DARK MATTER AND THE PAMELA/ATIC DATA

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Recent data from the PAMELA satellite and a number of balloon experiment have reported unexpected excesses in the measured fluxes of cosmic rays. Are these the first direct evidences for Dark Matter? If yes, which DM models and candidates can explain these anomalies and what do they imply for future searches? Is this all compatible with other constraints?
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1 Introduction

While compelling evidence for the existence of Dark Matter (DM) now comes from a number of astrophysical and cosmological probes, no explicit detection has been confirmed yet. The indirect detection strategy relies on the possibility of seeing signals of the presence of DM in terms of the final products ($e^{\pm}$, p, d, γ, $\nu \ldots$) of DM annihilations in the galactic halo, on top of the ordinary cosmic rays. The recent positive results from a number of indirect detection experiments have suggested the possibility that indeed such a signal has been seen. In particular, the signals point to an excess of electrons and positrons.

- Data from the PAMELA satellite show a steep increase in the energy spectrum of the positron fraction $e^+/(e^+ + e^-)$ above 10 GeV up to 100 GeV, compatibly with previous less certain hints from HEAT and AMS-01.
- Data from PAMELA also show no excess in the $\bar{p}/p$ energy spectrum compared with the predicted background.
- The balloon experiments ATIC-2 and PPB-BETS report the presence of a peak in the $e^+ + e^-$ energy spectrum at around 500-800 GeV.

- The HESS telescope has also reported the measurement of the $e^+ + e^-$ energy spectrum above energies of 600 GeV up to a few TeV: the data points show a steepening of the spectrum which is compatible both with the ATIC peak (which cannot however be fully tested) and with a power law with index -3.05 ± 0.02 and a cutoff at $\approx$2 TeV.

In this presentation I will address the following issues (the discussion in based on Ref. [?] and Ref. [?], where all references are given):

- Which characteristics must a Dark Matter candidate have in order to fit the above data?
- What are the constraints from other observations (e.g. γ from the Galactic Center region)?
- As a consequence, which conclusions can be drawn on the DM interpretation of the data?

2 Positrons, electrons and antiprotons: which Dark Matter can fit the data?

As a first example, the upper row of Fig.**??** shows the spectra of the positron fraction (first column), of the sum of electrons and positrons (second column) and of the antiprotons (third column) from a DM particle with 150 GeV mass and annihilating into W^+W^-. As apparent, the candidate can fit well the positron data, but produces too large a flux of antiprotons: such a DM is excluded by data with pretty high confidence. Let us instead consider (third row of Fig.**??**) a candidate with a (very large) 10 TeV mass, again annihilating into W^+W^-. The positron data points are well fitted (by the low energy tail of the spectrum, in this case) and the antiproton bounds are not exceded, thanks to the fact that an excess would show only at larger energies. However the peak reported by the balloon experiments at around 1 TeV is not reproduced. As a third exemple, we consider a 1 TeV candidate with annihilations into $\mu^+\mu^-$ (second row of Fig. **??**): it fits all the available datasets.

We now proceed to presenting the results of the fits in a more systematic way. In performing such fits, we smoothly scan over the charged cosmic ray propagation configurations and DM halo models, within the boundaries described in [?]. Moreover, we assume that the $e^+, e^-, \bar{p}$ background spectra can be freely renormalized, and have independent ± 0.05 errors in their energy slope. This mimics the main uncertainties in astrophysical backgrounds. We will show plots of the χ^2 as a function of the DM mass: an interval at n standard deviations corresponds (in Gaussian approximation) to $\chi^2 < \chi^2_{\rm min} + n^2$, irrespectively of the number of data points.

First, let us consider the fit to PAMELA positron data only (16 data points). We see in the upper left panel of fig. **??** that DM annihilations into e, μ, τ, W can reasonably well reproduce the data for any DM mass, while annihilations into Z, t, q, b, h give a good fit for DM heavier than about 1 TeV. It is perhaps interesting to note that, contrary to what commonly thought, the spectrum from W^+W^- annihilations is not too flat to give a good fit of the quite steep PAMELA rise.

