PROCEEDINGS OF SCIENCE

Sub-GeV Dark Matter and X-rays

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We present bounds on Dark Matter (DM) in the MeV to GeV mass range, obtained by using X-ray measurements from the INTEGRAL telescope. A crucial element, that allows us to derived bounds competitive or stronger than existing ones from other techniques, resides in the inclusion of the contribution from inverse Compton scattering on galactic radiation fields and on the CMB. This contribution is based on [1], to which we refer for additional details.

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1. Context and motivation

The possibility that dark matter (DM) is made up of a *light* particle (for definiteness we intend here a mass between a few MeV and about a GeV) has recently acquired interest, while in the past the search for DM has long been dominated by the paradigm of (heavier) WIMPs [2, 3], although with no convincing WIMP signal observed so far in Direct Detection [4], Indirect Detection [5–7] or Collider searches [8, 9]. Light DM is therefore in a sense a new frontier for dark matter searches, thus requiring new analysis strategies and experimental techniques to achieve the required sensitivity to be accessed [10].

Indirect Detection (ID) refers to searches of Standard Model particles (charged particles, such as electrons and positrons, or neutral ones, such as gamma rays and neutrinos) produced in the annihilation of DM in the Galaxy, with energies at or just below the DM mass. For light DM, concerning charged particles, solar activity holds back such sub-GeV charged cosmic rays and therefore they are not accessible.[1] For gamma-rays, the sensitivity of the Fermi-Lat drops below about 100 MeV: this means that DM particles lighter that about 1 GeV cannot be probed. At lower photon energies, below a few MeV, competitive data are provided by Integral. Between ∼1 and 250 MeV, only relatively old data from Comptel are available and no current competitive experiment exists. Indeed, many authors have advanced proposals to fill what is called the 'MeV gap' in a useful way for DM searches [11–23]. Low energy neutrinos can also be considered, but they are not very competitive with respect to photons (e.g. the projected sensitivity of 20 years of run with the future HyperKamiokaNDE detector is weaker than the existing bound that we will discuss below, and the new ones we will derive) [24, 25].

2. X-rays from sub-GeV DM

An interesting possibility for ID of light DM (which is the one we will entertain here) is to look at energies much lower than that of the DM mass.[2] The basic idea is that electrons and positrons produced in the Galactic halo by the annihilations of DM particles with a mass $m \simeq 1$ GeV naturally possess an energy $E \lesssim 1$ GeV; these electrons and positrons undergo Inverse Compton scattering (ICS) on the low-energy photons of the ambient radiation fields bath (the CMB, infrared light and starlight) thus producing X-rays, which can be searched for in X-ray surveys. Indeed, the ICS process boosts the photon energy from the initial low value E_0 to a final value which is approximately $E \approx 4\gamma^2 E_0$ after scattering off an electron with a relativistic Lorentz factor $\gamma = E_e/m_e$. Therefore, a 1 GeV electron will produce a $\sim$ 1.5 keV X-ray when scattering off the CMB ($E_0 \approx 10^{-4}$ eV). By the same reason, a mildly-relativistic MeV electron will produce a $\sim$ 0.15 keV X-ray when scattering off UV starlight ($E_0 \approx 10$ eV). These arguments roughly define our range of interest for DM masses: $m_{\rm DM} \simeq 1$ MeV $\to$ 1 GeV.[3] So our goal is to explore whether X-ray observations can impose constraints on sub-GeV DM that would otherwise fall below the sensitivity of the

[1] An exception to this point is the use of data from the Voyager spacecraft, which is making measurements outside of the heliosphere [26]. We will comment on the corresponding constraints later.

[2] For former applications of the same idea to heavy, WIMP-like, DM see for instance [27–36].

[3] Note that we are not interested here in keV DM, that can e.g. produce X-rays by direct annihilation or decay. That is a whole other set of searches, e.g. for keV sterile neutrino DM [37, 38].

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more conventional gamma-ray searches. To this end, we focus on data from the INTEGRAL X-ray satellite [39].

By focusssing on DM lighter than a few GeV, we can consider only three annihilation channels:

$$\text{DM}\,\text{DM} \to e^+e^-, \tag{1}$$

$$\text{DM}\,\text{DM} \to \mu^+\mu^-, \tag{2}$$

$$\text{DM}\,\text{DM} \to \pi^+\pi^-, \tag{3}$$

These channels are kinematically open when $m_{\text{DM}} > m_i$ (with $i = e, \mu, \pi$). The pion channel is representative of a hadronic DM channel. We do not consider the annihilation into a pair of neutral pions, since in this case the (boosted to the DM frame) γ-rays do not reach down to the energies covered by INTEGRAL.

