Dark matter and the PAMELA data

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The recent observation of a rising positron fraction up to ~ 100 GeV by the PAMELA experiment has triggered a considerable amount of interpretation attempts in terms of dark matter (DM) annihilation or decay, though most of the "natural" DM candidates arising in particle physics beyond the standard model are not expected to be observed in the cosmic antimatter spectrum. Here, we make a critical reassessment of such a possibility.

Introduction: Among interesting *astroparticle* signatures of DM annihilation or decay, antimatter cosmic rays (CRs) have long been considered as promising tracers [1], but it is only recently that precision data have become available to look for non-standard features [2]. Although the rise in the local cosmic positron fraction at GeV energies has been observed for a long time (*e.g.* [3]), the statistics accumulated by the PAMELA satellite experiment [4] is unprecedented and covers a much larger energy range, up to 100 GeV. A secondary origin of these positrons seems unlikely [5, 6], even when considering theoretical uncertainties. The main questions are therefore (i) whether or not standard astrophysics may supply for such a signal and (ii) whether or not DM annihilation or decay is expected to be (also) observed in this channel. It is noteworthy that this was already discussed by [7] twenty years ago, where the author pointed out that a pulsar origin was the best explanation to a rising positron fraction. It is not less interesting and sociologically striking to take a census of the articles addressing point (i) versus those focused on point (ii).

Astrophysical positrons: The general formalism of CR transport was designed a long time ago in the seminal book of Ginzburg & Syrovatskii [8], and refined many times since then (*e.g.* [9, 10]). In some cases, analytical solutions to the diffusion equation can be found in terms of Green functions $\mathcal{G}$. This is the case for electrons and positrons above a few GeV, for which all processes but spatial diffusion and energy losses (inverse Compton scattering on interstellar radiation fields, synchrotron) can safely be neglected. The infinite 3D Green function, valid at high energy when spatial boundaries of the diffusion zone cannot be reached, reads: $\mathcal{G}_e(E,\vec{x}\leftarrow E_s,\vec{x}_s) = \frac{1}{b(E)\{\pi\lambda^2\}^{3/2}}\exp\left\{-\frac{|\vec{x}-\vec{x}_s|^2}{\lambda^2}\right\}$, where $b(E) = -dE/dt$ is the energy loss function. Diffusion effects, set by the energy-dependent diffusion coefficient $K_d(E) = K_0(E/E_0)^\delta$, are hidden in the propagation scale $\lambda(E,E_s) = \left\{4\int_E^{E_s} dE'\, K_d(E')/b(E')\right\}^{1/2}$. In the solar neighborhood, the typical energy loss timescale at $E_0 = 1$ GeV is $\tau \simeq 315$ Myr. With a typical diffusion coefficient of $K_0 \simeq 0.01\,\mathrm{kpc}^2/\mathrm{Myr}$ [11], one finds $\lambda \sim 3.5$ kpc, which justifies *a posteriori* the use of the local interstellar properties to compute the energy losses [6]. In the Thomson approximation, that we will use throughout this proceeding, $b(E) = (E_0/\tau)\,\{\epsilon \equiv E/E_0\}^2$ [12], which implies that the propagation scale strongly decreases with energy ($\delta < 0.8$): in contrast to protons, high energy electrons have a short range propagation.

Positrons of astrophysical origin can be secondaries or primaries. Secondaries are produced from spallation reactions between the CR nuclei and the ISM gas. Primaries are those CRs which are accelerated in the shocked medium surrounding classical sources like supernova remnants (SNRs), pulsar wind nebulae (PWNe), *etc.* Up to a good approximation, the source term of these primary and secondary components can be approximated as a power law spectrum of index γ homogeneously distributed in the thin Galactic disk: $\mathcal{Q}(E,\vec{x}) = 2h\delta(z)\, Q_0\epsilon^{-\gamma}$, where $h \sim 100$ pc is the half-thickness of the disk — the normalization and the spectral index are of course different for secondaries and primaries. Convoluting this source term with the 3D propagator, we readily get the flux: $\phi(E) \simeq o\,c\,h\,\mathcal{Q}_0\,\epsilon^{-\tilde{\gamma}}/\sqrt{K_0/\tau}$, where $o = \sqrt{1-\delta}/4\pi^{3/2}(\gamma-1)$ and where the propagated spectral index is $\tilde{\gamma} = \gamma + (\delta+1)/2$, much softer than at source. For secondary positrons, since the $p-p$ cross section is almost constant at high energy, their source index is close to the CR proton index, which is not expected to vary significantly about its local value, *i.e.* $\gamma_s \sim 2.7$: with a typical diffusion slope of $\delta = 0.7$, we get $\tilde{\gamma}_s \sim 3.55$, close to the accurate prediction. Such a spectral behavior cannot explain the rising positron fraction measured by PAMELA. For primaries, the source index is close to 2.1 from shock wave acceleration theory and from observations of SNRs. We therefore get $\tilde{\gamma}_p \sim 2.95$, not far from current measurements. From the flux expression above, we can also understand why a large diffusion halo model, which must have a large K_0, gives a lower flux than a small diffusion halo model. Nevertheless, this simple smooth picture fails at high energy because of the short range of electrons, and contributions from discrete local sources are expected to dominate the flux above ~ 50 GeV, which is known for a long time [13]. A complete modeling including secondaries and primaries from SNRs and pulsars (which produce electron-positron pairs) in a self-consistent way can actually easily fit all the available data on electrons and positrons (see [14] and references therein). It is therefore not relevant anymore to talk about "excesses" as far as astrophysics is concerned.