Next, let us add the PAMELA $\bar{p}/p$ data (17 data points). Since no excess seems present in the $\bar{p}/p$ ratio, annihilation into leptons are not constrained as they do not produce antiprotons. On the contrary, all other annihilations into quarks, vector and Higgs bosons are significantly constrained, and allowed only if the DM particle is heavier than almost 10 TeV (see the upper left panel of fig. **??**). Only in such a case the proton excess lays at energies above those explored currently by PAMELA, while the low energy proton spectrum is consistent with the background (see Fig. **??** for illustration). The bound dominantly comes from high energy data points where the solar modulation is negligible. The implications of the complementarity of PAMELA $e^+/(e^+ + e^-)$ and $\bar{p}/p$ data on constraining new physics are therefore evident.

We add now to the fit the balloon (ATIC-2, PPB-BETS and EC) data (37 points in total). Because the balloon data shows a sharp cut-off in the excess just below 1 TeV, the DM mass

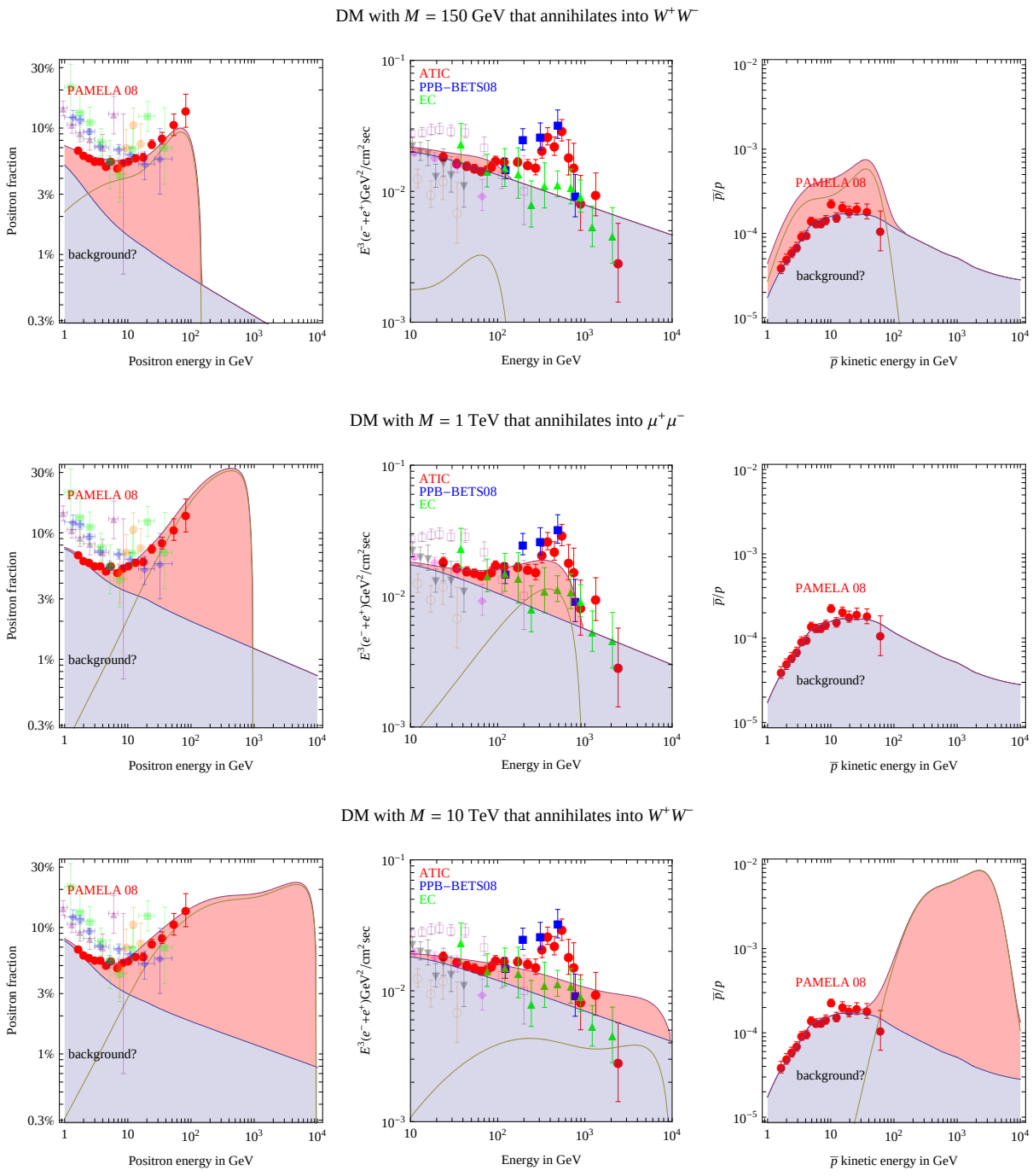


Figure 1: Three examples of fits of e^+ (left), $e^+ + e^-$ (center), $\bar{p}$ (right) data, for a DM particle with mass $M = 150$ GeV annihilating into W^+W^- (upper row, excluded by $\bar{p}$), $M = 10$ TeV into W^+W^- (lower row, disfavored by the $e^+ + e^-$ data), $M = 1$ TeV into $\mu^+\mu^-$ (middle row, favored by data). Galactic DM profiles and propagation models are varied to provide the best fit. See Sec. **??** for the discussion on the treatment of the uncertain astrophysical background.

