Electron anisotropy: A tool to discriminate dark matter in cosmic rays

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Abstract. Indirect searches of particle Dark Matter (DM) with high energy Cosmic Rays (CR) are typically affected by large uncertainties. We show that, on the contrary, the DM intrinsic degree of anisotropy in the arrival directions of high energy CR electrons and positrons (CRE) is basically model independent and offers a straightforward criterion to discriminate among CRE from DM or from local discrete sources, like e.g. pulsars. In particular, in absence of the latter, DM sets the maximum degree of total anisotropy. As a consequence, if a larger anisotropy is detected, this would constitute an unambiguous evidence for the presence of astrophysical local discrete CRE sources. The Fermi-LAT will be able to probe such scenarios in the next years.

1. Introduction

High energy Cosmic Ray (CR) positrons are promising targets for indirect searches of Galactic particle Dark Matter (DM) \cite{1}. The recent results reported by the PAMELA \cite{2} and Fermi collaborations \cite{3} on the positron fraction \(e^+/(e^+ + e^-)\) and on the \((e^+ + e^-)\) (CRE) spectra in the energy range few GeV \(\div\) 1 TeV show large discrepancies with standard astrophysical model predictions and have indeed received a large number of interpretations in terms of DM. In particular, it has been shown that a good fit of the PAMELA/Fermi data can be achieved with \(e^+e^-\) produced by a DM particle of \(\sim\)TeV mass annihilating or decaying predominantly via leptonic channels, and several models realizing this scenario have been proposed \cite{4}. However, interpretations based on astrophysical extra sources (like e.g. pulsars) \cite{5,6} have been shown to work equally well.

It is, however, very unlikely to distinguish the two scenarios using as observables only the fluxes, even with the larger statistics expected in the future \cite{7}. It is thus mandatory to find other observables accessible to experiments, that are as much model independent as possible and can provide a clear discrimination between a DM dominated scenario and an “astrophysically” dominated one. As we showed in \cite{8}, the intrinsic degree of dipole anisotropy in the arrival directions of high energy CREs expected from a DM scenario, \(\delta_{\text{DM}}\), is indeed insensitive to many uncertainties, and constitutes a universal characteristics of galactic DM, offering a straightforward criterion to discriminate among CRE from DM or from local sources. Indeed, we showed that if future experiments will find an anisotropy larger than the maximum DM anisotropy we derive here, then a dominant DM contribution to the CRE anisotropy can be
excluded in a basically model independent way, pointing instead to local discrete astrophysical CRE sources as the main source of anisotropy.

The reason why the dipole anisotropy has a very weak dependence on the various unknowns is, on the one hand, the very short electron path above $\sim 100$ GeV ($\sim 1$ kpc) which makes this quantity very local in origin, and on the other hand, the fact that it is a flux ratio, so that most of the uncertainties cancel each other in the ratio. Furthermore, we find that the anisotropy signal from DM is intrinsically different from the one due to local discrete sources. The key point here is that the number of galactic DM substructures is $\mathcal{O}(10^{17})$ and a very nearby clump is always accompanied by the large, dominant and almost isotropic flux from the whole population of clumps, which washes out the single clump anisotropy. This has to be compared with the case e.g. of pulsars, which can produce a similar amount of CREs as DM, but concentrated in only $10^3$ or less objects. In this scenario pulsars are rare and powerful enough that a few nearby objects can indeed dominate the flux and the anisotropy.

On the experimental side, the Fermi telescope recently placed the first upper limits on the integrated dipole anisotropy of the arrival directions of CRE with $E > 60$ GeV [9], and there are prospects for its actual observation after a few years of data taking [6].

2. Electron anisotropy
In the diffusive approach, the dipole anisotropy can be written as $\vec{\delta} = -(3D/\beta_c) \nabla \phi/\phi$ (see e.g. [10]), where $D$ is the isotropic diffusion coefficient, $\beta_c$ and $\phi$ are the CRE velocity and flux respectively. We considered three different models of diffusion: with Kolmogorov-like turbulence, Kraichnan-like turbulence, and a last one with high turbulence equal to 0.7. The diffusion coefficient is always normalized in order to be in agreement with CR nuclei observations [6].

