Dark Matter Indirect searches: phenomenological and theoretical aspects

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Abstract. I present a phenomenological, data-centered and data-driven assessment of the status of indirect searches for particle Dark Matter, with the main focus on some recent "anomalies" and of the main implications for DM model building. Tantalizing hints and stringent constraints seem to continuosly chase each other, as a number of well performing experiments keep delivering their data. This year may be the one in which we finally see the resolution of these dark puzzles, or it may not.

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1. Introduction

Cosmology and astrophysics provide several convincing evidences of the existence of Dark Matter (DM). The observation that some mass is missing to explain the internal dynamics of galaxy clusters and the rotations of galaxies dates back respectively to the '30s and the '70s. The observations from weak lensing, for instance in the spectacular case of the so-called 'bullet cluster', provide evidence that there is mass where nothing is optically seen. More generally, global fits to a number of cosmological datasets (Cosmic Microwave Background, Large Scale Structure and also Type Ia Supernovae) allow to determine very precisely the amount of DM in the global energy-matter content of the Universe at $\Omega_{\rm DM} h^2 = 0.1123 \pm 0.0035$ [1][1].

All these signals pertain to the gravitational effects of Dark Matter at the cosmological and extragalactical scale. Searches for explicit manifestation of the DM particles that are supposed to constitute the halo of our own galaxy (and the large scale structures beyond it) have instead so far been giving negative results, but this might be on the point of changing.

Indirect searches for Dark Matter aim at detecting the signatures of the annihilations or decays of DM particles in the fluxes of Cosmic Rays (CRs), intended in a broad sense: charged particles (electrons and positrons, protons and antiprotons, deuterium and antideuterium), photons (gamma rays, X-rays, synchrotron radiation), neutrinos. In general, a key point of all these searches is to look for channels and ranges of energy where it is possible to beat the background from ordinary astrophysical processes. This is for instance the basic reason why searches for charged particles focus on fluxes of antiparticles (positrons, antiprotons,

[1] Here $\Omega_{\rm DM} = \rho_{\rm DM}/\rho_c$ is defined as usual as the energy density in Dark Matter with respect to the critical energy density of the Universe $\rho_c = 3H_0^2/8\pi G_N$, where H_0 is the present Hubble parameter. h is its reduced value $h = H_0/100\ {\rm km\,s^{-1}Mpc^{-1}}$.

antideuterons), much less abundant in the Universe than the corresponding particles, and searches for photons or neutrinos have to look at areas where the DM-signal to astro-noise ratio can be maximized.

Pioneering works have explored indirect detection (ID) as a promising avenue of discovery since the late-70's. Since then, innumerable papers have explored the predicted signatures of countless particle physics DM models. In the past 3 years or so, however, the field has experienced a significant burst of activity, mainly due to the results presented by a few very well performing experiments, above all the Pamela satellite, the Fermi satellite and the Hess telescope. It is fair to say that the field has passed, for better or for worse, from a theory-driven state to a data-driven phase.

2. Charged cosmic rays and the Pamela, Fermi, Hess anomaly

2.1. Data

There has been a flurry of positive results from a few indirect detection experiments looking at the fluxes of charged cosmic rays. In particular, the signals pointed to an excess of electrons and positrons at the TeV and sub-TeV scale:

- Data from the Pamela satellite [2] showed a steep increase in the energy spectrum of the positron fraction $e^+/(e^+ + e^-)$ above 10 GeV up to 100 GeV, compatibly with previous hints from Heat [3] and Ams-01 [4].
- Recently, these findings have been confirmed with an independent measurement by the Fermi satellite [5], and extended to about 200 GeV.
- Data from Pamela [6] also showed no excess in the $\bar{p}/p$ energy spectrum compared with the predicted background.
- The balloon experiments Atic-2 [7] and Ppb-Bets [8] were reporting the presence of a peak in the $e^+ + e^-$ energy spectrum at around 500-800 GeV.
- This sharp feature has been later questioned and superseded by the results of the Fermi satellite [9]: while an excess with respect to the expected background is confirmed, the $e^+ + e^-$ spectrum is found to be instead reproduced by a simple power law.
- The Hess telescope also reports the measurement of the $e^+ + e^-$ energy spectrum above energies of 600 GeV [10], showing a power law spectrum in agreement with the one from Fermi and eventually a steepening at energies of a few TeV.

The data are displayed in fig. 1, together with the expected astrophysical 'backgrounds'. The latter ones are uncertain and are an interesting subject of study by themselves in CR physics, but I will not discuss them further here. The signals presented above are striking because they imply the existence of a source of 'primary' e^+ (and e^-) other than the ordinary astrophysical ones. This unknown new source can well be itself of astrophysical nature, e.g. one or more pulsar(s) / pulsar wind nebula(æ), supernova remnants etc [11]. It is however very tempting to try and read in these 'excesses' the signature of DM.