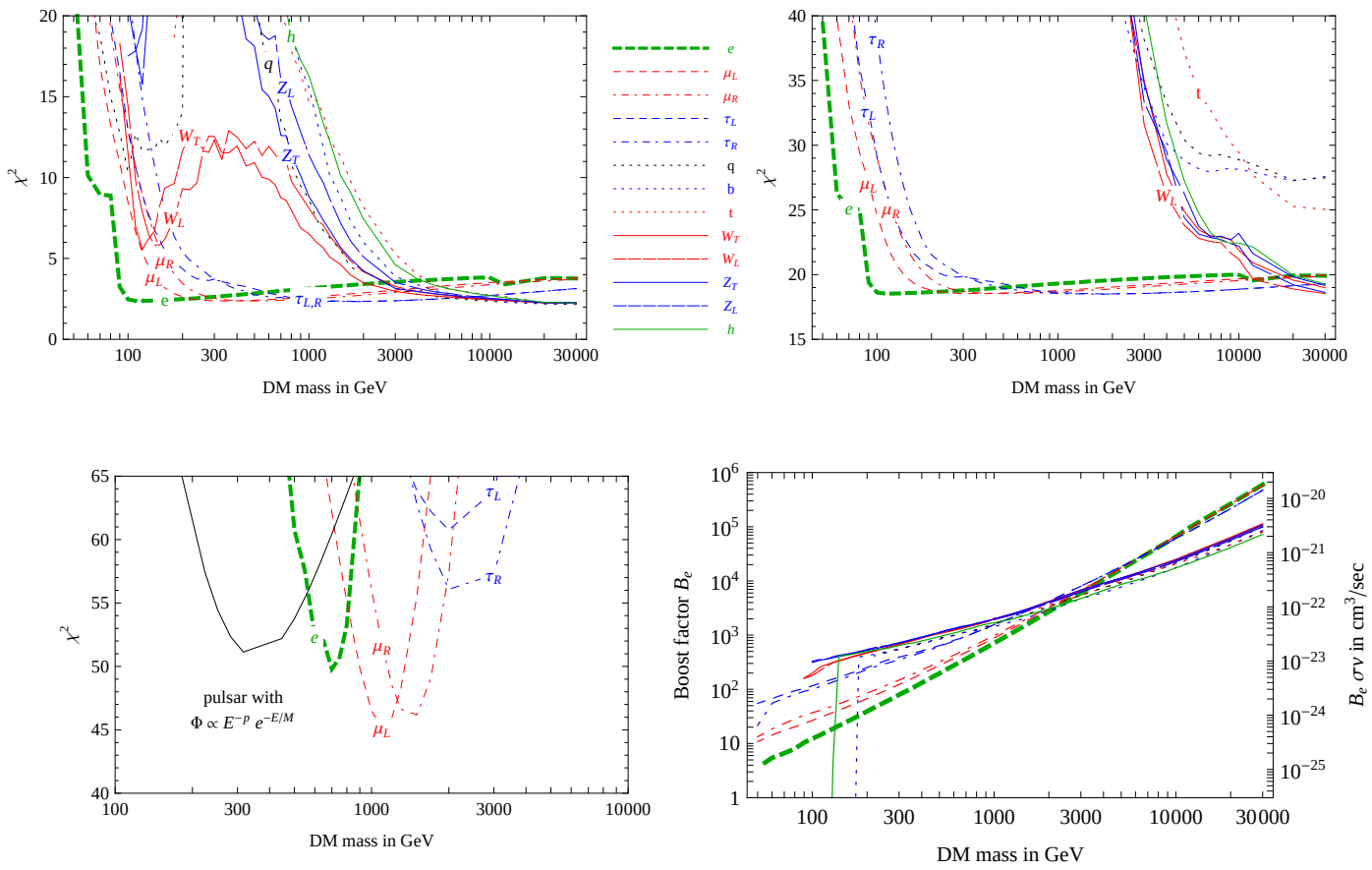


Figure 2: Global fits of different DM annihilation channels to the data. The labels on each curve indicate the primary annihilation channel. Upper left: fit to PAMELA e^+ fraction data only. Upper right: with the inclusion of PAMELA antiproton data. Lower left: with the inclusion of balloon $e^+ + e^-$ data. Lower right: values of $B_e \cdot \sigma v$ (right axis) and of the boost factor B_e (left axis, for $\sigma v = 3\ 10^{-26}$cm^3/sec) needed to fit the data.

should be close to 1 TeV, and all other but leptonic DM annihilation channels are strongly disfavored or excluded. This is shown in the lower left panel of Fig. **??**. More precisely, DM annihilations into μ seem to give the optimal energy spectrum and the best fit (see e.g. the example discussed above in Fig.**??**). Annihilations into e (τ) give a slightly poorer fit, because of a too (not enough) steep spectrum.

The lower right panel of Fig. **??** illustrates the last important point: the values of the annihilation cross section which are required in order to fit the data (for a given mass and given primary annihilation channel). Values of the order of $10^{-23}\,\mathrm{cm}^3/\mathrm{sec}$ or more (for the masses under consideration) are needed. These are much larger than the typical cross section required