Dark matter synchrotron emission and radio observations

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Abstract. We compute the synchrotron emission induced by electrons produced by DM annihilations inside our galaxy. The signal is compared with observations in a large range of frequencies, from 22 MHz up to 1420 MHz. We set constraints on the DM mass and annihilation cross-section and highlight the impact of astrophysical uncertainties.

1. Introduction
The detection of a non-gravitational signal of Dark Matter (DM) would be one of the greatest pillars of modern physics, simultaneously confirming our views of cosmology, astrophysics and particle physics. This possibility might be not far ahead if DM is in the form of Weakly Interacting Massive Particles (WIMPs), which currently are the most investigated class of DM candidates. Signatures of this scenario include a multiwavelength spectrum associated to radiative emissions involving electrons and positrons generated in WIMP annihilations or decays. In this work, we focus our attention on the galactic synchrotron emission from DM annihilations and we concentrate on observations in the low-frequency range from 22 to 1420 MHz (see Ref. [1]). Low radio frequencies have not been addressed in the past in connection with DM studies, and we will show that they may be quite adequate in the search for DM, especially for low-mass WIMPs. Indeed, for a magnetic field of $\mu$G strength, as typical in the Galaxy, synchrotron emission below GHz-frequency is generated by electrons and positrons with energies well below 10 GeV. In particular, we will show that WIMP candidates annihilating into light leptons with a thermal annihilation cross-sections can be strongly constrained for masses $M_{DM} \leq 10$ GeV.

Radio emission arising from DM annihilation have instead been addressed in Refs. [2, 3] by using higher frequency surveys and by studying heavier dark matter candidates, with a particular focus on the galactic Center by Refs. [4, 5, 6, 7, 8], or in order to reproduce the so called WMAP Haze in Refs. [9, 10, 11]. DM searches with radio observations can also be pursued with the cosmological diffuse radio background, using both intensity [12] and anisotropies informations [13].

In Sec. 2 we describe the formalism used to compute the radio emission induced by DM annihilations. In Sec. 3 we compare the predictions for DM radio fluxes with observations and we derive bounds on the DM annihilation cross sections. We conclude in Sec. 4.
Figure 1. Left: Temperature versus frequency calculated for the galactic poles ($b = \pm 90^\circ$) for different DM masses and annihilation channels. Here we adopt a NFW profile and the MED propagation model. The data points are the temperature at north and south galactic poles averaged in a 10° circle. Right: Temperature versus galactic latitude at 45 MHz. The data corresponds to a thin strip $|l| < 3^\circ$, with $l$ the galactic longitude. Lines are predictions for DM models for $l = 0^\circ$. Blue band corresponds to $|b| < 10^\circ$ and it denotes the directions towards the galactic center region.

2. Synchrotron emission from galactic DM annihilations

The rate and spectrum of electron and positrons injected in the galaxy by DM annihilations depends on the DM density distribution and on particle physics inputs: the DM mass $M_{DM}$, the annihilation cross-section $(\sigma v)$ and the energy spectrum of electrons/positrons per single annihilation, which in turn depends on the particular DM annihilation channel. In our analysis, we consider two DM density profiles, the popular NFW profile, which nicely fits the results of N-body simulations, and an isothermal profile which is instead used as a conservative case of a cored DM distribution. The propagation of cosmic rays electrons is then modeled following a semi-analytical approach [14]. Cosmic rays are assumed to be confined by the galactic magnetic field inside a propagation zone which is described by a cylinder centered at the galactic center with a radius $R_g = 20$ kpc. The number density of electrons per unit of energy $n_e(E, x)$ follows a transport equation which takes into account the spatial diffusion of the electrons and the energy losses due to the interactions with the galactic magnetic field and the interstellar radiation field. The parameters of the propagation model are constrained by cosmic-rays data, notably the Boron over Carbon ratio (B/C) and radioactive isotopes. In order to bracket the uncertainties on the electrons propagation we consider three propagation benchmarks, the so-called MIN, MED, and MAX models. These models are fully compatible with B/C and antiproton/proton ratio observations, describing the extreme behaviors (MIN and MAX) and best fit (MED) of these observables [15]. Finally, the synchrotron flux observed at the Earth results from the integration along the line of sight of the synchrotron emissivity $j_\nu$:  

$$j_\nu(x) = \int dE n_e(E, x) \frac{dw}{d\nu}(x)$$  

(1)

where $dw/d\nu$ denotes the emission power, which depends on the galactic magnetic field (GMF) strength $B(x)$ (see Appendix of Ref. [1] for details). The structure of the GMF is still not well understood. Mainly, it is composed by a regular and a turbulent part, the last one responsible for the diffusive behaviour of the cosmic rays. Here, the total magnetic field is assumed to have a cylindrical symmetry with an exponential dependence on the distance on the galactic center and on the vertical height (more details in Ref. [1]). The normalization at the Sun position is set to 6$\mu$G, which is well consistent with the measurements.
3. Comparison with observations and constraints