2.2. Dark Matter interpretation

As already mentioned above, the DM particles that constitute the DM halo of the Milky Way are expected to annihilate into pairs of primary SM particles (such as $b\bar{b}$, $\mu^+\mu^-$, $\tau^+\tau^-$, W^+W^- and so on) which, after decaying and through the processes of showering and hadronizing, give origin to fluxes of energetic cosmic rays: $e^-, e^+, \bar{p}$ (and also γ-rays, ν...), denoted dN_f/dE. Depending on which one has been the primary SM particle, the resulting spectra differ substantially in the details. Generically, however, they feature a 'bump'-like shape, characterized by a high-energy cutoff at the DM particle mass and, for $e^\pm$ in particular, a softly decreasing tail at lower energies (see e.g. the examples in fig. 2). It is thus clear that it is very natural to expect a DM source to

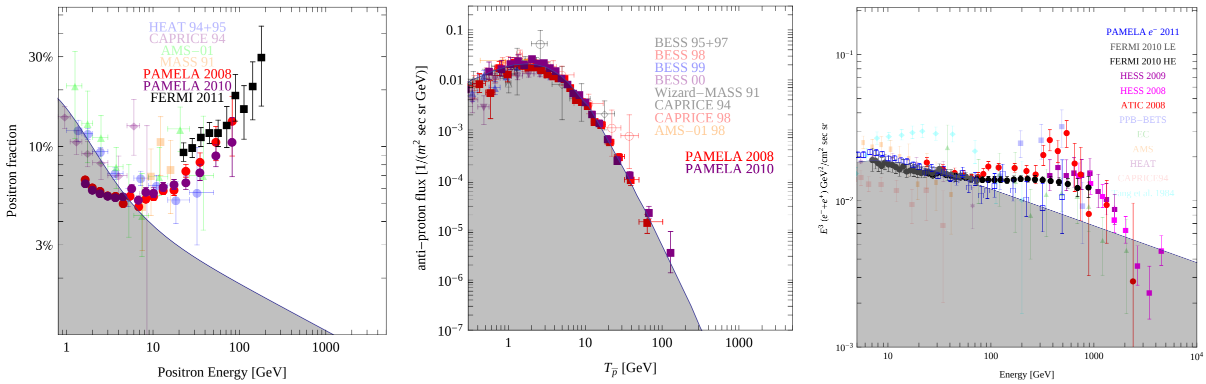

Figure 1. A compilation of recent and less recent data in charged cosmic rays, superimposed on plausible but uncertain astrophysical backgrounds from secondary production. Left: positron fraction. Center: antiproton flux. Right: sum of electrons and positrons.

'kick in' on top of the secondary background and explain the $e^{\pm}$ excesses. The energy range, in particular, is tantalizingly right: the theoretically preferred TeV-ish DM would naturally give origin to TeV and sub-TeV bumps and rises.

The e^-, e^+ and $\bar{p}$ produced in any given point of the halo propagate immersed in the turbulent galactic magnetic field. The field consists of random inhomogeneities that act as scattering centers for charged particles, so that their journey can effectively be described as a diffusion process from an extended source (the DM halo) to some final given point (the location of the Earth, in the case of interest). While diffusing, charged CRs experience several other processes, and in particular energy losses due to synchrotron radiation, Inverse Compton Scattering (ICS) on the low energy photons of the CMB and starlight, Coulomb losses, bremsstrahlung, nuclear spallations.... Quantitatively, the steady-state number density $n_f(\vec{x}, E)$ per unit energy E of the cosmic ray species f $(= e^+, e^-, \bar{p})$ in any given point $\vec{x}$ obeys to a diffusion-loss equation [12]

$$
\begin{aligned}
-\mathcal{K}(E)\cdot\nabla^2 n_f - \frac{\partial}{\partial E}\left(b(E,\vec{x})\, n_f\right) \quad &+ \quad \frac{\partial}{\partial z}\left(\mathrm{sign}(z)\, V_{\rm conv}\, n_f\right) \\
&= \quad Q(E,\vec{x}) - 2h\,\delta(z)\,\Gamma\, n_f\,. \qquad (1)
\end{aligned}
$$

The first term accounts for diffusion, with a coefficient conventionally parameterized as $\mathcal{K}(E) = \mathcal{K}_0 (E/\mathrm{GeV})^{\delta}$. The second term describes energy losses: the coefficient b is position-dependent since the intensity of the magnetic field (which determines losses due to synchrotron radiation) and the distribution of the photon field (which determines losses due to ICS) vary across the galactic halo. The third term deals with convection while the last term accounts for nuclear spallations, that occur with rate Γ in the disk of thickness $h \simeq 100$ pc. The different processes described above have a different importance depending on the particle species: the journey of electrons and positrons is primarily affected by synchrotron radiation and inverse Compton energy losses, while for antiprotons these losses are negligible and convection and spallation dominate.
The source, DM annihilations, is given by $Q = 1/2\,(\rho(\vec{x})/m_{\rm DM})^2 \sum_i \mathrm{BR}_i \langle\sigma v\rangle\ (dN^i_f/dE)$, where $m_{\rm DM}$ is the DM mass, σv is the total annihilation cross section and the sum runs over all primary channels i in which the cosmic ray species f is produced. $\rho(\vec{x})$ is the DM density distribution in the galactic halo. What to adopt for the latter is another one of the main open problems in the field. Based on the results of increasingly more refined numerical simulations or on direct observations, profiles that differ even by several orders of magnitude at the Galactic Center are