by DM thermal production in cosmology ($\sim 3 \cdot 10^{-26}\mathrm{cm}^3/\mathrm{sec}$). They can be justified in specific models in terms of some enhancement mechanism which is effective today but not in the early universe (such as a resonance or Sommerfeld enhancement, the presence of an astrophysical boost factor due to DM substructures –unlikely–, or a combination of these).

3 Constraints from gamma and radio observations of the Galactic Center region

Given these tantalizing but surprising hints of Dark Matter annihilations in the charged particle signals, it is now crucial to consider the constraints on this interpretation that come from the

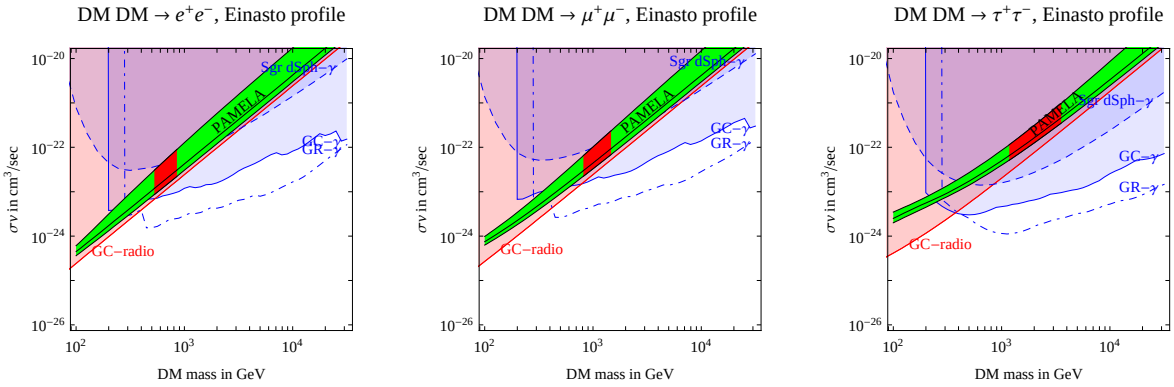


Figure 3: Comparison of the regions favored by PAMELA (green bands) and ATIC (red regions within the bands) with the bounds from HESS observations of the Galatic Center (blue continuous line), Galactic Ridge (blue dot-dashed), and SgrDwarf (blue dashed) and of observations of the Galactic Center at radio-frequencies $\nu = 408\,\mathrm{GHz}$ by Davies et al. (red lines). We considered DM annihilations into e^+e^- (left), $\mu^+\mu^-$ (middle), $\tau^+\tau^-$ (right) and an Einasto DM density profile for the Milky Way and a density profile for Sgr dSph characterized by a large core. We assume unit boost and Sommerfeld factors.

