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Dark matter electron anisotropy: a universal upper limit

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Indirect searches of particle Dark Matter (DM) with high energy Cosmic Rays (CR) are affected by large uncertainties, coming both from the DM side, and from poor understanding of the astrophysical backgrounds. We show that, on the contrary, the DM intrinsic degree of anisotropy in the arrival directions of high energy CR electrons and positrons does not suffer from these unknowns. Furthermore, if contributions from possible local sources are neglected, the intrinsic DM anisotropy sets the maximum degree of total anisotropy. As a consequence, if some anisotropy larger than the DM upper bound is detected, its origin could not be ascribed to DM, and would constitute an unambiguous evidence for the presence of astrophysical local discrete sources of high energy electrons and positrons. The Fermi-LAT will be able to probe such scenarios in the next years.

Introduction: High energy Cosmic Ray (CR) positrons are promising targets for indirect searches of galactic particle Dark Matter (DM). After the publication of the PAMELA [1] and Fermi [2, 3] results on the positron fraction $e^+/(e^+ + e^-)$ and on the positron + electron (CRE) spectra in the energy range few GeV $\div$ 1 TeV, showing large discrepancies with standard astrophysical model predictions, DM explanations were put forward [4–7], as well as interpretations based on astrophysical extra sources [8–13].

However, large uncertainties affect the computation of the astrophysical CRE fluxes, and the contributions expected from local sources. On the other hand, the DM contribution to the observed fluxes is itself affected by several unknowns. In the presence of so large uncertainties, it is mandatory to find observable quantities that are least dependent upon the unknowns, that might be accessible to experiments and can provide a clear discrimination between a DM dominated scenario and an "astrophysically" dominated one. As we will show in this Letter, the intrinsic degree of anisotropy in the arrival directions of high energy CREs expected from a DM scenario, δ_{DM}, is indeed insensitive to many unknowns, and constitutes a universal characteristics of galactic DM. In this respect, CRE anisotropies share similar promising capabilities as anisotropies in the photon domain [14–16].

As we will argue, the CRE anisotropy offers a straightforward criterion to discriminate a dominant contribution of DM to the CRE high energy spectrum from a dominant contribution of local sources. 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 ~ 100 GeV (~ 1 kpc) which makes this quantity very local in origin, and on the other hand, the fact that it is a flux ratio (see Eq. 1) 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 10^5 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 [17], and there are prospects for its actual observation after a few years of data taking [12].

DM intrinsic electron anisotropy: In the diffusive approach, the dipole anisotropy can be written as [18]

$$\vec{\delta} = -\frac{3D}{\beta c}\frac{\vec{\nabla}\phi}{\phi} \ , \qquad (1)$$

where D is the diffusion coefficient, βc and ϕ are the CRE velocity and flux respectively. The total DM contribution to the e^+e^- fluxes is in general the sum of two components, $\phi_{DM} = \phi_h + \phi_s$, where ϕ_h is the contribution from the smooth halo while ϕ_s is the contribution from the substructures. In general, we have

$$\phi_i(E) = \frac{\beta c}{4\pi}\frac{\langle\sigma v\rangle}{2}\left(\frac{\rho_\odot}{m_\chi}\right)^2 \int_V d^3\vec{x}' \int_E^{m_\chi} dE' \qquad (2)$$
$$\times G(\vec{x}_S, E \leftarrow \vec{x}', E')\rho_i^{eff}(\vec{x}')^2 \frac{dN_\chi}{dE'}(E')$$

where G is the Green function associated to the transport equation [18], $\rho_\odot$ is the DM density at the Solar System position and dN_χ/dE' is the annihilation spectrum into e^+ and e^-. The term $\rho_i^{eff}(\vec{x}')^2$ is defined as $(\rho_h(\vec{x}')/\rho_\odot)^2$ in the case of the DM halo density ($i = h$), while in the case of the substructures ($i = s$) is written as $\rho_s^{eff}(\vec{x}')^2 = \sum_j (\rho_j(\vec{x}')/\rho_\odot)^2$, with the sum running over the substructures and ρ_j representing the DM density of the single substructure.