To summarize this part, we emphasize that the background to consider when looking for exotic signatures in the positron (or electron) spectrum is not only made of secondaries, but also of astrophysical primaries. Moreover, standard astrophysics can naturally explain the current data without over-tuning the parameters [14]. This means that no exotic source of positrons is needed at this stage. Finally, not only are astrophysical primaries expected in significant amount and with various spectral features, but also the associated predictions are not yet under control: this is bad news for DM searches in the local positron spectrum. To make it clearer to us, particle physicists, it is like trying to interpret features in the products of $p-p$ collisions, in a phase-space zone where the QCD background is expected to be large, but without knowing it accurately. Would anybody bet on a discovery there?

Positrons from dark matter annihilation: The conditions for a cosmic messenger to be a good tracer of any exotic signal are: (i) the signal to background ratio is favorable, given the experimental capability; (ii) the background is known/calculable, and controled; (iii) specific features make the signal distinguishable from the background. It is already clear that conditions (ii) and (iii) are not fulfilled. It is therefore difficult to hope to identify a DM signal in the current *local* positron data. Nevertheless, we can still ask whether DM is about to provide a sizable contribution (or use the data as pure constraints), should it be subdominant. If so, there might still be some hopes for isolating it with future experiments, provided improvements in the understanding of the background.