For each annihilation channel, the photon flux is given by the sum of two contributions: the emission from the charged particles in the final state (Final State Radiation, FSR, and, whenever relevant, other radiative decays, Rad) and the photons produced via ICS by DM-produced energetic $e^{\pm}$. As mentioned above, the ICS component is produced by scatterings on different light fields: the CMB, infrared dust-rescattered light and optical galactic light. All these components need to be computed carefully (we refer the reader to [1] for all details) and can then be compared to data, in order to derive constraints on Dark Matter. Two examples are presented in Fig. 1, illustrating the main points of our analysis.

We use the data from the INTEGRAL/SPI X-ray spectrometer, as reported in [39], which follows previous work in [40, 41]. For each DM annihilation channel, we compute the total photon flux from DM annihilation in each energy band and per each latitude/longitude bin provided by the experimental collaboration in [39]. We then proceed to derive constraints on Dark Matter in two different ways: we first derive conservative bounds by not including any astrophysical galactic X-ray emission; we then derive more optimistic limits by adopting a model for the astrophysical background and adding a DM component on top of it.

3. Results and discussion

The constraints on Dark Matter annihilation derived in our analysis are reported in Figure 2, which shows our main result, i.e. the overall (conservative) bounds on the annihilation cross section $\langle\sigma v\rangle$ as a function of the DM mass for each of the three annihilation channels. The bounds are obtained by combining the data from all angular and energy bins discusses in Ref. [1] and for the total photon flux originating from both FSR and ICS processes.

The left panel of Figure 3 shows the bounds obtained with a conservative and with a more optimistic procedure (see Ref. [1] for details). The optimistic bounds are more stringent by about half an order of magnitude.

The right panel of Fig. 3 shows the impact of astrophysical uncertainties, that we briefly detail here. First of all, the DM density profile in the Galaxy is uncertain. By changing profile (with respect to the standard NFW profile), all the different components (FSR, Rad and the 3 ICS component) which enter the analysis change. To identify the extent of uncertainty, we adopted in our analysis a

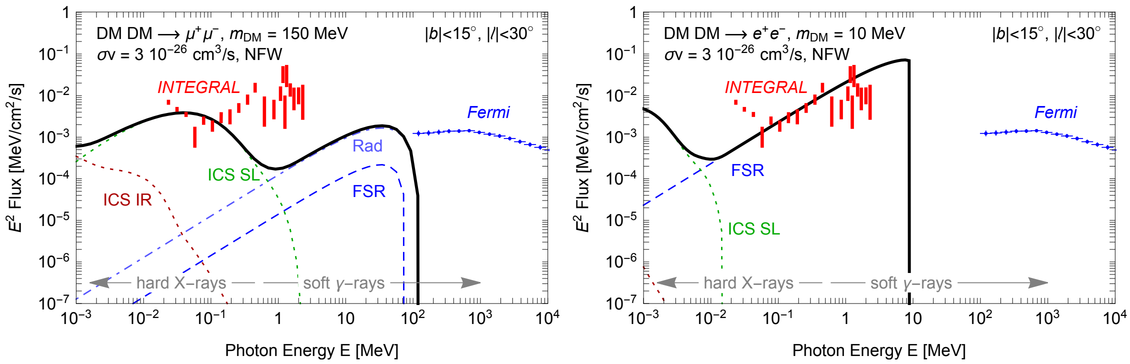

Figure 1: ***Example photon spectra from sub-GeV DM, that illustrate our main points***. Left: *The hard X-ray and soft γ-ray spectrum produced by a 150 MeV DM particle annihilating into $\mu^+\mu^-$. We show the different components in color and the total flux in thick black. The spectrum cuts off before reaching* Fermi*'s data (taken from [44] and reported here just for reference, as they are not the focus of our work), but produces a signal in X-rays that can be constrained by* Integral *(taken from [39], Fig. 7). The Final State Radiation (FSR, blue dashed) and Radiative Decay (Rad, blue dot-dashed) contributions yield signals that pass well below the X-ray data. However, the inclusion of the DM-induced Inverse Compton Scattering (ICS) contribution on the different components of the Galactic ambient light (starlight (SL, green dotted), dust-reprocessed infrared light (IR, brown dotted)) and the CMB (not visible in the plot), leads to a flux which is orders of magnitude larger, thus producing stronger constraints.* Right: *The same for a 10 MeV DM particle annihilating into e^+e^-. In this case the limit is instead driven by the FSR contribution because the DM ICS contributions fall to too low energy for* Integral*. In these illustrations, the signals are computed over the $|b| < 15°, |\ell| < 30°$ region of interest (RoI): in our analysis we actually use smaller RoIs, removing low latitudes.*