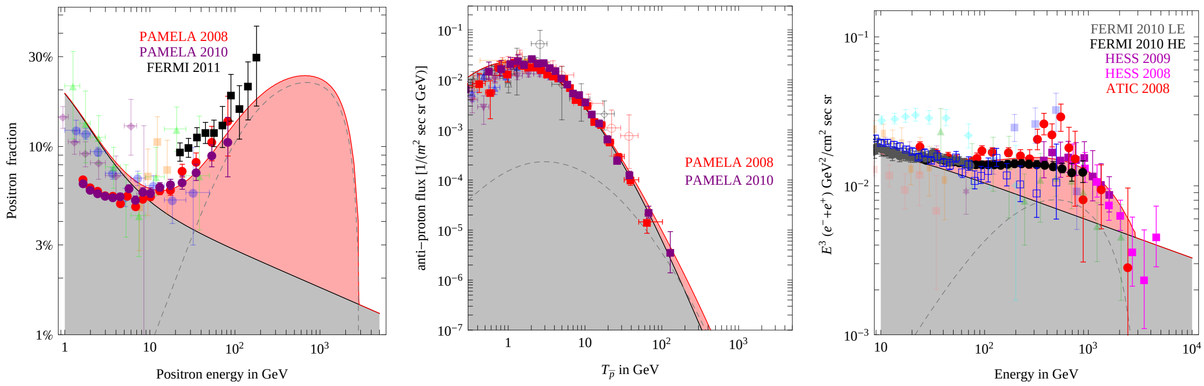

Figure 2. Charged cosmic ray data interpreted in terms of Dark Matter annihilations: the flux from the best fit DM candidate (a 3 TeV DM particle annihilating into $\tau^+\tau^-$ with a cross section of $2 \cdot 10^{-22}\,\mathrm{cm}^3/\mathrm{sec}$) is the lower dashed line and is summed to the supposed background, giving the pink flux which fits the data. Left, center and right like in fig. 1.

routinely adopted: e.g. the classical Navarro-Frenk-White (NFW) or the Einasto one, which exhibit a cusp at the galactic center, or the truncated isothermal or the Burkert one, which feature a central core. All profiles, on the other hand, are roughly normalized at the same value at the location of the Earth (≈ 0.3 GeV/cm^3). These features generically imply that observables which depend mostly on the local DM density (for instance, the flux of high energy positrons, which cannot come from far away due to energy losses) will not be very affected by the choice of profile, while those that are sensitive to the density at the GC will be affected the most (e.g. gamma rays observations of regions close to the GC).
Eq. (1) is usually solved numerically in a diffusive region with the shape of a solid flat cylinder that sandwiches the galactic plane, with height $2L$ in the z direction and radius $R = 20\,\mathrm{kpc}$ in the r direction. The location of the solar system corresponds to $\vec{x}_\odot = (r_\odot, z_\odot) = (8.33\,\mathrm{kpc}, 0)$. Boundary conditions are imposed such that the number density n_f vanishes on the surface of the cylinder, outside of which the charged cosmic rays freely propagate and escape. The values of the propagation parameters δ, K_0, $V_{\rm conv}$ and L are deduced from a variety of (ordinary) cosmic ray data and modelizations.

The datasets listed in Sec. 2 pin-point the properties of the DM particle needed to interpret them in terms of annihilations quite precisely. The DM has to be:

- ▷ With a mass of a *few TeV*, in order to reproduce the feature in the $e^+ + e^-$ spectrum.
- ▷ *Leptophilic*, i.e. annihilating almost exclusively into leptonic channels, otherwise the antiproton measurements would be exceeded.
- ▷ With a *very large annihilation cross section*, of the order of $10^{-23}\,\mathrm{cm}^3/\mathrm{sec}$ or more (for the masses under consideration), much larger than the thermal one, in order to produce a large enough flux that can fit the positron rise and the $e^+ + e^-$ bump.

Fig. 3 illustrates these points in a systematic way. On the left, it shows how the DM DM $\to \tau^+\tau^-$ has the best χ^2; other leptonic channels (e.g. $\mu^+\mu^-$) can give acceptable fits, but all other annihilations into quarks, vector and Higgs bosons are significantly disfavored. The value of the required annihilation cross section as a function of the DM mass is illustrated in fig. 3 (right). The actual best fit case is illustrated in fig. 2: it consists of a candidate with a mass of 3 TeV and annihilating into $\tau^+\tau^-$, a channel which produces smooth leptonic spectra, with a cross section of $2 \cdot 10^{-22}\,\mathrm{cm}^3/\mathrm{sec}$.