The 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 [19]) or $m^{-1.9}$ (Aquarius [20]). 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 [21]. The internal concentration of substructures is parameterized as in [22], which we follow also for the treatment of the effects of tidal disruption. We considered also a very different set of hypotheses (concentration parametrization taken from [23] and no tidal effect) finding almost unchanged results, which suggests that the internal concentration and the tidal forces play only a minor role on the dipole anisotropy. Finally, we chose a clump mass range $10^{-6} \div 10^{10}\ M_\odot$, where the upper limit comes from constraints due to disk stability [24], while the more debatable lower limit is set following the most common choice in the literature. We checked however that our results do not depend on the assumed mass lower limit, in the allowed mass range [25].

We solve the well known diffusion-loss equation [18]

$$\frac{\partial N}{\partial t} - \vec{\nabla} \cdot \left(D(E) \vec{\nabla} N \right) - \frac{\partial}{\partial E} \left(b(E) N \right) = Q(E, \vec{x}) \ , \quad (3)$$

where N is the particle number density, $b(E)$ represents energy losses, $D(E) = D_0 (E/3\ \text{GeV})^\alpha$ is the (spatially constant) diffusion coefficient and Q is the source term. We solve Eq. (3) in the stationary limit $\partial N/\partial t = 0$. Since the CRE dipole anisotropy is measured at $E > 60$ GeV only diffusion and continuous energy losses have a relevant effect in shaping the propagated spectra. For this reason we have neglected reacceleration and convection. Moreover, at these high energies leptons cannot travel more than a few kpc [18]. Hence we assume that the magnetic field and the interstellar radiation fields are constant over the relevant propagation region, whose vertical height scale we fix as $L = 4$ kpc. As a further consequence, the effect of boundary conditions on the propagated fluxes at $E > 60$ GeV is negligible. It can be checked however that changing L in the range allowed by CR nuclei constraints [26] does not produce a significant effect. We consider two different models of diffusion: one (KOL) with Kolmogorov-like turbulence $\alpha = 0.33$ and $D_0 = 5.8 \times 10^{28}\ \text{cm}^2\text{s}^{-1}$, and another (KRA) with Kraichnan-like turbulence $\alpha = 0.5$ and $D_0 = 3 \times 10^{28}\ \text{cm}^2\text{s}^{-1}$. The chosen values for D_0 are in agreement with CR nuclei observations [12].

A problem arises when trying to evaluate the sum over the substructure distribution, as in principle it must be run over a sizeable fraction of the $\mathcal{O}(10^{17})$ substructures lying within the diffusive region. This is computationally prohibitive at present. Therefore, we compute analytically the contribution from substructures with $M < 10^2\ M_\odot$, while we compute explicitly the contribution of each clump more massive than $10^2\ M_\odot$. A MonteCarlo procedure as described in [27] is employed to produce a realization of the $M > 10^2\ M_\odot$ substructures and the results are then averaged over 100 realizations to take into account fluctuations. In total, we computed the contribution of $\mathcal{O}(10^9)$ substructures for each considered model. The anisotropy produced by clumps smaller than $10^2\ M_\odot$ is expected to be small since the extremely large number of such clumps flattens completely the overall anisotropy to much less than percent level. Indeed, as can be seen in Fig. 1, substructures with $10 < M/M_\odot < 10^2$ contribute to about 10% of the final anisotropy at 600 GeV, while most of the signal comes from substructures with $10^2 < M/M_\odot < 10^6$.

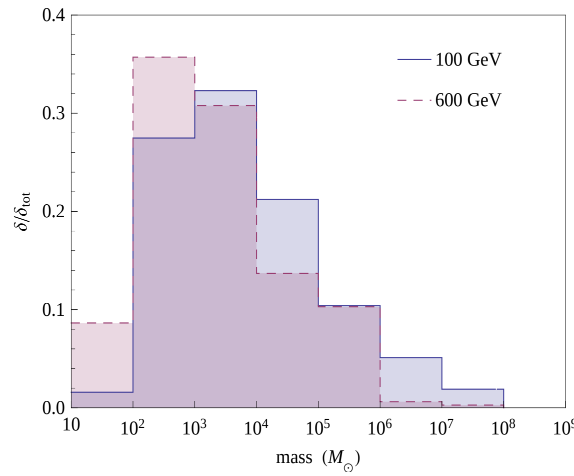

FIG. 1. Relative contribution to the integrated DM anisotropy above 100 and 600 GeV as a function of the substructure mass, in the case of a 1 TeV DM particle annihilating into μ pairs, for a NFW distribution and a KRA propagation setup.

