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Astrophysical boost factor and Dark Matter indirect detection

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Abstract. The PAMELA [1], ATIC[2] and Fermi[3] collaborations have recently reported an excess in the cosmic ray positron and electron fluxes. These lepton anomalies might be related to cold dark matter particles annihilating within a nearby dark matter sub-halo. We outline regions of the parameter space for both the dark matter sub-halo and particle model, where data from the different experiments are reproduced. We then confront this interpretation of the data with the results of the cosmological N-body simulation Via Lactea 2. Having a sizeable sub-halo at a distance of only 1.2 kpc could explain the PAMELA excess, but such a configuration has a probability of only 0.37 percent. Reproducing also the ATIC bump would require a very large, nearby sub-halo, which is extremely unlikely (p ~ 3×10^{-5}). It is even less probable for the smaller Fermi bump to be caused by the presence of such an object. In either case, we predict Fermi will detect the gamma-ray emission from the sub-halo. We conclude that under canonical assumptions, the cosmic ray lepton anomalies are unlikely to originate from a nearby cold Dark Matter sub-halo.

1. Introduction

The positron fraction (that is the positron flux divided by the flux of both positrons and electrons) recently measured by PAMELA is higher than most estimations[1]. This excess starts around 50 GeV and may be related to the one seen at much higher energies ($\sim 500 \text{ GeV}$) by ATIC[2], Fermi[3] and HESS[8] in positron plus electron flux. It is possible that theses features have astrophysical explanation but it has also been suggested that annihilating Dark Matter of the Galactic halo may produce these unexpected electrons and positrons.

Relic density considerations require the annihilation cross-section of Dark Matter to be $\langle \sigma v \rangle \simeq 3 \times 10^{-26} \text{cm}^3 \text{.s}^{-1}$ and Galactical Dark Matter distribution is fixed thanks to N-body simulations such as Via Lactea 2 [6]. When one applies these conditions and uses propagation

models[9] in agreement with various cosmic ray data, it appears that the positron flux is far too low to produce an excess above the astrophysical expectation[4].

2. Boost factors

Two kinds of process have been suggested to "boost" the exotic component of electron/positron cosmic rays. The first one comes from particle physics and consists in finding mechanisms that can increase the annihilation cross-section without changing the thermal density. Here we have not considered particle physics boost. The other mechanism comes from the consideration that the Dark Matter halo of our Galaxy, as it is computed by Via Lactea 2 is not smooth but extremely clumpy. In these sub-haloes the Dark Matter density is much higher and hence the annihilation rate too.

It has been shown[7] that the astrophysical boost, on average, cannot be extremely large. Moreover, as Pamela has seen no excess in anti-proton to proton ratio [3], one should be careful not to overproduce anti-proton while boosting the positrons.

Unlike heavier cosmic ray species, positrons and electrons, when propagating in the Galaxy, loose a lot of energy. Therefore, the ones we detect at the Earth cannot come from much further than 1 kpc away from us. The question we have tried to answer is, how likely is it, considering the sub-halo distribution computed by Via Lactea 2, that the features we are dealing with are produced by a nearby sub-halo ?

3. The method

Considering a few model-independent annihilation channels and masses for the Dark Matter particle, we have computed the positron fraction (or the electron plus positron flux) as in [4] and added the exotic component from the big Galactic halo and from a nearby sub-halo. For each candidate of Dark Matter, we have found the position and size of sub-halo which gives the best fit to the data (either PAMELA or Fermi). Of course this result depends a lot on the electron flux for which we cannot rely on any recent measurement. The choice of the propagation model (even within Boron/Carbon constraints) can also affect the result, but one should not expect extremely different conclusions.

Once we have found the best distance to the Sun and luminosity of the sub-halo that matches observations, we have looked how often this kind of sub-halo actually appears in the results of the many runs of the Via Lactea 2 simulation. From this, we can estimate the probability that the PAMELA (or the Fermi) feature is due to a nearby sub-structure of Dark Matter.

4. Results

Results are summed up in Figure 1. What appears is that for light candidates of Dark Matter (a few hundred of GeV), to fit the PAMELA data, one requires a quite heavy sub-structure situated at less than 1 kpc away, this kind of sub-structures, according to Via Lactea 2, is expected to be much further (~ 7 kpc) therefore the associated probability is very low (0.37%). If we go to heavier Dark Matter particle candidates (1 TeV), then one needs a sub-structure almost three hundred times heavier and even closer to the Sun. These substructures weight a non-negligible fraction of the total Galactic halo and are extremely unlikely to exist (~ $3 \times 10^{-3}\%$).

If we consider the cases of the ATIC and Fermi excesses, because the features appears at much higher energy, we need heavy Dark Matter particle (≥ 1 TeV). Because the annihilation rate of Dark Matter is suppressed by the mass of the particle to the square, we need very bright substructures, so heavy that they can even be of the same mass than the whole Galactic halo. This is absolutely excluded. However, for these very heavy Dark Mater candidates, one should keep in mind that the particle physics boost factor may come into play. If the annihilation cross section is indeed higher at low velocity, it may be possible to release these constraints.

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In all the cases we have considered here, the annihilation of Dark Matter should also create gamma rays at a rate high enough for the sensitivity of the Fermi telescope. Therefore, one should expect a clear answer to this problem very soon.



Figure 1. In this plot, the luminosity of the nearest subhalo is plotted against its distance from the Sun. The full straight line corresponds to the average realisation to the Via Lactea 2 simulation, the dashed and dotted lines delimit the phase space that is reached by less than 10, 1 or 0.1 % of the realisations of the simulation. The elliptic contours correspond to the subhalo required for the best fit to cosmic ray data, for masses growing from 100 GeV to 2.5 TeV. Only one experiment has been fitted at once.

5. Conclusion

Though there are some way-outs due to the uncertainties on the electron flux and the propagation of cosmic rays, it is extremely unlikely that the ATIC/Fermi/HESS feature can be caused by a nearby sub-halo of Dark Matter. If one tries to explain only the Pamela spectrum, the required sub-halo is a little bit more in agreement with the computations of the N-body simulation Via Lactea 2 but not enough to be seriously considered as a solution to the Pamela puzzle. Therefore it seems extremely difficult to explain the present cosmic ray data with a relic cold Dark Matter even if it is annihilating only into light leptons.

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