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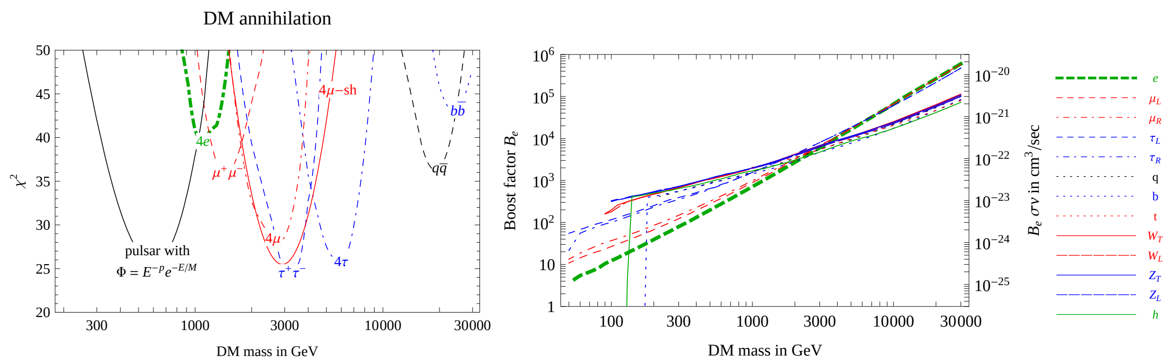

Figure 3. Left: Global fit of different DM annihilation channels to the PAMELA, FERMI and HESS data. The labels on each curve indicate the primary channel (figure from [13] (2009); the fit results remain essentially valid even through the subsequent data updates; the four-lepton lines refer to exotic channels discussed later). Right: Values of $B_e \cdot \sigma v$ (right axis) and of the boost factor B_e (left axis, for $\sigma v = 3\ 10^{-26}\text{cm}^3/\text{sec}$) needed to fit the data (figure from [14]).

The appearence of a small but visible flux of antiprotons from a DM DM $\to \tau^+\tau^-$ annihilation mode in fig. 2 (center) may be at first sight surprising. It is due to the fact that these fluxes are computed including electroweak corrections, i.e. the radiation from the initial $\tau^\pm$ of EW gauge bosons ($W^\pm$, Z) which then decay into many other SM particles, including quarks that hadronize into antiprotons. More generally, the importance of such corrections has been appreciated only relatively recently, in a string of papers with varying scopes and levels of accuracy [15]. Without entering in the details, it is enough for my purposes to remind that (i) the corrections are particularly relevant for large DM masses (above a TeV); (ii) they can alter significantly the ID fluxes, both in their spectral shape and in their amplitude, affecting especially the low energies portion [16], and (iii) in some cases they can also largely modify the annihilation cross section itself, since they can lift the helicity suppression into light fermions [17].

This concludes my overview of the phenomenological interpretation of charged CR data. I now move to a discussion of how natural or preposterous the properties in page 4 are and of what it takes to realize them.

2.3. DM model building

Inspired by the flurry of data discussed above, the field of DM model building has experienced a huge surge of activity in the latest few years. This is essentially because the DM properties individuated by the charged CR signals, and the associated constraints, pose a tough challenge for the traditional DM candidates. Let us take the supersymmetric neutralino as a strawman and see how it fares as a candidate for the DM phenomenology outlined in page 4: (i) The data require a multi-TeV DM mass, but this fits rather uncomfortably in a theory, such as SuSy, whose typical scale should be close to the mass of the higgs boson, if naturalness is a valid criterion. (ii) The data require leptophilicness, but typical neutralino annihilation channels do not distinguish between leptons and quarks, and often couple to gauge bosons, so a dangerous component of hadrons is generically expected. (iii) The data require a huge annihilation cross section into relatively light final states such as leptons, but the neutralino is a Majorana particle and, as such, its (s-wave) annihilation cross section is helicity suppressed by a large factor of $(m_f/m_{\rm DM})^2$, where m_f is the fermion mass. The scorecard for the neutralino does not look great. Of course these generic arguments can be circumvented in specific situations. Indeed several works have argued that it *is* possible to explain the CR excesses insisting on an MSSM DM candidate [18, 19, 20, 21, 22]. This, however, happens at the price of finely tuning at least some aspect: the properties of the $\bar{p}$ background, the position of a nearby DM clump, assuming (uplifted) resonances, finding just few configurations in a scatter plot, explaining only the positron rise and leaving the rest to ad-hoc astrophysics... . These examples are therefore perceived as somewhat anecdotical. Similar arguments would apply for other 'traditional' DM frameworks, e.g. Kaluza-Klein (extradimensional) DM.

This is why the community has preferred to explore new model building possibilities and a lot of works have been published since 2008. Before sketching the main directions of this activity, let us first address an aspect which finds application in several models: how to obtain the large flux.