The total DM contribution to the $e^+e^-$ fluxes is in general the sum of two components, $\phi_{DM} = \phi_h + \phi_s$, where $\phi_h$ is the contribution from the smooth halo while $\phi_s$ is the contribution from the substructures. Current highest resolution N-body simulations roughly agree on the mass distribution of substructures, predicting a number density scaling like $m^{-2}$ (Via Lactea II [11]) or $m^{-1.9}$ (Aquarius [12]). How substructures are distributed in the smooth halo is however more uncertain. We considered the two extreme cases of an unbiased distribution where substructures follow the main halo and an anti-biased case as suggested by the Via Lactea II simulation [13]. The internal concentration of substructures and the effects of tidal disruption were parameterized as in [14]. We chose a clump mass range $10^{-6} \div 10^{10} M_\odot$. For the spatial distribution of the smooth component and for the DM distribution inside the substructures we considered Navarro-Frenk-White (NFW) [15] and Burkert [10] profiles. Finally, we considered annihilation in $\mu, \tau$ and quark pairs, for values of the DM mass: 100, 316, 1000, and 3162 GeV.

The sum over the substructure distribution in principle should run over a sizable fraction of the $\mathcal{O}(10^{17})$ substructures lying within the diffusive region. This is computationally prohibitive at present. We then computed analytically the average contribution from substructures with $10^{-6} < M/M_\odot < 10^2$, while we computed explicitly the contribution of each clump with $M > 10^2 M_\odot$. We sampled the distribution of $M > 10^2 M_\odot$ substructures via a MonteCarlo procedure as described in [17]. Further details can be found in [8].

3. Results and discussion
Both the analytic calculation and the MonteCarlo simulation give a mean anisotropy which is only slightly dependent by the mass decade. Fluctuations in the distribution of the high mass substructures however lead to large variability of $|\vec{\delta}|$, which is more relevant at the highest energies, because higher energy electrons probe smaller volumes than lower energy ones, thereby being more sensitive to fluctuations in the clump distribution.

The first two panels in fig. [1] show the results for the mean and maximum $\delta_{DM} = |\vec{\delta}_{DM}|$ for the considered annihilation channels and DM masses for our chosen DM density profiles and
is given by a composition of the AP and the DM intrinsic anisotropies. It is easy to see that an astrophysical (AP) flux and a DM originated one, only slightly change for different DM profiles. are almost independent of the diffusion setup, even in the extreme case of HA diffusion, and model independent. The third panel in fig. 1, in particular, shows that the maximal anisotropies like the annihilation spectrum. Moreover, because CREs propagate only a few kpc distance in fact that at higher energies smaller and smaller propagation volumes are probed by the CREs and the role of fluctuations is more relevant.

The main property emerging from the above plots is that $\delta_{\text{DM}}$ is almost independent of the detailed characteristics of the DM models and distributions in substructures and, in this sense, $\delta_{\text{DM}}$ is a universal property of DM. Being a ratio, it is very little sensitive to integrated quantities, like the annihilation spectrum. Moreover, because CREs propagate only a few kpc distance in the Galaxy, $\delta_{\text{DM}}$ is also little sensitive to the DM spatial profile, in particular on whether it is peaked or cored. The anisotropy is also not strongly sensitive to the internal concentration of the subhaloes, because diffusion over kpc scales smooths out the effect of a possible cusped overdensity region. For these reasons, as we checked, the case of decaying DM gives similar results as the case of annihilating DM. Finally, remarkably, also the fluctuations in $\delta_{\text{DM}}$ are basically model independent. The third panel in fig. 1 in particular, shows that the maximal anisotropies are almost independent of the diffusion setup, even in the extreme case of HA diffusion, and only slightly change for different DM profiles.

We now consider the role of the background. If the total flux is given by the contribution of an astrophysical (AP) flux and a DM originated one, $\phi = \phi_{\text{AP}} + \phi_{\text{DM}}$, the degree of anisotropy is given by a composition of the AP and the DM intrinsic anisotropies. It is easy to see that the bound $|\delta| \leq \delta_{\text{max}}$ holds, with $\delta_{\text{max}} = x_\delta \delta_{\text{DM}} + (1 - x_\delta) \delta_{\text{AP}}$, being $x = \phi_{\text{DM}} / \phi$. In a specific scenario, $\delta_{\text{max}}$ is determined by $x$, the relative contributions of $\phi_{\text{DM}}$ to the total flux $\phi$, although, clearly, $\delta_{\text{max}} \leq \max(\delta_{\text{DM}}, \delta_{\text{AP}})$. If DM is distributed in substructures, and if local discrete CRE astrophysical sources are neglected, then we can have $\delta_{\text{DM}} > \delta_{\text{AP}}$ (fig. 1). In this case, $\delta_{\text{DM}}$ sets the maximum anisotropy we can expect, with $\delta \simeq \delta_{\text{DM}}$ when $\phi_{\text{DM}} \gg \phi_{\text{AP}}$. Being the maximum of $\delta_{\text{DM}}$ insensitive to the specific DM scenario, and to the details of the

