# DARK MATTER INDIRECT SEARCHES:
# SOME ANOMALIES AND MANY CONSTRAINTS

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I discuss four recent anomalies in Dark Matter Indirect Detection (the positron excess, the 130 GeV line, the GeV GC excess and the 3.5 KeV line) and some relevant constraints.

## 1 Introduction

Indirect searches for Dark Matter (DM) 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, 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 (typically the Galactic Center and DM-dominated structures such as dwarf satellite galaxies).

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 6 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.

In this presentation I intend to briefly review the current status of the field, using the pretext of discussing four recent experimental 'anomalies' and the ensuing phenomenological activity. The four anomalies are: 1) the positron and electron excesses, first soundly detected by Pamela in 2008 in the positron fraction and then corroborated by many results from Fermi, Hess and recently Ams-02; 2) the '130 GeV line' from the Galactic Center (GC), first identified in 2012 by

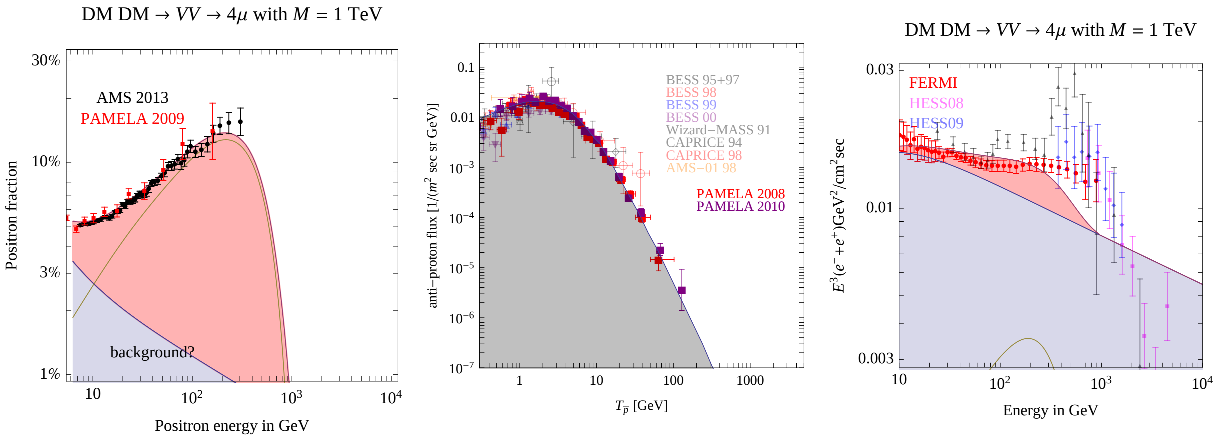


Figure 1 – A compilation of recent and less recent data in charged cosmic rays, superimposed on plausible but uncertain astrophysical backgrounds from secondary production and on the flux produced by Dark Matter annihilations for a specific model. Left: positron fraction. Center: antiproton flux. Right: sum of electrons and positrons. Figures from ref. [9].

Christoph Weniger and collaborators in Fermi data; 3) the 'GeV Galactic Center $\gamma$-ray excess', promoted since 2010 most notably by Dan Hooper; 4) the 3.5 KeV X-ray line, supposedly detected in march 2014 in data from the Xmm-Newton satellite from several galaxy clusters and the Andromeda galaxy (M31).

## 2 The positron and electron excesses

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:

- Notorius data from the Pamela satellite [1] showed, back in 2008, 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 [2] and Ams-01 [3]. These findings have later been confirmed with independent measurements by the Fermi satellite [4] and, recently, by the Ams-02 experiment [5] and extended to about 430 GeV.

- Data from Pamela [6] also showed no excess in the $\bar{p}$ energy spectrum compared with the predicted background.

- In the $e^+ + e^-$ energy spectrum, the results of the Fermi satellite [7], combined with the results from the Hess telescope [8], hint to an excess (with respect to the expected background) reproduced by a simple power law up to about 1 TeV and eventually a steepening at energies of a few TeVs.

The data are displayed in fig. 1, together with the expected astrophysical 'backgrounds' and with the contribution from an annihilating DM particle which fits them reasonably well (see below). The properties of such a particle are pin-pointed quit precisely by the data. The DM has to be:

- ▷ With a mass of *1 to few TeV*, in order to reproduce the feature in the $e^+ + e^-$ spectrum. Actually, the hint of a flattening in the positron fraction suggested by Ams-02 favours a DM mass below about 1 TeV with about $3\sigma$ statistical significance, depending on the DM annihilation channel, so that a little bit of a tension is present with the $e^+ + e^-$ spectrum, which requires a slightly larger value.