2.3.1. Tools for enhancements So the question is: is it possible to reconcile the very large value of the annihilation rate (corresponding to $\langle\sigma v\rangle \gtrsim 10^{-23}\,\mathrm{cm}^3/\mathrm{sec}$) required 'today' to fit the CR excesses and the smaller value (corresponding to $\langle\sigma v\rangle \simeq 3\,10^{-26}\,\mathrm{cm}^3/\mathrm{sec}$) individuated by the paradigm of DM production as a thermal relic in the Early Universe? More generically, and thinking beyond the current CR excesses, a large flux would greatly increase our hopes for detection: are there ways to naturally obtain large rates?

The ingenuity of theorists has found at least three positive possible answers to these questions. Yes, it is possible:...

A) Via an astrophysical boost factor: the presence, in today's galactic halo, of DM overdensities predicted by numerical simulations boosts the annihilation rate (proportional to the squared density of DM particles). If the boost could reach a $\mathcal{O}(10^3)$ value, this would explain why the rate is much larger today, without modifying the cross section itself. The typical realistic values, however, have been proven to be $\mathcal{O}(10)$ at most [23].

B) Annihilating via a resonance [14, 24, 25, 26]: if the resonance mass is just below twice the DM mass, the annihilation cross section becomes sensitive to the details of the velocity distribution of the DM particles; since (on average) DM particles are slower today than in the Early Universe, many more of them meet the conditions of resonant annihilation and therefore the rate is enhanced, provided that the relevant parameters are appropriately fine tuned. Typically one needs the mass of the resonance to differ by less than 1% from twice the DM mass and the width of the resonance to be of the order of 10^{-5} of its mass, in order to obtain an enhancement of $\mathcal{O}(10^3)$.

C) Thanks to the Sommerfeld enhancement (see [27, 28, 14], and then [34, 29, 30]), a non-perturbative effect which modifies the annihilation cross section in the regime of *small relative velocity* of the annihilating particles and in presence of an effectively *long-range force* between them. Indeed this well known quantum mechanical effect, first discussed by Sommerfeld in the context of positronium e^+e^- annihilations under the effect of resummed γ exchanges, can occur in DM annihilations if the two annihilating particles exchange an interaction mediated by a force carrier of mass m_V and with a coupling constant $g \approx \sqrt{4\pi\,\alpha}$ such that $\alpha M_{\rm DM}/m_V \gtrsim 1$. For very heavy DM particles ($\gtrsim$ 10 TeV), the exchange of SM weak bosons can mediate the effect, in which case α is just the one of weak interactions and $m_V \approx m_{W^\pm,Z} \approx 100$ GeV. If a new force exist, however, mediated by a particle with mass $m_V \approx 1$ GeV and gauge-like coupling strength with DM particles only, even DM particles of mass $\lesssim 1$ TeV would enjoy the Sommerfeld enhancement. The details of the enhancement of the cross–section are model dependent (see [31, 32, 33] for some examples), but some general features can be identified: in particular, the enhancement shows an inverse proportionality with the relative velocity of the two particles, and it typically saturates to a maximum value when that is $\beta \lesssim 10^{-3}$.

While in some models the enhancement factors discussed above are natural or even unavoidable [2],

[2] See e.g. the Sommerfeld enhancement in [28, 35], published before the CR data made an enhancement needed,

it is fair to say that in many cases they have been used quite liberally in model building, along the lines of 'If I miss a factor of N to fit the data, I throw in A, B or C, or a combination thereof, until I get N' [3]. Perhaps precisely for this reason, they have been studied in detail and they have become kind of a tool in the model builder toolbox. So they are likely to stay with us in the near future.

2.3.2. Recent theory directions A possible categorization of the intense model building work of the past few years would identify the following classes:

★ Minimalistic Dark Matter models. These are models loosely identified by the fact that they aim at providing a viable DM candidate insisting on introducing the minimal set of new particles beyond the Standard Model. They arised originally in opposition to the mainstream direction of obtaining DM as a byproduct of a more ambitious and comprehensive theory, such as SuSy or Extra Dimensions. The namesake Minimal Dark Matter (MDM) [37] falls in this class, as well as less fundamentalist theories such as the model in [38], the hidden vector [43], the Inert Doublet Model (IDM) [39, 40] and others.
Thanks to their relative simplicity, the models in this class are often free of many free parameter and therefore are quite predictive: their ID signatures can be computed and compared univocally with data. The MDM model, featuring, in its minimal realization, a 9.6 TeV DM particle annihilating almost exclusively into W^+W^-, initially excited its authors since it had predicted the size and shape of the positron rise (and the $\bar{p}$ null result) in Pamela, provided that an astrophysical boost factor of ~ 50 was adopted. Later it has been disfavored by the Fermi+Hess $e^\pm$ data, which prefer a lower mass, and γ-ray data, see e.g. [41] (it remains a viable DM candidate –albeit obviously not an explanation for the CR excesses– for a smaller –and, by the way, more realistic– astrophysical boost factor). The phenomenology of the IDM shares a similar history [42].