![Figure 1](image-url)
CRE propagation, this upper limit is robust and universal. If a positive detection of anisotropy will occur in the future, and the anisotropy will be found larger than $\delta_{\text{DM}}$, we can then exclude the presence of a substantial DM contribution, and therefore we have to demand $\delta_{\text{AP}} > \delta_{\text{DM}}$. This would point then unambiguously to a scenario dominated by local, discrete astrophysical sources, such as pulsars, as source of high energy CRE. However, this argument does not exclude that a subdominant contribution from DM annihilation in substructures can still be present [18].

Although our arguments are very natural, our findings result from a MonteCarlo computation of the local distribution of DM substructures. A possible bias of this approach is that we might have missed configurations whose probability is less than 1%, in which, e.g., a large mass clump emerges isolated and very close to the Earth. This could in principle produce an anisotropy larger than what we quote as a “maximum”. We checked, however, that this configuration cannot produce a high degree of anisotropy. In fact, even in the unlikely case of a $10^8 M_\odot$ clump at 100 pc from Earth (whose probability is much less then 1%) the anisotropy is strongly suppressed by the nearly isotropic flux of the much more abundant smaller substructures and it is thus always diluted below max($\delta_{\text{DM}}$). This feature makes the DM signal intrinsically different from the one expected from pulsars. Indeed, while there might be a close-by, isolated pulsar, that can possibly lead to a large anisotropy [6], it is not possible to reproduce this configuration with DM.

In summary, our result is robust and can be used as a criterion to reject a DM dominated scenario in the framework of high energy CREs, in the case of detection of a large anisotropy.

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References
[1] G. Bertone, D. Hooper, J. Silk, Phys. Rept. 405 (2005) 279.
[2] O. Adriani et al. [PAMELA Collaboration ], Nature 458 (2009) 607-609. [arXiv:0810.4995 [astro-ph]].
[3] A. A. Abdo et al. [Fermi LAT Collaboration], Phys. Rev. Lett. 102 (2009) 181101. M. Ackermann et al. [Fermi LAT Collaboration], arXiv:1008.3999 [astro-ph.HE].
[4] L. Bergström, T. Bringmann, J. Edsjo, Phys. Rev. D 78 (2008) 103520. I. Cholis et al. Phys. Rev. D 80, 123511 (2009). M. Cirelli et al. Nucl. Phys. B 813, 1 (2009). N. Arkani-Hamed, D. P. Finkbeiner, T. R. Slatyer, N. Weiner, Phys. Rev. D 79 (2009) 015014. L. Bergström, J. Edsjo, G. Zaharijas, Phys. Rev. Lett. 103 (2009) 031103.
[5] P. Blasi, Phys. Rev. Lett. 103 (2009) 051104. P. Blasi and E. Amato, arXiv:1007.4745 [astro-ph.HE]. P. D. Serpico, Phys. Rev. D 79, 021302 (2009). D. Grasso et al., Astropart. Phys. 32 (2009) 140. S. Profumo, Central Eur. J. Phys. 10 (2011) 1.
[6] G. Di Bernardo et al., Astropart. Phys. 34 (2011) 528-538.
[7] M. Pato, M. Lattanzi, G. Bertone, JCAP 1012 (2010) 020.
[8] E. Borriello, L. Maccione, A. Cuoco, arXiv:1012.0041 [astro-ph.HE].
[9] M. Ackermann et al. [Fermi-LAT collaboration] arXiv:1008.5119 [astro-ph.HE].
[10] Berezinsky V S et al., Astrophysics of Cosmic Rays, North-Holland, 1990.
[11] J. Diemand et al. Nature 454 (2008) 735.
[12] V. Springel et al., Mon. Not. Roy. Astron. Soc. 391 (2008) 1685.
[13] M. Kuhlen, J. Diemand, P. Madau, [arXiv:0805.4416].
[14] L. Pieri, J. Lavalle, G. Bertone, E. Branchini, arXiv:0908.0195 [astro-ph.HE].
[15] J. F. Navarro, C. S. Frenk, S. D. M. White, Astrophys. J. 490 (1997) 493.
[16] A. Burkert, Astrophys. J. 447 (1995) L25.
[17] E. Borriello, A. Cuoco, G. Miele, Phys. Rev. D79 (2009) 023518.
[18] I. Cernuda, Astropart. Phys. 34 (2010) 59.