For the spatial distribution of the smooth component, and for the DM distribution inside the substructures, we consider Navarro-Frenk-White (NFW) [28] and Burkert [29] profiles. As it can be checked by a direct computation, the contributions to $\vec{\delta}_{DM}$ coming from the halo and the analytically computed low mass components are at least one order of magnitude smaller than the contribution from large clumps. Therefore, we compute the total degree of anisotropy intrinsic to DM as

$$\vec{\delta}_{DM} = -\frac{3D(E)}{\beta c} \frac{\vec{\nabla} \phi_s^{HM}(E)}{\phi_h(E) + \phi_s(E)} \ , \quad (4)$$

where HM denotes substructures with $M > 10^2\ M_\odot$.

We consider annihilation in μ, τ and quark pairs, for values of the DM mass: 100, 316, 1000, and 3162 GeV.

Results: Figure 2 shows the results on the degree of anisotropy $\delta_{DM} = |\vec{\delta}_{DM}|$ for the considered annihilation channels and DM masses, different assumptions on the global halo and internal substructure matter density, and different propagation setups. We used an unbiased spatial distribution to produce Fig. 2. The anti-biased case

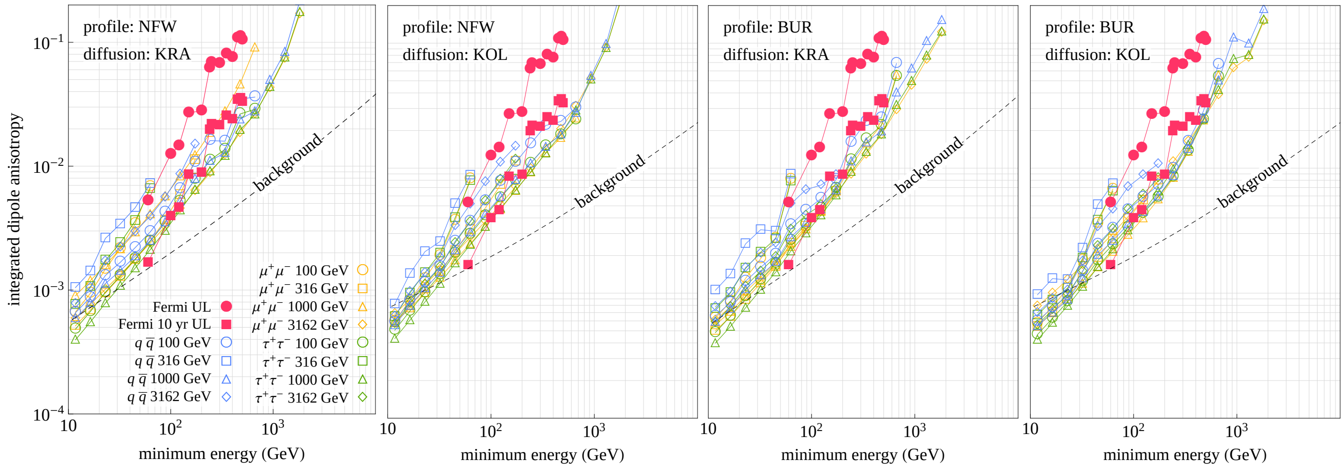

FIG. 2. Intrinsic integrated dipole anisotropy of DM. A comparison is made with the standard astrophysical background, current Fermi upper limits and the sensitivity expected after 10 years of data taking (actual limits rescaled by a factor $\sqrt{10}$). The points correspond to different annihilation channels and masses of the DM particle. The energy dependence of the integrated anisotropy is only slightly affected by the injection spectrum, apart from the mass dependent end point. Moreover, it is also independent, within a factor of a few, of any of the unknowns related to propagation and smooth distribution of DM. The black dashed curve shows the anisotropy of the standard astrophysical background, δ_{AP}.

gives results smaller by a factor of ~ 5 at 500 GeV, hence in the range of model variability we find.

The main property of δ_{DM} is that it is independent, within a factor of a few, of the detailed characteristics of the DM models and distributions in substructures. In this sense δ_{DM} is a universal property of DM. It follows directly from its definition that it does not depend on any spatially constant multiplicative factor (e.g. the annihilation cross section and the local value of the DM density), but, being a ratio, it is also very little sensitive to integrated quantities, like the annihilation spectrum (apart from the mass dependent end-point). Because CREs propagate only a few kpc distance in the Galaxy, δ_{DM} is also little sensitive to the DM spatial profile, in particular on whether it is peaked or cored.