★ Models with new dark forces or, more generically, a rich Dark Sector. In this class fall most of the models whose construction has been directly stimulated by the CR excesses.
The model which undoubtedly has most attracted attention and has best spelled out the ingredients is presented in [34], although similar ideas have been proposed before or around the same time [44, 25, 45, 46, 47, 48, 49]. The model in [34] features a TeV-ish DM particle which is sterile under the SM gauge group but which interacts with itself via a new force-carrying boson ϕ (with the strength of typical gauge couplings). The DM annihilation therefore proceeds through DM DM $\to \phi\phi$. A small mixing between ϕ and the electromagnetic current assures that ϕ eventually decays. Therefore the process of DM annihilation occurs in 2 steps: first two DM's go into two ϕ's and then each ϕ's, thanks to its mixing with a photon, goes into a couple of SM particles. The crucial ingredient is that the mass of ϕ is chosen to be light, of the order of $\lesssim 1$ GeV. This simple assumption, remarkably, kills two birds with a stone. On one side, the exchange of ϕ realizes the Sommerfeld enhancement discussed in Sec. 2.3.1, thus providing a very large annihilation cross section today but preserving the thermal production of DM in the Early Universe. On the other side, ϕ can only decay into SM particles lighter than a GeV, i.e. electrons, muons and possibly pions, but not protons: this assures that the annihilation is leptophilic, for a simple kinematical reason. The model therefore fulfils all the requirements listed in page 4.
The construction can then be complicated *ad libitum*, e.g. assuming that the dark gauge group is non-abelian and the DM sits in a multiplet of such group, with small splitting

just to mention an example that I know well.
[3] See e.g. the boost factor of ~ 50 in [35, 36], introduced after the CR data showed that a little bit more of an enhancement was needed, just to mention an example that I know well.

between the components. This allows to accommodate other experimental anomalies, not discussed here.
The kinematical argument is not the only one available to justify a leptophilic nature for DM. In the literature, variations have been proposed in which DM is coupled preferentially to leptons because it carries a lepton number [57], because it shares a quantum number with a lepton [14, 58], because quarks live on another brane [59] or... 'because I say so' [60].[4]
The Indirect Detection phenomenology of these theories has of course been worked out in detail [50, 13, 51]. In short, they can easily provide a fit to the charged CR excesses as good as, or better than, the one from ordinary annihilating DM, also thanks to the fact that the 2-step annihilation softens the spectrum of final $e^{\pm}$ and allows a better agreement with the data. [5] They are also subject to the same constraints from neutrinos and especially gamma rays: the bottom line of a series of analyses [52, 53, 54, 55] is that, while the bounds are somewhat alleviated (essentially thanks to the smaller yield of γ-rays and the softening of the spectra mentioned above), there still remain a tension. The conclusion of, e.g., [56], which also considers cosmological constraints, is that it is possible for these models to constitute an explanation of the CR excesses while remaining consistent with the constraints, albeit barely and at the condition of assuming a specific admixture of $4e$ and 4μ final states and quite a specific mass for ϕ.

★ Decaying Dark Matter. The possibility that Dark Matter consists of a particle that actually decays on a very long time scale has been considered since a long time, e.g. in the context of gravitino DM with R-parity violation [61].
More recently, this option has gained steam (see e.g. [62, 63, 64, 65, 66, 67, 68]), precisely because of the cosmic ray excesses and the difficulty of explaining them with annihilating DM. Indeed, if the decay half-life is tuned to $\approx 10^{26}$ seconds (a figure possibly motivated by some high enegy physics scale suppressed operators) [6] and if the production of hadrons is adequately suppressed by some a priori unrelated mechanism, the features needed to fit the data are obtained. A crucial advantage is also that gamma ray (and neutrino) constraints are in general less severe in these scenarios, as they are proportional to the first power of the DM density (and not the second, like for annihilations).
The ID phenomenology of decaying DM has been studied in detail [13, 65, 70]. Generally speaking, it is not much different from the phenomenology of annihilating DM, modulo a few points: i) decay channels other than the ordinary particle-antiparticle pair become possible for fermionic DM (e.g. DM $\to W^{\pm}\ell^{\mp}$, DM $\to \ell^+\ell^-\nu$); ii) the local spectrum of charged CR is often somewhat harder for decaying DM than for annihilating DM, since in the latter case a sizable fraction of low energy particles manage to diffuse to the Earth from the high production regions in the inner Galaxy, softening the spectrum. All in all, it is possible to find fits to the data as good as, or even better than, those of ordinary annihilating DM. On the other hand, as anticipated, the gamma ray constraints from the Galaxy are not as stringent as in the case of annihilating DM. The most stringent bounds come from the isotropic γ flux [71, 54, 74] and, recently, from galaxy clusters in Fermi data [72, 73]: in both cases decay half-lives shorter than $\sim$ few $\cdot 10^{26}$ sec or even up to 10^{27} sec (with the precise value depending on the $m_{\rm DM}$ and the decay channel) are excluded [7]. This represents a serious blow for the decaying DM interpretation of the CR excesses: [74] shows that they

[4] Strictly speaking, ref.s [59] and [60] should not fall in the class of models with new dark forces, since the former works in an extradimensional setup and the latter works in the framework of an effective field theory.
[5] See however [11] for some points of criticism.
[6] Of course, this value of $\tau_{\rm dec}$ is so much longer than the age of the Universe that the slow decay does not make a dent in the overall cosmological DM abundance and does not spoil the agreement with a number of astrophysical and cosmological observations, including the Cosmic Microwave Background [69].
[7] The more stringent constraints from clusters derived in [75] are irrealistic.

are ruled out unless very conservative choices are adopted. The CMB constraints turn out to be not competitive for decaying DM [76, 77].