photon fluxes that necessarily accompany them. These photon fluxes are produced:

i) directly as a product of the DM annihilations themselves (mainly from the bremsstrahlung of charged particles and the fragmentation of hadrons, e.g. π^0, produced in the annihilations), at energies comparable to the DM mass M, i.e. in the γ-ray energy range of tens of GeV to multi-TeV.

ii) at much lower energies, e.g. radio to visible frequency, by the synchrotron radiation emitted in the galactic magnetic field by the electrons and positrons produced by DM annihilations.

The best targets to search for these annihilation signals are regions with high DM densities, such as the Milky Way Galactic Center (GC), the Milky Way Galactic Ridge (GR) and the Sagittarius Dwarf spheroidal satellite galaxy (Sgr dSph). The predicted photon fluxes can then be compared with observational data, in order to rule out combinations of astrophysical and particle physics parameters that violate observational constraints. The results of this are shown in fig. **??**, for the case of leptonic annihilations and choosing a benchmark Einasto profile. It is apparent that the regions identified by PAMELA (and ATIC) are excluded by these constraints. It is possible to relax these constraints by assuming a less steep DM profile, such as isothermal (less DM concentration in the GC region leads to less gamma ray production), which is however disfavored by numerical simulations. For a full discussion, see Ref. [?].

4 Conclusions

En lieu of conclusions, let us try to answer the questions raised in the Introduction.

- *Which characteristics must a Dark Matter candidate have in order to fit the above data?*

  a) on the basis of the e^+ and $\bar{p}$ data from PAMELA, the Dark Matter can be:

  a1) a particle that dominantly annihilates into leptons, with no strong preference for the mass, if above a few hundred GeV;

  a2) a particle that annihilates into W, Z or higgses and that has a mass $\gtrsim 10$ TeV.

b) adding the peak from ATIC-2, a clear indication for the mass emerges: DM has to be a particle with mass ~ 1 TeV that dominantly annihilates into leptons.

The upcoming results of ATIC-4, PAMELA, or the first data from the Fermi LAT calorimeter can soon check if a peak is really present in the $e^+ + e^-$ spectrum just below 1 TeV, or if other features appear indicating a preferred value for the mass. Models with $M \ll 1$ TeV appear anyway to be already disfavored.

For what concerns the magnitude of the annihilation cross section, the large flux above the background in the PAMELA and ATIC data indicates a very large σv, of the order of $10^{-23}\text{cm}^3/\text{sec}$ or more (see lower right panel of Fig. **??**).

- *What are the constraints from other observations (mainly of photons from the Galactic Center region)?*

  Constraints are imposed by high energy gamma rays (generated directly from the DM annihilation process) from the galactic center region and from satellite galaxies and by synchrotron radiation (generated by $e^\pm$ in the galactic center's magnetic field). The results show that the regions of the parameter space that allow to fit the PAMELA (and ATIC) data are disfavored by about one order of magnitude if a benchmark Einasto (or NFW) profile is assumed. But choosing a smoother profile and/or assuming that a part of the cross section is due to an astrophysical boost factor that would not be present in dwarf galaxies and the Galactic Center due to tidal disruption re-allows part of the space.

- *Which conclusions can be drawn on the Dark Matter interpretation of the data?*

  As apparent, the data point to a Dark Matter particle that (1) features really 'unexpected' properties and (2) has anyway disturbing 'internal' tensions (e.g. with γ ray constraints). So, either the DM interpretation is not the right one, i.e. an astrophysical source will turn out to be responsible for the excesses[a]. Or we are on the verge of a big change of paradigm in the field of Dark Matter modelling.

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References

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[a] Of course, the origin of the e^+e^- excesses could simply lie in ordinary (albeit possibly peculiar) astrophysical sources, such as one or more pulsars, sources of Cosmic Rays in galactic spiral arms, aged SuperNova remnants or exploding stars. In this case, the sources would be located in the galactic disk, and moreover not too far from the Earth, since $e^\pm$ quickly loose energy when travelling from more that about 1 kpc away.