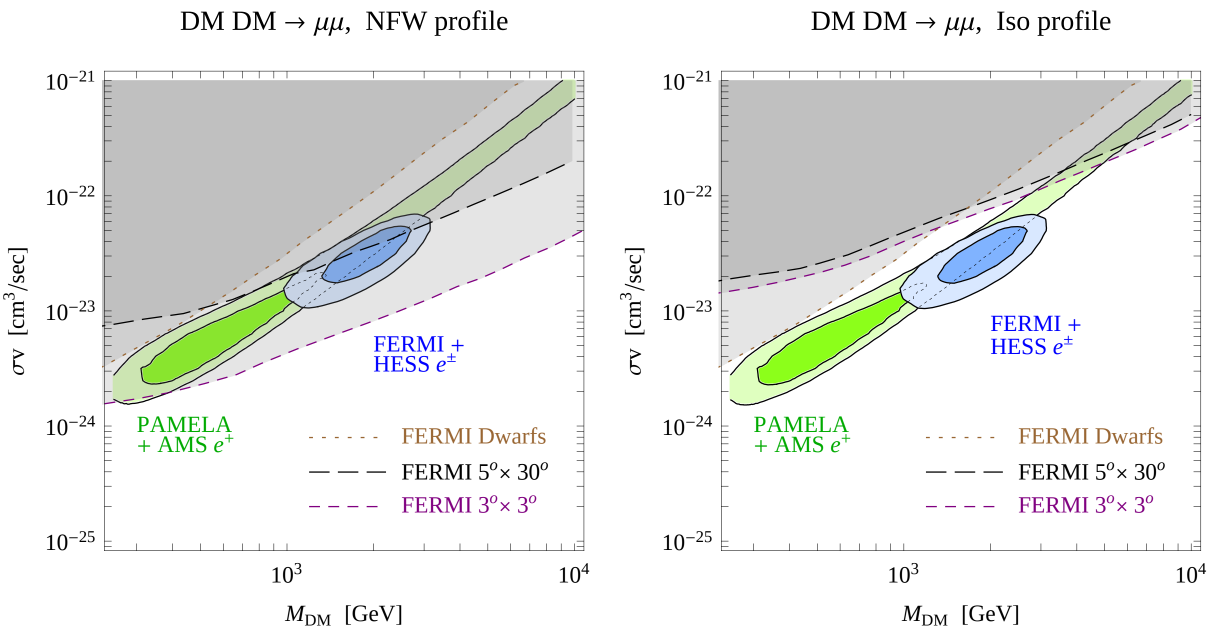


Figure 2 – Best fit regions for the positron and electron excesses, together with some representative $\gamma$-ray constraints. Figure from ref. [9].

- *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 $10^{-23}$ cm$^3$/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.

As tantalizing as these hints of DM can be, they have to be confronted with associated constraints. Many possible constraints can be considered, but here I will focus on two classes only. The first one is observations of $\gamma$-rays. In fig. 2 we show representative $\gamma$-ray bounds (the constraints are taken from [10,11], more recent analyses find similar or slightly more stringent bounds). We see that the fit region shows some tension with $\gamma$-ray data (or it is rather clearly excluded) if (left) we have chosen a benchmark NFW galactic Dark Matter profile. Choosing the shallower isothermal profile (right), however, makes the constraints looser. It is therefore difficult to get a final answer from $\gamma$-rays. The second class of constraints comes from observations of the cosmic microwave background (CMB), which imposes bounds on DM annihilations (based on the fact that they would have re-ionized the primordial universe) that disfavor at various degrees and for most channels the DM interpretation of the positron excess [12].

## 3 The 130 GeV line

The '130 GeV line' claim has gathered a lot of attention in the past two years (for a more thorough review see [13]). Originally spotted by [14] and, above all, by [15] in the publicly available Fermi data from an extended region including the GC (fig. 3 left reports the most evocative of the original analysis' figures), it has later found support in other analyses [16,17,18,19], with varying degrees of accuracy and claimed significance. [16,19] 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 [20,17]. [18] has seen it in galaxy clusters too. For a response, [21,22,23] challenged the analyses in a number of ways, suggesting that the line(s) could be due to unidentified instrumental, statistical or astrophysical origin. Although it is probably too early for a final conclusion on this claim, it is fair to say that the current consensus seems to be that the line has been a rather unfortunate combination of an instrumental effect and a statistical fluctuation. The right panel of fig. 3 illustrates that, as