3. Gamma rays and the Fermi 135 GeV line anomaly

3.1. Hints of DM in gamma rays

Actually, sporadically, claims of evidence of DM in γ-rays data from the Fermi satellite have been made.

Evidences for DM have been reported at the GC in [78, 79, 80],[81], in the isotropic flux [82], in the Virgo cluster [83], possibly in the MW halo [84]... Most notably and most recently an evidence for one (or two) γ-ray line(s) around 130 GeV has been reported, as discussed below.

Setting aside for a moment this latter claim, it is fair to say that none of the other ones, so far, has gathered enough consensus to be considered more than a tentative hint. The crucial points of criticism often have to do with the assumptions made for the astrophysical background (which can, at this stage of significance, mimic a DM signal) or the lack of independent confirmations of the same signal in other channels or in other locations.

In this respect there are two strings of papers that illustrate well the difficulty of the analyses and of the debate. (i) The claim in [79] in favor of light ($\mathcal{O}(10)$ GeV) DM annihilations at the GC has been questioned in [85, 86], which essentially affirm that known astrophysical sources (e.g. millisecond pulsars, MSP) can explain it away. But it has then been re-claimed in [80, 87], saying that those sources are too few, too point-like, too dim or too soft to produce the emission. The latest installment consists of [81], which reaffirms the MSP hypothesis while entertaining the DM one as well. (ii) The claim in [83] of DM annihilations in the Virgo cluster has been refuted first in [88] and then by an extended set of authors of the original paper in [93]. In particular, the latter found that, removing previously-unaccounted-for astrophysical point sources, the evidence in [83] evaporates and actually one can impose stringent bounds (possibly the most stringent ones) using the very same Virgo cluster observation.

Let's now come to '130 GeV line' claim (for a more thorough review see [89]). Originally spotted by [101] and, above all, by [90] in the publicly available Fermi data from an extended region including the GC, it has later found support in other analyses [91, 94, 95, 96], with varying degrees of accuracy and claimed significance. [91, 96] have seen it in what could possibly be DM subhaloes of the MW, and there might be two lines, at 111 GeV and 129 GeV [92, 94]. [95] has seen it in galaxy clusters too. For a response, [97, 98, 99] challenged the analyses in a number of ways, suggesting that the line(s) could be due to unidentified instrumental, statistical or astrophysical origin. [8] If however the line(s) is (are) from DM, it is plausible to expect an associated γ-ray continuum (and possibly a flux of other CRs, e.g. anti-protons) at lower energies, originating from the annihilations of DM into other SM particles; if the cross section into $\gamma\gamma$ is normalized to the one required by Fermi data ($\mathcal{O}(10^{-27})\,\mathrm{cm}^3/\mathrm{s}$), the inferred flux in the continuum poses problems in a variety of cases [102, 103, 104, 105, 106]. However, the details are model dependent: there is no airtight exclusion and working exceptions can be built [107].

In any case, it is clear that this is one of the most interesting areas of development and no claim should be dismissed without deep scrutiny. It might well be that one of these claims will prove to be the harbinger of a full-fledged discovery!

In general, some of our best hopes for clarifying the situation lie in the Fermi satellite itself, of which the prelaunch predicted sensitivities [108] let us believe that a DM with thermal cross section will be probed at 3σ up to a mass of several tens or even hundreds of GeV, depending

[8] By the way, can astrophysics produce a γ-ray line (something which has been advertised for decades as a 'smoking gun' evidence for DM)? Yes, of course, it sufficed to ask and pulsars (always pulsars...) took on themselves the task of producing lines at 100 GeV or somewhat above, via cold electron winds impinging on environmental gamma radiation [100]. It is challenging, though, to see how this process could give rise to a spatially extended emission.

on the annihilation channel and the chosen target. Another set of upcoming experiments will further improve the sensitivity on γ-ray lines, e.g. HESS-II which will soon be operational, CTA which should start in a few years and GAMMA-400 which is being advocated for. In the merit of the 130 GeV line signal, they will provide precious information [109].

