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Enhancement of the Dark Matter Positron Signal in the Intermediate Mass Black Holes Scenario

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Abstract. A way to search for dark matter is to look for an excess in the cosmic positron spectrum above 1 GeV. In that context, an enhancement of the signal due to dark matter substructures is often introduced and referred to as the boost (or clumpiness) factor. Recent studies show not only that the boost factor does depend on energy, but is a statistical property of the distribution of substructures inside the Milky Way. Bertone's scenarios in which a relatively small number of intermediate-mass black holes are present in the Milky Way are investigated here. For $m_\chi = 100$ GeV, boosts of order 10^3 are found, with a high dispersion, especially near the source energy.

1. Indirect Detection of Dark Matter and Boost Factors

A large collection of observational data now indicates the presence in our Universe of a high proportion of non baryonic and therefore unknown dark matter [1]. Recent experimental results seem to favor scenarios for which dark matter consists of new particles (weakly interactive massive particles, WIMPs). These are for example the small scale anisotropies of the Cosmic Microwave Background measurement [2] and the combination of X-rays and gravitational lensing data from the 1E0657-56 galaxy cluster [3]. Assuming dark matter is made of new particles, these are expected to self-annihilate in the regions when it is concentrated, like *e.g.* at the Galactic Center or in dense dark matter substructures. The annihilation products lead to an exotic primary production of cosmic rays and γ . Of particular interest is the positron case, which energy spectrum shows an excess above 8 GeV with respect to the conventional expectations [4]. This anomaly in the positron spectrum can be interpreted in term of particle dark matter. It is then assumed that WIMPs annihilate in the local halo and produce positrons. Those diffuse in the Milky Way and experience energy losses due to synchrotron radiation and inverse compton scattering. A key point is that for almost any reasonable dark matter model with a proper WIMPs mass, the shape of the exotic spectrum fits quite well the excess but the *normalization* of the flux is too low. Indeed, the presence of dark matter substructures is expected to enhance the positron signal. Astrophysical data do not constrain dark matter substructures properties such as number, mass nor inner density. Consequently the enhancement factor is often considered as a free parameter and is fitted to the data as an energy independent number.

Recently Lavalle *et al.* developed tools in order to perform for the first time the exact calculation of the boost factor [5], let us go through their argument. Let $\rho_s(\vec{x})$ be the smooth part of the dark matter density in the halo at the location \vec{x} . For annihilations taking place in the whole halo considered as being smooth, the exotic positron flux at the Earth takes into account the annihilation rate ($\propto \rho_s^2$) and the positrons propagation in the interstellar medium,

$$\phi_s(E) dE = \frac{1}{8\pi} \frac{\sigma v}{m_\chi^2} dN_{e^+}(E) \int_{halo} \mathcal{G}((E, \vec{x}_\odot) \leftarrow (E_0, \vec{x})) \rho_s^2(\vec{x}) d^3\vec{x} . \quad (1)$$

Here the Green function \mathcal{G} describes the propagation of the positrons from their source \vec{x} towards us \vec{x}_\odot as well as their energy losses from their source energy E_0 to the energy E at which we detect them.

In the presence of a substructure inducing a local over density $\delta\rho$, the total dark matter annihilation rate is $\propto (\rho_s + \delta\rho)^2 \simeq \delta\rho^2$. We can define the *local boost factor* I as the integral

$$I = \int_V \left(\frac{\delta\rho}{\rho_0} \right)^2 d^3\vec{x} , \quad (2)$$

where ρ_0 is a reference density (in the following we take $\rho_0 = \rho_\odot$) and V denotes the volume of the substructure. This number compares the annihilation rate in the dark matter substructure to the one which would occur in an equivalent volume with density ρ_0 . The flux φ_i resulting from annihilations in a single substructure is given by

$$\varphi_i dE = \frac{1}{8\pi} \frac{\sigma v}{m_\chi^2} dN_{e^+}(E) \mathcal{G}_i(E) I_i , \quad (3)$$

where \mathcal{G} is the Green function describing the positrons propagation from the i^{th} substructure.