cored profile and a peaked NFW one (characterized by a slope $r^{1.26}$ towards the GC). Secondly, the gas density in the Galaxy possesses large uncertainties. This affects the energy losses by Coulomb, ionization and bremsstrahlung, and therefore affects the spectrum of the emitting $e^{\pm}$. We vary by a factor 2 the overall gas density in the Galaxy in order to bracket the size of uncertainty. Thirdly, the ISRF also carries uncertainties, which affect the energy losses by ICS and consequently the ICS signal emission. We vary by a factor of 2 overall the intensity of the ISRF in the Galaxy to mimic this error. Finally, the galactic magnetic field also carries significant uncertainties, which impact the energy losses by synchrotron. We adopt the different magnetic field configurations discussed in [42]. The final effect is however quite limited, since the synchrotron radiation losses are always subdominant in our regime of interest. One sees that, overall, uncertainties span up to two orders of magnitude.

Figure 2 also shows the comparison with other existing constraints. Essig et al. [43] obtained bounds using a compilation of X-ray and soft γ-ray data from Heao-1, Integral, Comptel, Egret and Fermi. They consider only e^+e^-, they do not include the ICS and use Integral data in the region $|b| < 15°, |\ell| < 30°$ rather than in the latitude bins that we use (from which we exclude the Galactic plane). Their bound is similar to ours at small masses, becoming stronger in the mass range 5-40 MeV due to the inclusion of Comptel data, but then becoming weaker for $m_{\rm DM} \gtrsim 50$

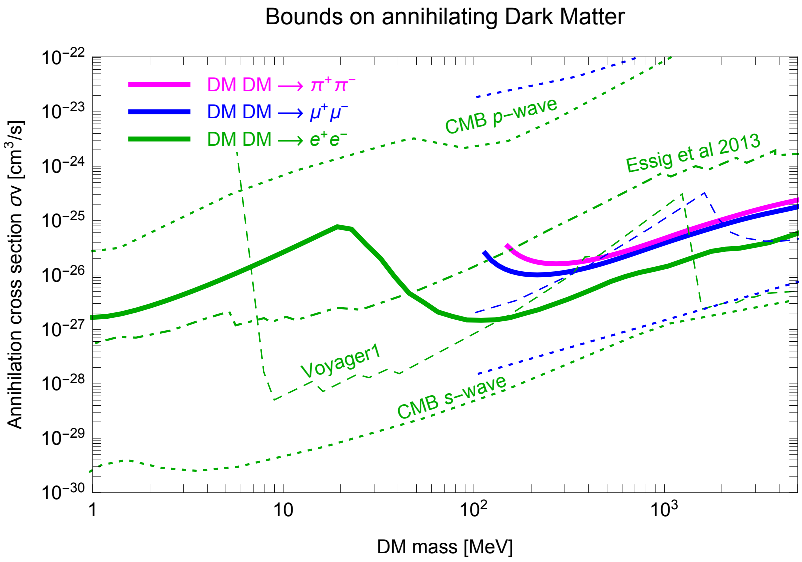

Figure 2: *Our conservative* ***constraints on sub-GeV DM*** *from* INTEGRAL *data (solid thick lines), compared to other existing bounds: from* VOYAGER 1 $e^{\pm}$ *data (dashed green and blue lines, from Boudaud et al. [26]), from a compilation of X-ray data (dot-dashed green line, from Essig et al. [43]) and from the CMB assuming s-wave (dotted green and blue lines in the lower portion of the plot, from Slatyer [45] and Lopez-Honorez et al. [46]) or p-wave annihilation (dotted green and blue lines in the upper portion of the plot, from Diamanti et al. [49] and Liu et al. [50]; these bounds are rescaled up by a factor* $(v/v_{\rm ref})^2 = (220/100)^2$ *since they are provided in the literature for* $v_{\rm ref} = 100$ *km/s while we consider* $v \simeq 220$ *km/s in the Milky Way). For each probe, we use the color code specified in the legend: green for the DM DM* $\to e^+e^-$ *annihilation channel, blue for DM DM* $\to \mu^+\mu^-$ *and magenta for DM DM* $\to \pi^+\pi^-$*. When results on a channel are not present in the literature, the corresponding color is missing. For instance, there are no bounds from these probes on the* $\pi^+\pi^-$ *channel besides ours.*