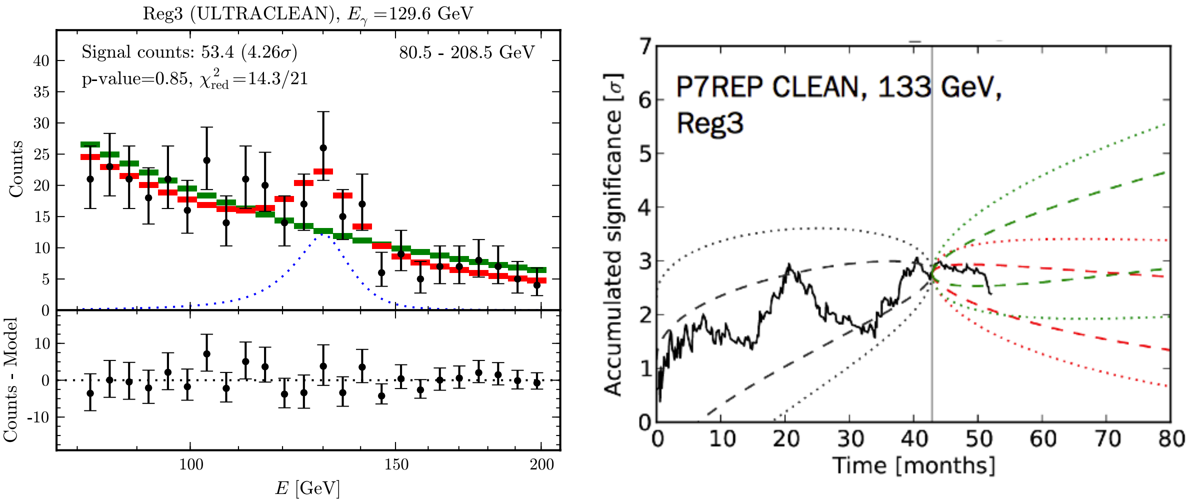


Figure 3 – Left: FERMI $\gamma$-ray data and fits pointing to a line at about 130 GeV. Right: behavior with time of the accumulated significance for this signal. Figures from ref. [15] and ref. [24].

more data are accumulated, the significance of the signal lowers, hence pointing at something which is probably not an actual signal.

## 4 The GeV Galactic Center excess

Several authors have reported since 2009 the detection of a gamma-ray signal from the inner few degrees around the GC [25,26], with the most notable early claims by Dan Hooper. Its spectrum and morphology are found to be compatible with those expected from annihilating DM particles: to fix the ideas, the results of one of the most recent analysis [27] confirm the presence of this excess at an incredibly high level of significance (if taken at face value) and find this signal to be best fit by 31-40 GeV DM particles distributed according to a (contracted) NFW profile and annihilating into $b\bar{b}$ with $\langle\sigma v\rangle = 1.4 \div 2 \times 10^{-26}$ cm$^3$/s. Fig. 4 displays the earliest fit to the data (from [25]) and one of the most recent ones (from [27]).

Of course, one should not forget that, in very general terms, the identification of an 'excess' strongly relies on the capability of carefully assessing the background over which the excess is supposed to emerge. The claim under scrutiny constitutes no exception, quite the contrary. The extraction of the residuals strongly relies on the modeling of the diffuse gamma-ray back-

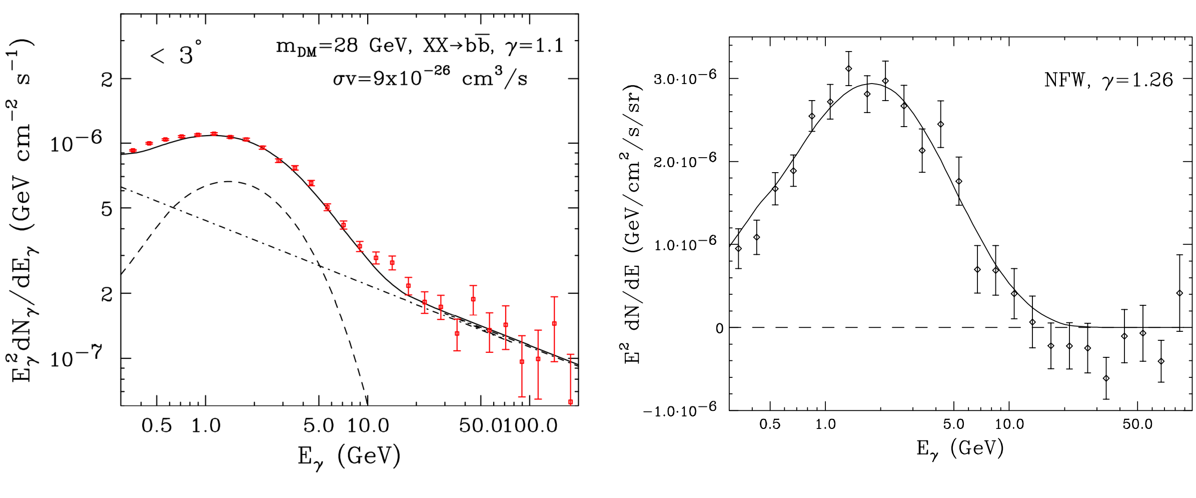


Figure 4 – Earliest and latest fits to the GeV excess at the GC. From ref. [25] and ref. [27].