The total exotic flux receives contributions from both the smooth part of the halo and substructures. We define the *effective* boost factor as the ratio of the total flux to the flux one would expect from the smooth part of the dark matter halo only. Therefore, in the case of N substructures, this quantity is expressed as

$$B = \frac{\phi_{total}}{\phi_s} = 1 + \frac{1}{\phi_s} \sum_{i=1}^N \varphi_i . \quad (4)$$

It appears that the boost factor depends on the inner structure of the over-density (*via* I_i), the considered cosmic ray specie and on the energy (*via* \mathcal{G}). This latter dependence had never been pointed out before the authors of Ref. [5] did, it can induce a modulation of the dark matter signal. In order to make a prediction for the value of the effective boost factor one can expect in the Milky Way, we have to make hypotheses on both the inner structure for the over-densities and their location in the Galaxy. This is a key point since the locations of the over-densities are unknown. We then have to parameterize our lack of knowledge by assuming a statistical repartition. The prediction of B is therefore affected by galactic variance. The physical quantities one can compute are the mean value of the boost factor $\langle B \rangle$ over all possible realizations of the Milky Way and the associated variance.

The general procedure leading to the prediction of the boost factor starts with a cosmological simulation of structure formation. This provides the input to the computation of B : number of substructures, their volume probability and their inner structure. In ref. [5], a computation of the boost factor is performed in the case of dark matter clumps. It is shown that one can expect a boost of order 20 in this scenario, with a variation of order 50 % in the 1 to 100 GeV range. In the following, we focus on a scenario for which substructures consist of dark matter concentrated around black holes of mass of $10^{4-5} M_\odot$.

2. Intermediate Mass Black Holes and their Mini-Spikes

There is now no doubt about the existence of supermassive black holes (SMBHs) in the Universe. However, their formation is still an open question. It appears that the Universe is not old enough to let them grow by accretion from stellar black holes to masses that are measured (up to $10^{6-9} M_{\odot}$). Some scenarios propose that massive objects formed prior to them could play the role of seeds for their formation. Such an object can be a black hole, more massive than a stellar black hole but less than a SMBH. These intermediate mass black holes (IMBHs) can be born early in the universe and then form SMBHs by merging and accretion or still be present in an unmerged form in Galaxies. Two typical IMBHs formation scenarios are detailed in [6], and consist of pop. III stars remnants (A) or collapse of primordial gas (B). It can be shown that if the forming black hole is dipped in a primordial dark matter mini halo that is cusped in the center, then the density near the center will be spectacularly steepened during the black hole formation. For example in case (B), a Navarro-Frenk-White (NFW) type profile with an index $\gamma = 1$ will end with a mini-spike of index $9-2\gamma/4-\gamma = 7/3$. During the evolution of the Universe, IMBHs can merge and destroy their mini-spikes by tidal forces. With regard to the indirect detection of dark matter, the interesting population is therefore the unmerged IMBHs that can populate the Milky Way halo. IMBHs have no specific reason to be near the Galactic disk nor to follow the dark matter density and can consequently never have accreted baryons thus have never been detected. Future Gamma ray and neutrino experiments may be able to detect the annihilation product in mini-spikes and provide a smoking gun signature for the presence of dark matter and IMBHs [6],[7]. In the following, we focus on scenario (B), for which about 100 unmerged IMBHs are expected to orbit in the Milky Way. Cosmological simulation of structure formations are performed by the authors of [6] and their results are used as inputs for the present computation. The relevant quantities are the integral over the mini-spike volume of the squared dark matter density, the number of black holes and their location.