3.2. DM interpretation and model building
The findings briefly introduced in the previous Subsection have started inspiring some model building activity in the latest few months (for a more thorough review see [89]). The exercise is: produce a $\gamma\gamma$ line (or something narrow enough to look like a line) with relative cross section $\langle\sigma v\rangle_{\gamma\gamma} \sim 10^{-27}\,\mathrm{cm}^3/\mathrm{sec}$. The starting point is well known: since DM is electrically neutral, it does not directly couple to photons and therefore one needs some mediating mechanism in order to produce the $\gamma\gamma$ pair: (i) via a loop of charged particles, which can be SM ones [110], SuperSymmetric ones [111, 112, 113] or from a new sector [114, 115, 116]; (ib) via Chern-Simons terms [117], the remnants of loops that have been integrated-away; (ii) via a normally subdominant DM-photon coupling, e.g. a magnetic dipole [107, 118, 119]; (iii) via axions [120]... As another option, one may produce a 'top-hat' gamma ray spectrum by having DM annihilate into two metastable states ϕ that then decay into $\gamma\gamma$ (see e.g. [121, 122]): the spectrum is flat between the edges $E_\pm = m_{\rm DM}/2\left(1 \pm \sqrt{1 - m_\phi^2/m_{\rm DM}^2}\right)$, so for m_ϕ close enough to $m_{\rm DM}$ the top-hat fakes a line. As yet another option one may interpret the feature at 130 GeV not as a proper line but rather as the peak of internal bremsstrahlung radiation [123, 124].

Next, one is confronted to two possible (possibly related) problems: the added 'mediator' physics usually implies that the $\gamma\gamma$ process is suppressed with respect to other processes (for instance, the tree level annihilation into the particles running in the loops of (i)), but the needed $\langle\sigma v\rangle_{\gamma\gamma}$ required by FERMI data is relatively large and therefore the 'other processes' are expected to have an even larger $\langle\sigma v\rangle$, with the result that: (1) they might be constrained by other observations (e.g. by FERMI data themselves); (2) they might tend to give a too large annihilation in the Early Universe and therefore an insufficient yield of the thermal DM abundance. This latter point is similar to the one already encountered for the charged CR anomalies (see Sec. 2.3.1), so that some of the tools already explored might apply. Additional proposed solutions include: (a) assuming that the tree level process is not accessible kinematically (e.g. the particles in the loop are heavier than the c.o.m. energy, i.e. the DM mass [110]) [9], (b) engineering other mechanisms which obtain a correct relic abundance but which turn off today (e.g. coannihilations), (c) decoupling the relic DM from the one that produces signal, in model with multi-component DM, (d) giving up altogether the thermal relic mechanism... See [107] for a lucid summary.

Another quite generic 'theory' consequence is that, wherever you can attach a γ emission you can usually also attach a Z or a h emission, with the result that another line is expected at an energy $E = m_{\rm DM}(1 - m_{Z,h}^2/4m_{\rm DM}^2)$ (see e.g. [92]).

4. Conclusions

Like possibly other fields in particle physics in these days, the one of Dark Matter Indirect Detection is currently characterized by an exciting mix of tantalizing hints, increasingly stringent constraints and ever rising hopes. According to my taste, and to the material presented above, I would classify:

- $\triangle$ **Hints**: the e^+ and $e^\pm$ excesses in PAMELA, FERMI and HESS.

[9] Actually, in a model like [110], one postulates that (or selects a scenario in which) DM annihilates (only) into top quarks via a Z'. Demanding the correct relic abundance leads to requiring (a). Which naturally solves (1) and (2) and produces line-like features via (i).

If interpreted in terms of DM annihilations, these point to a rather preposterous particle: multi-TeV, leptophilic and with a huge annihilation cross section.

the '130 GeV line' in Fermi data.

If interpreted in terms of DM annihilations, this seems to point to particle which reassures at first and then puzzles: its mass-scale and its spatial distribution are consistent with the phenomenologists' best dreams, but the large cross section is unsettling.

▽ **Constraints**: the γ-ray measurements from Fermi and Hess (and, to a smaller extent, Veritas and the other Čerenkov telescopes), the neutrino measurements from SuperKamiokande and Icecube and the CMB bounds based on Wmap.
These rule out most or all of the parameter space for the preposterous DM above. They also put in a difficult spot some of the more exotic models discussed in Sec. 2.3.2.
On the other hand, they show how far-reaching these kinds of searches can be. They are starting to explore the parameter space of ordinary (thermally produced) DM and already rule out the lower mass portion of the tens-of-GeV range.

◊ **Hopes**: from the point of view of data, the γ-ray (and, probably to a smaller extent, the neutrino) telescopes will continue to play a major role: they will keep up their march across the parameter space and at some point they may see something totally convincing. The Ams-02 detector, onboard of the International Space Station, will probably deliver data in 2013: if the $e^{\pm}$ excesses are of astrophysical origin (as it is probably judicious to believe) then they constitute a formidable background to any future signal from DM in this channel; we have to place our hopes in another channel: the $\bar{p}$ one looks promising, and the $\bar{d}$ one (also explored by the Gaps experiment) may reserve surprises.
From the point of view of theory, the single most striking result of the recent activity is that the community has diversified its interests and explored many new directions, both in terms of phenomena that might enhance the DM signal (see Sec. 2.3.1) and in terms of model-building (see Sec. 2.3.2 and 3.2). The hope is that one or more of these interesting ramifications will bear fruit soon.

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