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, both from the DM side, and to poor understanding of the astrophysical backgrounds. We show here 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, and constitutes an upper limit to the total anisotropy if contributions from possible local sources are neglected. As a consequence, if some anisotropy larger than the DM upper bound is detected, its origin would be not ascribable to DM, and would constitute an unambiguous evidence for the presence of astrophysical "non-standard" (as e.g. pulsars) 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 considered as very well suited 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 ÷ 1 TeV, showing large discrepancies with standard astrophysical model predictions, DM explanations were put forward [4–7], together with 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 CRE 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 for DM searches as shown already for 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 has a very weak dependence on the various unknowns is, on the one hand, the very short electron path above ~ 100 GeV (about 1 kpc) which makes this quantity very local in origin, and on the other hand, the fact that is a flux ratio (see Eq. 1) so that most of the uncertainties cancel each other. 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 [18]. There are prospects for its actual observation after a few years of data taking, if the high energy CRE spectrum is dominated by local astrophysical sources [12].

One of the main findings of this Letter is, further, the fact that the dipole DM anisotropy is also very weakly dependent on the particular stochastic realization of the population of DM sub-structures, so that scenarios like an extremely near DM clump giving a large anisotropy can be safely excluded. The key point to notice here is that the number of Galactic DM substructures is $\mathcal{O}(10^{17})$ and a very nearby clump (whatever its mass) 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 produce a similar amount of e^+ and e^- as DM (likely larger), but concentrated in only 10^5 or less objects. In this scenario pulsars are rare and powerful enough that a few nearby pulsars can indeed dominate the flux and the anisotropy.

DM intrinsic electron anisotropy: In the diffusive approach, the dipole anisotropy can be written as [17]

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

where D is the diffusion coefficient, βc and ϕ are the CRE velocity and flux respectively. The total DM contribution to the electron+positron 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

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

where G is the Green function associated to the transport equation [17], $\rho_\odot$ 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) or $m^{-1.9}$ (Aquarius). The largest uncertainty comes from how substructures are distributed in the smooth halo. 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]. We observe that the anti-biased case gives systematically about a factor of 10 lower anisotropy. Therefore, since we are interested in assessing the maximum degree of DM anisotropy, in the following we report results for the unbiased case only. 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 [27] 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 $10^{-6}\ M_\odot < M_{substr} < 10^{10}\ M_\odot$, where the upper limit comes from constraints due to disk stability [26], 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 [28].

We solve the well known diffusion-loss equation [17]

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

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 [17]. 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. We consider two different models of diffusion: one (KOL) with Kolmogorov-like turbulence $\alpha = 0.33$ and $D_0 = 5.8\times10^{28}\ \text{cm}^2\text{s}^{-1}$, and another (KRA) with Kraichnan-like turbulence $\alpha = 0.5$ and $D_0 = 3\times10^{28}\ \text{cm}^2\text{s}^{-1}$. The chosen values for D_0 are shown to be 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 sizable fraction of the $\mathcal{O}(10^{17})$ structures lying within the diffusive region. This is computationally prohibitive at present. Therefore, we compute analytically the contribution from substructures with $M < 10^4\ M_\odot$, which thus plays the role of an effective additional smooth halo component, while we compute explicitly the contribution coming from each more massive substructures. A MonteCarlo procedure as described in [23] is employed to produce a realization of these more massive substructures and the results are then averaged over 100 realizations. In total, we computed the contribution of $\mathcal{O}(10^7)$ substructures for each considered model. The contribution to the anisotropy from clumps smaller than $10^4\ M_\odot$ is anyway expected to be small since the extremely large number of such clumps flattens completely the overall anisotropy to much less than percent level. For the spatial distribution of the smooth component, and for the DM distribution inside the substructures, we consider Navarro-Frenk-White (NFW) [24] and Burkert [25] profiles. As it can be checked by a direct computation, the contributions to the total anisotropy coming from the halo and the analytically computed low mass components are at most 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 the superscript HM denotes substructures with $M > 10^4\ M_\odot$.

We consider DM annihilation in μ, τ and quark pairs, for 4 different values of the DM mass: 100, 316, 1000, and 3162 GeV.

Results: Figure 1 shows the results on the degree of anisotropy $\delta = |\vec{\delta}|$ for the considered annihilation channels and DM masses, different assumptions on the global halo and internal substructure matter density, and different propagation setups.