We now consider again the role of the background. If the total flux is given by the contribution of an astrophysical (AP) flux and a DM originated one, $\phi = \phi_{AP} + \phi_{DM}$, the degree of anisotropy is bounded by $|\vec{\delta}| \leq \delta_{max}$, with

$$\delta_{max} = \frac{\delta_{AP}/\phi_{DM} + \delta_{DM}/\phi_{AP}}{1/\phi_{AP} + 1/\phi_{DM}} \ . \tag{5}$$

In a specific scenario, δ_{max} is determined by the relative contributions of ϕ_{DM} and ϕ_{AP} to the total flux, although, clearly, $\delta_{max} \leq \max(\delta_{DM}, \delta_{AP})$. If DM is distributed in substructures, and if local discrete CRE astrophysical sources are neglected, then $\delta_{DM} > \delta_{AP}$ (Fig. 2). In this case, δ_{DM} sets the maximum anisotropy we can expect, with $\delta \simeq \delta_{DM}$ when $\phi_{DM} \gg \phi_{AP}$. Being δ_{DM} insensitive to the actual realization of a DM scenario, and to many details of the 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 δ_{DM}, we can then exclude the presence of a substantial DM contribution, and therefore we have to demand $\delta_{AP} > \delta_{DM}$. 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 [30]. Figure 2 also shows that Fermi can indeed probe these scenarios within 10 years data taking.

Discussion: Although the arguments we described 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 a larger anisotropy than what we quote as a "maximum". We remark however that even this configuration cannot produce a higher degree of anisotropy. For example, we considered the unlikely case of a $10^8\ M_\odot$ clump at 100 pc from Earth (whose probability is $< 0.1\%$ [31]). The anisotropy below 100 GeV is strongly suppressed by the large diffusion length. At higher energies the anisotropy increases, but the nearly isotropic flux of the much more abundant smaller mass substructures present within 100 pc dilutes the anisotropy of the clump always below the values of δ_{DM} in Fig. 2 . This feature makes the signal from DM intrinsically different from the pulsar expected one. Indeed, while there might be a close-by, isolated pulsar, that can possibly lead to a large anisotropy [12], it is not possible to reproduce this configuration with DM. Also, the situation is different from gamma-rays, where this clump would be, instead, a quite bright point source.

Finally, close-by small mass substructures, such as $10^{-6}\ M_\odot$ clumps, cannot be responsible for a large anisotropy either, as it can be inferred extrapolating from Fig. 1. A possible caveat here is that low mass clumps are so abundant that in principle they can be found within 1 pc from Earth, hence CREs could reach the Earth before diffusing significantly. Based on their number density, we expect to find only a few substructures with mass $10^{-6}\ M_\odot$ within 1 pc from Earth, with larger mass clumps having a filling factor of less than 10%. These clumps would look more as point-like sources of e^+e^- than as a dipole. Even in this case, however, their point-like flux both in e^+e^- and γ-rays would be several orders of magnitude below the Fermi sensitivity.

Another remark concerns the density profiles we considered. While N-body simulations suggest spiked halo and subhalo matter density profiles, astrophysical observations of many dwarf spiral galaxies point to a shallower, Burkert-like density profile [32]. Our results are stable under the relevant change from a spiked to a cored profile. Indeed, high energy CREs arriving at Earth do not carry information on the DM distribution in the galactic center, as they propagate only a few kpc in the interstellar medium. The anisotropy is not sensitive to the internal concentration of the subhaloes as well, because diffusion over kpc scales smooths out the effect of a possible cusped over-density region. Indeed, for the same reason, the case of decaying DM, as we explicitly checked, gives similar anisotropy to the case of annihilating DM.

Being interested in the upper limit of the DM anisotropy, we neglected the effects of a possible proper motion of substructures. Indeed, as it was pointed out in [33] for the case of an isolated substructure, a dynamical treatment would lead to a slightly enhanced dipole anisotropy only for sources moving towards the Solar System. However, while this effect can be relevant for a single clump, it is expected to average away for a population of clumps as considered here.

We finally remark that no boost factor has been included in our calculation. Indeed any global boost factor of the annihilation cross section would simplify in an exact way in the definition of δ_{DM}, while it is unlikely that the energy-dependent boost factor due to the clumpy DM distribution could be larger than $\mathcal{O}(1)$ [22, 34].

We conclude that 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. The detection is at hand of current experiments.

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