One important ingredient for indirect detection predictions is the DM density profile. Since we deal with short propagation scales here, we will only consider the local environment. The local source term associated with DM annihilation reads: $\mathcal{Q}_\chi(\odot, E) = \mathcal{S}\,\frac{dN(E)}{dE}$ with $\mathcal{S} \equiv \delta\frac{\langle\sigma v\rangle}{2}\left\{\frac{\rho_\odot}{m_\chi}\right\}^2$ where $\delta = 1/2$ for Dirac fermionic WIMPs, 1 otherwise; $\langle\sigma v\rangle$ is the WIMP annihilation cross section, m_χ the WIMP mass and $dN(E)/dE$ is the injected spectrum of positrons. In the local limit (*i.e.* vanishingly small propagation scale), the positron propagator is $\mathcal{G}_e(E, \vec{x} \leftarrow E_s, \vec{x}_s) \xrightarrow{\lambda\to 0} \delta(E_s - E)\delta^3(\vec{x}_s - \vec{x})/b(E)$. Assuming annihilation in e^+e^-, then $dN(E)/dE = \delta(E - m_\chi)$ and the positron flux in the local limit is analytical: $\phi^\chi_\odot(E \to m_\chi) \xrightarrow{\chi\chi\to e^+e^-} \frac{c}{4\pi}\,\frac{\mathcal{Q}_\chi(\vec{x}_\odot,E)}{b(E)} \approx 3.2{\times}10^{-10}\mathrm{cm}^{-2}.\mathrm{GeV}^{-1}.\mathrm{s}^{-1}.\mathrm{sr}^{-1}{\times}\frac{\langle\sigma v\rangle}{3{\times}10^{-26}\mathrm{cm}^3/\mathrm{s}}\;\frac{\tau}{10^{16}\mathrm{s}}\left[\frac{\rho_\odot}{0.3\,\mathrm{GeV/cm}^3}\right]^2\left[\frac{m_\chi}{100\,\mathrm{GeV}}\right]^{-4}$. For these values, the result is very close to the prediction of the secondary positron flux at 100 GeV, which means that boosting the local DM density by a factor of a few is enough to feed the PAMELA data significantly. Nevertheless, this is, at least to our knowledge, the unique (still contrived) example for which one may recover the observed positron fraction up to 100 GeV without over-tuning the annihilation cross section. The presence of DM substructures (also called subhalos or clumps), expected from structure formation theory, could boost the annihilation rate. Extensive calculations of the effects of subhalos on the antimatter signatures of DM annihilation can be found in [15, 16], where the mass and spatial distributions of the objects are crucial inputs. Here, we will again focus on the local impact of subhalos. Any subhalo can be modeled from its mass m, inner density profile ρ and radius R in the Galaxy, such that the resulting DM annihilation rate is set by its *annihilation volume*: $\xi(m, R) = 4\pi\int_0^{r_v} dr\, r^2\left\{\frac{\rho_{\rm cl}(m,R,r)}{\rho_\odot}\right\}^2$, which measures the ratio of its intrinsic emissivity to the local DM emissivity. The local subhalo flux is then: $\phi^\chi_{\rm cl,\odot}(E) \xrightarrow{\lambda\to 0} \frac{\beta c}{4\pi}\,\mathcal{S}\,N_{\rm cl}\frac{d\mathcal{P}_V(\vec{x}_\odot)}{dV}\,\frac{\langle\xi(\vec{x}_\odot)\rangle_m}{b(E)}\,\frac{dN(E)}{dE}$, where $\langle\rangle_m$ denotes the average over the mass distribution. The so-called *boost factor* is defined by the ratio of smooth+subhalo to smooth-only flux predictions. Since the effective volume contributing to the flux depends on the positron propagation scale, and therefore on energy, the boost factor depends on energy. We have in the short range limit, which turns out to be an average upper limit: $\mathcal{B}_\odot \xrightarrow{\lambda\to 0} 1 + N_{\rm cl}\,\frac{d\mathcal{P}_V(\vec{x}_\odot)}{dV}\,\langle\xi(\vec{x}_\odot)\rangle_m$. The boost limit is naturally given by the local number density of objects $N_{\rm cl}d\mathcal{P}_V(\vec{x}_\odot)/dV$ times the average annihilation volume of a single object $\langle\xi(\vec{x}_\odot)\rangle_m$ (already normalized to the local smooth luminosity). For large propagation scales, *i.e.* low energy, the signal coming from the cuspy smooth distribution in the Galactic center will have larger contribution to the total flux, lowering the boost factor. This is an important trend which is very often neglected. The global subhalo flux should be associated with a statistical variance σ related to the number of objects *seen* in positrons; σ therefore increases with energy [15, 16]. This translates into a large variance for the boost factor at high energy if the subhalo contribution dominates. One can play with any subhalo model, but it turns out that even in extreme cases, $\mathcal{B}_\odot \lesssim 20$ [16]. Using results from high resolution N-body simulations, it was shown in [17] that $\mathcal{B}_\odot \lesssim 5$ (enough for direct annihilation in e^+e^- only). One can still invoke the presence of massive nearby subhalos or other dark objects, but such a improbable possibility is in tension with gamma-ray constraints [18].

Conclusion: We have argued that the rising local positron fraction observed by the PAMELA experiment can be explained by properly including known astrophysical sources of primary positrons like pulsars, as already suggested twenty years ago [7]. Therefore, it seems that understanding this measurement, as well as the so-called "electron excess" sometimes *seen* in the Fermi data [19], are no longer theoretical issues, since standard and not contrived explanations are available. Remains open the question of identifying and modeling more accurately the local sources in order to sustain this solution on more detailed grounds. These are good news for this research domain.

Regarding the DM hypothesis, we have shown that usual thermal WIMP candidates are not expected to contribute significantly to the local positron flux, even when treated in a self-consistent framework including subhalos. The only possibility without over-tuning the annihilation cross section allowed for thermal relics is to consider direct production of e^+e^- and a mass scale ~ 100 GeV, a quite contrived case. Likewise, we have also emphasized that should DM yield a sizable positron signal, it would be difficult to disentangle it from standard astrophysical sources; the background is not yet under control.

Nevertheless, WIMPs remain excellent DM candidates, far from excluded. The crucial issue of their detection is still challenging, since their expected properties have made them continuously escape from observations despite the advent of new experimental techniques. It seems important to develop more complex strategies based on multi-messenger, multi-wavelength and multi-scale approaches, for which big efforts should be made (i) to quantify and minimize the associated theoretical uncertainties and (ii) to control the backgrounds. Other detection methods are also very important, among which the LHC results are particularly expected.

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