cross section limit for any mixture is always confined between the bounding channels. Hence, we can generalize our obtained constraints to any arbitrary combination of channels: the exclusion curve for the latter would lie between the lowest and highest (at each mass) curves at Fig. 2. The latter is mainly formed by $\tau^+\tau^-, e^+e^-$ and $b\bar{b}$ channels.

A. $\chi\chi \rightarrow \gamma\gamma, \nu\nu, g\bar{g}$ channels

According to e.g. [8], these channels are unusual in the sense that they are suppressed in many models and, hence, are expected to have small branching ratios. For this reason, $\chi\chi \rightarrow \gamma\gamma$ channel (direct annihilation to photons) is typically considered as a small admixture to other channels rather than a dominating channel. This channel still produces few $e^\pm$, but our radio constraints appeared to be very weak for this channel – they reach the thermal level only for the lowest WIMP masses considered. It is evident to constrain this channel effectively by gamma-ray observations.
$\chi\chi \rightarrow \mu^+\mu^-$
$\chi\chi \rightarrow e^+e^-$
$\chi\chi \rightarrow Z^0 Z^0$
$\chi\chi \rightarrow W^+W^-$
$\chi\chi \rightarrow \tau^+\tau^-$

Limiting annihilation cross section $<\sigma v>$ at 95% C.L. [cm$^3$/s]
FIG. 1. (all seven panels above) The limits on annihilation cross section vs. WIMP mass for various annihilation channels marked at each panel ($q \equiv u, d, s$). Each panel shows all nine computed configurations of DM density profiles and MF/prop. The (almost) horizontal dashed line shows the thermal relic cross section.

FIG. 2. The fiducial or effective average exclusions for all the channels together. These exclusions represent the geometric averages of all nine DM density and MF/prop. models.

Thus Fermi-LAT [11] and H.E.S.S. [12] observations of the inner Galactic halo severely excluded the thermal
WIMP annihilating directly to photons up to \( m_x \sim 10 \) TeV! And the next-generation gamma-ray telescopes – HERD [13], GAMMA-400 [14], CTA [15] – are expected to constrain the diphoton annihilation cross section further.

The neutrino channels are constrained much less: according to e.g. [16], \( \langle \sigma v \rangle_{\chi \chi \to \nu \nu} \lesssim 10^{-24} \) cm\(^3\)/s with a little dependence on WIMP mass and neutrino flavor. However, taking into account a small probability (mentioned above) of high branching ratio to neutrinos, this potential channel would unlikely change the "big picture" of the obtained constraints – i.e., the exclusion of the thermal WIMP lighter than several decades of GeV regardless of the channel. And the exclusion for gluonic channel lies among those for "normal" channels – see Table I.

III. CONCLUSIONS AND DISCUSSION

This paper generalized WIMP DM annihilation constraints by radio observations of M31 derived in [3] (for \( \chi \chi \to b \bar{b}, \tau^+\tau^- \) channels) to other possible annihilation channels under exactly the same methodology. Our methodology does not assume anything specific about the intensity of usual astrophysical emission at any frequency inside our region of interest (i.e., M31 bulge region) – i.e. the flat prior was set for this intensity. This makes our constraints rather robust and model-independent.

Fig. 2 illustrates the obtained fiducial (geometric average) exclusions for all the channels. The following useful theorem was proved by the way, which generalizes our limits for the individual channels to their arbitrary mixture.

For any kind of the emission due to DM annihilation, the (upper) limit on the annihilation cross section for some arbitrary combination of annihilation channels is always confined between the limits for the least and most constrained channels from the combination, when the latter channels are considered alone.

Table I lists the thermal WIMP mass lower limits for all the channels: fiducial average and the uncertainty ranges. It was assumed in [3] that the mass limits for all the kinematically allowed channels would lie between the limits for \( b\bar{b}, \tau^+\tau^- \). This assumption was confirmed here quantitatively, as can be seen from the table.

We may outline the following mass limits depending on the DM density / MF / prop. configuration. If one would assume the pessimistic (MIN) configuration, then only light-product channels can be probed, \( m_x \geq (18 - 37) \) GeV depending on the channel. In the opposite case of the optimistic (MAX) configuration, all the channels can be probed and \( m_x \geq (89 - 220) \) GeV depending on the channel. The real DM density / MF / prop. configuration and the respective WIMP mass limit lie most likely somewhere between these hard bounds. If one would like to have some representative (averaged over the uncertainties) limits, then the geometric averages (over nine possible configurations) can be taken: they are possible for the light-product channels only and \( m_x \gtrsim (40 - 70) \) GeV depending on the channel. Indeed, this represents a somewhat fiducial/intuitive limit rather than statistically precise. The outlined mass threshold ranges are also true for any arbitrary mixture of the considered channels according to the theorem above.

The lower bounds of the mass threshold ranges outlined above can be naturally considered as channel-independent mass limits. Thus, we may finally conclude that \( m_x \gtrsim 20 \) GeV represents the hard limit for the thermal WIMP; i.e. the former holds under any reasonable assumptions about DM density and MF distributions, and propagation parameters. \( m_x \gtrsim 40 \) GeV is the fiducial (effective average over the uncertainties) limit, and \( m_x \gtrsim 90 \) GeV is the most optimistic limit.

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