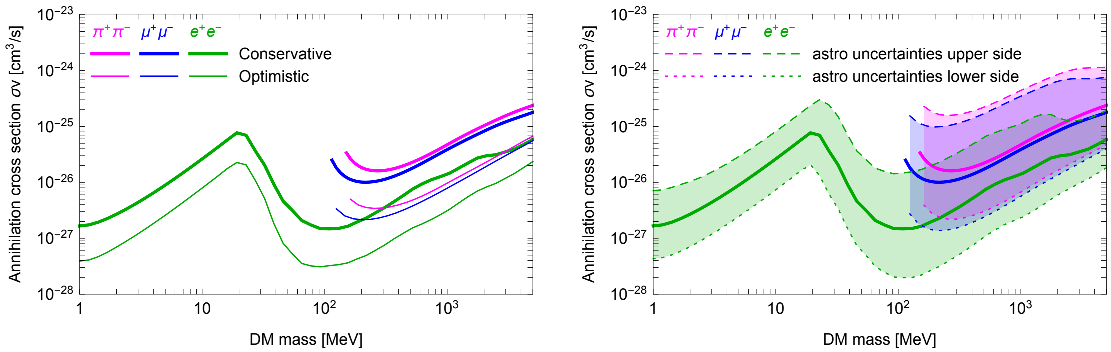

Figure 3: ***Impact of the methodology and the uncertainties on the constraints****. Left: constraints with and without astrophysical background. Right: variation of the bounds due to the astrophysical uncertainties.*

MeV when ICS emission sets in.[4]

[4]Laha et al. [47], in v1 on the arXiv, also present a result in agreement with Essig et al. [43], while in v2 the bound is no longer present.

Boudaud el al. [26] have derived constraints on the e^+e^- and $\mu^+\mu^-$ channel using low energy measurements by Voyager 1 of the $e^\pm$ cosmic ray flux outside of the heliosphere, using different propagation assumptions (we show here the bounds of their model B, characterized by weak reacceleration). Their constraints intertwine with ours over the mass range under consideration, being stronger in the mass range 7-100 MeV and weaker otherwise.

The CMB constraints derived in [45] are the most stringent across the whole mass range (they are given in [45] for the e^+e^- channel and in the earlier study [46] for the $\mu^+\mu^-$ channel, in the mass range of interest).[5] However, they hold under the assumption that DM annihilation is speed-independent (s-wave). If the DM annihilation is instead p-wave, i.e. $\langle \sigma v \rangle \propto v^2$, the bounds weaken considerably. This can be understood qualitatively with the following argument (see [49] and the discussion in [43] for a more precise assessment). The CMB constrains the energy injection from DM annihilations at high redshift (at the time of recombination or somewhat later). For p-wave annihilation, such injection is suppressed since DM is very cold (slow) at that times. In the galactic halo, at present times, DM particles move faster, as an effect of the gravitational collapse that formed large scale structures, and therefore annihilate more efficiently. In other words, a large value for the annihilation cross section at present-day is allowed as it corresponds to a much smaller value and hence at a limited effect at the time of the CMB. The bounds obtained in our analysis, and the other bounds that we report, are sensitive only to DM annihilation at the present time and therefore are independent of the s-wave/p-wave assumption if we assume, as usually done, a constant DM speed in the galactic halo. If instead we introduce a radial dependence of the DM speed, the p-wave bounds are affected. We have estimated that they depart from the s-wave ones by a factor $O(40\%)$, for typical assumptions on the DM speed and density profile in the Galaxy.

Fermi constraints as computed by the Collaboration (e.g. [51]) are not provided for DM masses below a few GeV, therefore we do not report them here.

4. Conclusions

In this analysis, we have derived and obtained constraints on Dark Matter particles in the mass range 1 MeV to 5 GeV. The bounds have been derived from the comparison of X-ray emission from the annihilation of such light DM with data, by using data from the Integral telescope. Our constraints (see Fig. 2) are comparable with previous results obtained with X-ray data and $e^\pm$ data from Voyager 1. However, the bounds we present here are the strongest to-date on the present-day annihilation cross-section of Dark Matter for masses in the range 150 MeV to 1.5 GeV. CMB bounds remain stronger over the whole mass range, but they do rest on the assumption that the DM annihilation cross section at the time of recombination is the same as the present-day one. When this is not the case, the CMB bounds largely relax.

The strength of our constraints is due in large part to the inclusion of Inverse Compton Scattering (ICS) emission, produced by the upscattering of ambient photons by electrons and positrons produced by Dark Matter annihilation. The energy of these ICS photons is typically a few orders of magnitude lower than the DM mass, allowing us to use data from Integral to help plug the 'MeV gap' and produce novel constraints on sub-GeV DM.

[5] Additional bounds, somehow weaker that the CMB ones, can be obtained using only the DM effect on the temperature of the intergalactic medium [48].

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