3. Enhancement of the Positron Signal in the IMBHs Scenario

We now wish to quantify the enhancement of the positron signal in the case IMBHs would be present in the Milky Way. We will then consider a very pedagogical case for which a 100 GeV WIMP annihilates into a e^+e^- pair. The annihilation cross section is chosen in order to provide the correct order of magnitude for the relic density, we use here $\sigma v = 3.10^{-26} \text{ cm}^3 \cdot \text{s}^{-1}$. We do not intend here to perform any precise study with specific particle physics models but rather to give an order of magnitude for the enhancement of the positron signal. A more detailed study is being performed for both positrons and antiprotons, and will appear in [8]. The boost factor is computed with regards to a NFW galactic halo with a 20 kpc core. The IMBHs radial probability function is obtained through the numerical simulation and have a different radial dependence. The neutralino cloud around each IMBH is composed of a plateau and a part for which density goes down as $r^{-7/3}$. The mean value of the integral (2) is $\sim 10^6 \text{ kpc}^3$ in the considered case. It means that each black hole is as bright as a 60 kpc sphere with density $\rho_{\odot} = 0.3 \text{ GeV} \cdot \text{cm}^{-3}$, *i.e.* as bright as almost the whole smooth halo. This number arises from the IMBHs properties inferred from the cosmological simulations and differ from one black hole to another. 100 IMBHs of $10^{4-5} M_{\odot}$ is a very small fraction of the total halo mass ($\sim 10^{12} M_{\odot}$), we can therefore neglect the correction to the smooth flux due to the amount of clumped mass. The mean value of the boost factor is computed according to

$$\langle B \rangle = 1 + \frac{\langle N_{BH} \rangle \langle I \rangle}{\phi_s} \int_{halo} d^3\vec{x} p(x) \mathcal{G}(E, \vec{x}) , \quad (5)$$

where $p(\vec{x})$ is the probability to find an IMBH within the elementary volume $d^3\vec{x}$, $\langle N_{BH} \rangle$ is the mean number of black holes and $\langle I \rangle$ the mean value of the integral of Eq. (2). The expected variance for the effective boost factor is computed as $\sigma_B = \langle B^2 \rangle - \langle B \rangle^2$. Monte

Carlo simulations of the Milky Way filled with these objects are also performed. For each realization of the Galaxy, the flux from IMBHs is computed and compared to the flux from the smooth halo. The results are presented in Fig. 1. It is remarkable that the prediction for the IMBHs-induced boost factor is more specific at low energy, with a divergence of the variance near the source energy. This is because positrons loose energy as they propagate. Therefore the more energy they loose during their trip, the further away they come from. Positrons emitted at 100 GeV and detected at 90 GeV come in average from a ~ 500 pc radius sphere, whereas a positron detected at 20 GeV have a mean free path of ~ 2 kpc. As a consequence, the number of IMBHs contributing to the effective boost factor is more stable from one realization to another at low energy than it is at high energy. The decrease of the sensitivity volume as the detection energy increases is a typical feature of the positrons propagation, it leads to the variance shape presented in Fig. 1.

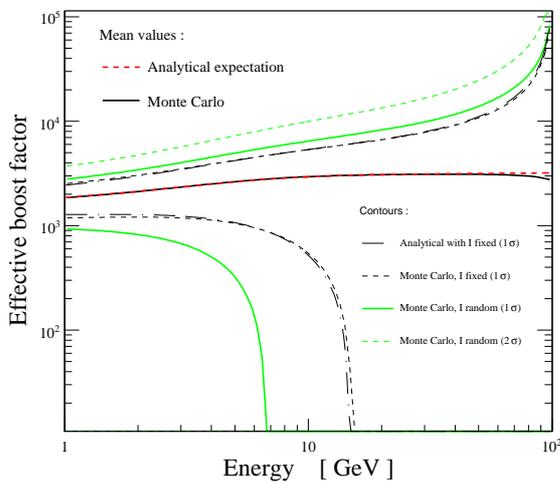


Figure 1. Effective boost factor for e^+ and associated uncertainties in the IMBHs scenario. Monte Carlo results are shown for 10^5 realizations of the Milky Way.

4. Conclusions

The presence of intermediate mass black holes in the Milky Way could dramatically increase the positron signal from dark matter annihilation. In a realistic (though optimistic) model of IMBHs, enhancement factors of order 10^3 are obtained for 100 GeV WIMPs, with a high variance. Further studies are needed to determine which WIMP models resist to the existing experimental constrains within this scenario. Some examples will be given in Ref. [8]. Such an enhancement is very promising for future antimatter experiments such as PAMELA and AMS02.

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