The main property of δ_{DM}, as resulting from Fig. 1, 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 δ_{DM} does not depend on any spatially constant multiplicative factor (such as 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). We remark that because electrons

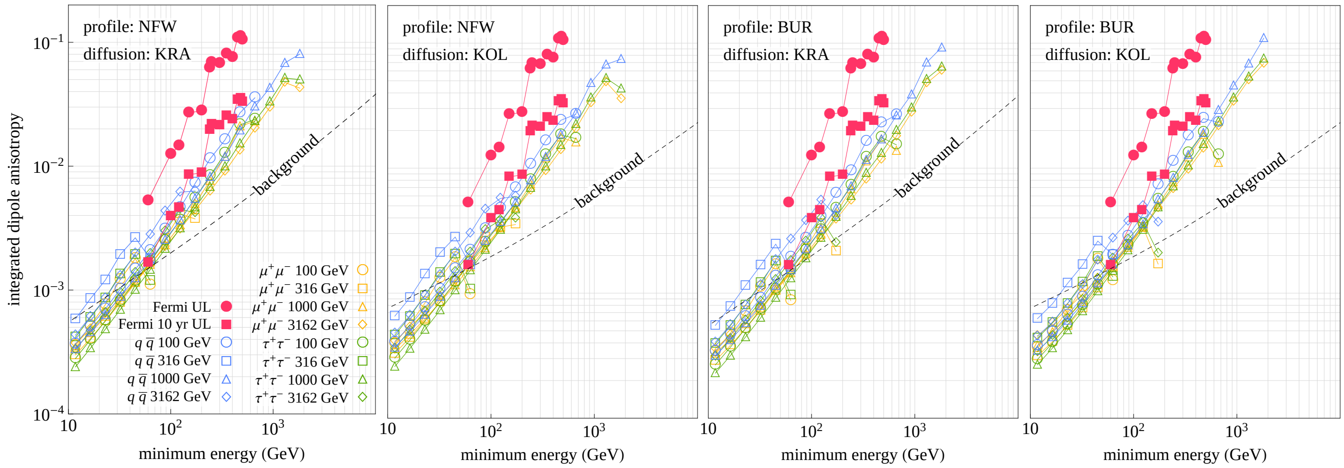

FIG. 1. Intrinsic integrated dipole anisotropy of DM. A comparison is made with the standard astrophysical background, current Fermi upper limits and the sensitivity expected after 10 years of data taking (actual limits rescaled by a factor $\sqrt{10}$). The points correspond to different annihilation 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}.

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

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

Although δ_{max} is determined, in a specific scenario, by the relative contributions of ϕ_{DM} and ϕ_{AP} to the total flux, it is 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. 1). 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, as a consequence, we have to demand $\delta_{AP} > \delta_{DM}$. Hence, this would point unambiguously to a scenario dominated by "non-standard" 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 [19].

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

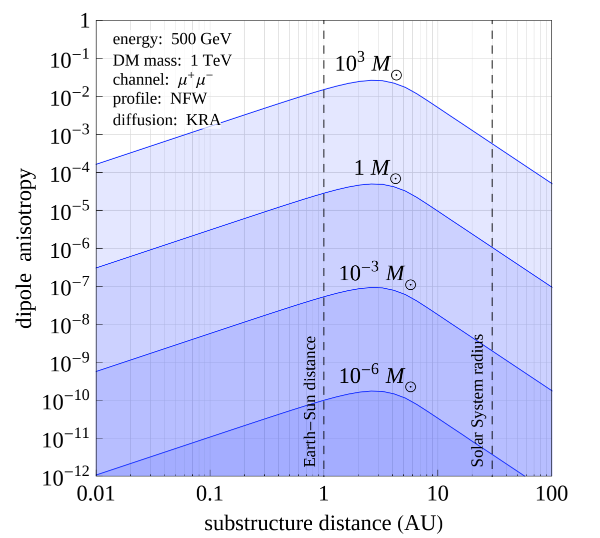

FIG. 2. Dipole anisotropy of the CRE flux at 500 GeV due to a small, nearby DM substructure. The plot refers to the KRA diffusion model, the NFW density profile, and 1 TeV DM fully annihilating muon pairs.

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, even if it is possible to find a clump with $M > 10^8\ M_\odot$ at $d \simeq 100$ pc from the Earth –and the probability for this is $< 0.1\%$ [31]– we should take into account the much more (by several orders of magnitude) abundant substructures with smaller mass which are present within 100 pc from us. Their flux would dilute the large anisotropy produced by the close-by, high mass clump. 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.

We now consider the case in which the leading contribution to the DM anisotropy is given by a small mass substructure. We explicitly evaluated the resulting degree of anisotropy as a function of the subhalo distance from the Earth, Fig. 2. We found that the maximum anisotropy is produced when the center of the clump falls inside the Solar System. Even in this case, the mass of the substructure has to be as high as $10^3\,M_\odot$ in order to overshoot our limit. However, the probability of such configuration is only 10^{-18}.

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 more 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, because they propagate only a few kpc in the interstellar medium. In the same way CRE fluxes are not sensitive to the internal concentration of the subhaloes, because diffusion over kpc scales smooths out the effect of a possible cusped over-density region.

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.

Besides, we always referred to annihilating DM but, as we checked explicitly, even the case of decaying DM gives similar anisotropy. This is clearly a consequence of the way in which δ_{DM} is defined.

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 distinguish a DM dominated scenario from a non-standard astrophysical local sources dominated scenario in the framework of high energy CREs.

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