Using the formalism explained in the previous section we have generated skymaps of the synchrotron radiation produced by DM annihilations at different frequencies and compared with different radio surveys available. We found that low (≤GHz) radio frequencies are particularly suitable to search for light/intermediate DM masses O(100) GeV. Indeed, both WIMP models with dominant hadronic/bosonic annihilation final states and leptophilic light WIMP models induce a synchrotron spectrum which is softer than the observed galactic one, as shown in Fig. 1. In the right panel of Fig. 1 we compare observations and DM emissions at 45 MHz for a 10 GeV DM particle annihilating into muon pairs and with a thermal annihilation cross section, \((\sigma v) = 3 \times 10^{-26} \text{ cm}^3 \text{s}^{-1}\). The observational data correspond to a thin strip crossing the galactic center and perpendicular to the galactic plane (|l| < 3°). We notice that the emission is more extended for propagation models with larger diffuse height, like the MED and MAX models. This means that in these cases it is possible to search for the DM signal outside the inner galactic center region (|b| < 10°). While the observed radio emission is dominated by the astrophysical background, Fig. 1 suggests that DM could substantially contribute to the radio flux, especially close to the galactic center region. Certainly a possible DM detection is challenged by the large uncertainties which affect the determination of the background. In the following, in order to be conservative we just use the present observational data to constrain DM models, without attempting any background subtraction. In order to that we consider five surveys from 22 MHz to 1420 MHz (see Ref. [1] for more details about the method adopted to set the bounds.) In Fig. 2 we show the results for the muonic channel. Models with DM masses \(M_{DM} \leq 10\) GeV and thermal value of the annihilation cross section are strongly constrained in the case of the NFW profile. Despite the morphology of the emission is quite different for the three propagation models, the derived bounds are instead similar. The constraints significantly weaken for the isothermal profile, which presents a much lower DM density in a large region around the galactic center. Then, we compute the bounds by cutting a large region around the galactic plane by imposing |b| > 15° (right panel in Fig. 2). In general, with this conservative choice, we reduce the uncertainties on the propagation related to possible unaccounted astrophysical effects occurring on the galactic disk. Moreover, the fact that the radio astrophysical background and its uncertainties are maximal in the galactic plane, complicates the searches of DM signals in this region. Therefore, by avoiding the region |b| < 15°, we study the reach of current radio surveys in the DM parameter space focusing on cleaner targets of observations. Interestingly, we find that the bounds are almost unchanged for the MAX model and only slightly affected for the MED one. For the MIN model, they are more altered since the emission is more concentrated.
in the galactic center region.

4. Conclusions
We have argued that radio observations in the low-frequency regime are particularly suitable to search for DM annihilations in the galactic halo. To show that, we have compared available radio surveys with the synchrotron emission produced by DM annihilations for different DM setups and astrophysical assumptions. Assuming a NFW density profile and for realistic galactic magnetic fields, current radio surveys constraint thermal values of DM the annihilation cross section for DM masses $M_{DM} \leq 10$ GeV. We notice that this is the mass range suggested by the signals recently found in some DM direct detection experiments: DAMA [16], CoGeNT [17] and CRESST-II [18].

While we have conservatively focused on the bounds which can be inferred from observations, it could be possible that the present data already contain a significant DM contribution. In Ref. [1] we have tried to single out this DM component using the 408 MHz map as a spatial template to model the galactic CR synchrotron emission in the low-frequency maps. With this method, a DM-induced component softer than the astrophysical galactic synchrotron emission would appear as an excess in the central galactic center region with an approximately spherical shape. We have concluded that present data does not support any evidence for the presence of this additional synchrotron component. However, we expect that future radio surveys, in particular with the LOFAR telescope [19], will improve coverage, angular resolution, and sensitivity in low-frequency radio maps, which may allow to disentangle a faint DM contribution.

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