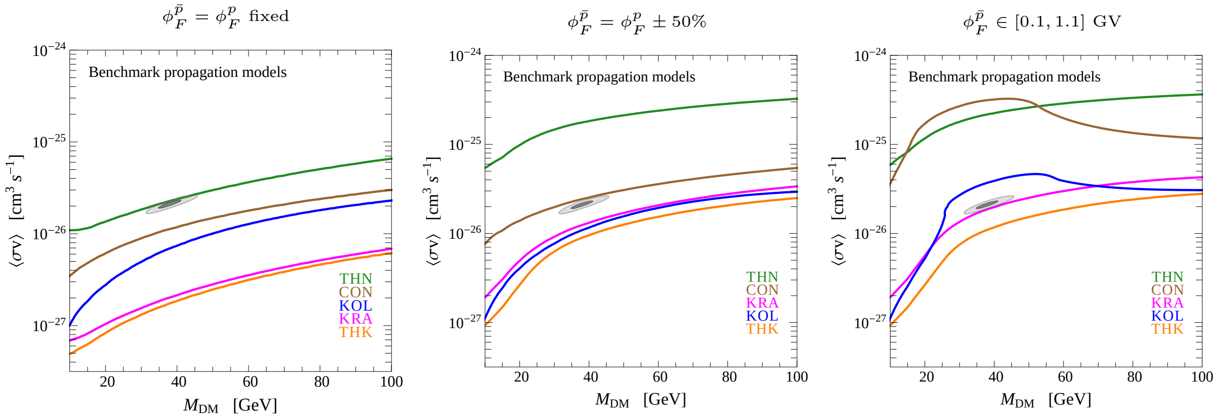


Figure 5 – 3-$\sigma$ exclusion contours on $\langle \sigma v \rangle$ for 100% DM annihilation into $b\bar{b}$, for the three approaches to solar modulation briefly discussed in the text. The grey area is the best-fit region. Fig. from ref. [32].

ground (in particular the one publicly made available by the FERMI collaboration) as well as on additional modeling of astrophysical emissions, e.g. from FERMI bubbles, isotropic component, unresolved point sources, molecular gas... While this is probably the best that can be done, it is not guaranteed to be (and in general is not expected to be) the optimal strategy. Also, one should not forget that there might be alternative astrophysical explanations for the excess. A population of milli-second pulsars has been extensively discussed since the beginning [28], as well as the possibility of a spectral break in the emission of the central Black Hole [29]. More recently, the possibility has been suggested that isolated injections of charged particles (electrons [30] or protons [31]) sometime in the past, possibly connected with the activity of the central Black Hole, can produce secondary radiation able to account for the anomalous signal. While reproducing with these models all the details of the observed emission might be not easy, they represent plausible and useful counterexamples to the DM interpretation.

Still, it is interesting to insist on the tantalizing DM hypothesis and to explore ways to confirm or disprove the result within the DM framework. In particular, given the alleged hadronic origin of the signal, it is very useful to analyze the antiproton channel to put constraints on the DM interpretation of such excess. Ref. [32] delved precisely into this issue, and the condensed results are displayed in fig. 5. It considered several galactic propagation models for antiprotons (THN, CON, KOL, KRA, THK, roughly distinguished by the thickness of the diffusive halo, the diffusion properties and the presence of side effects such as convection) and several assumptions for the so-called solar modulation, i.e. the complicated effect of the magnetic field and solar cosmic ray wind of the heliosphere on the last segment of the antiproton journey. More precisely, it considered a solar force field for $\bar{p}$ fixed and equal to $p$ one (left panel of fig. 5), variable within 50% (central panel) or free within a wide range (right panel).

The overall conclusions are the following: adopting the most realistic propagation models and well motivated choices for the solar modulation potential, the hadronic ($b\bar{b}$) DM interpretation for the GeV excess is definitely in strong tension with the antiproton data. Nevertheless, given that our knowledge of CR diffusion both in the Galaxy and in the heliosphere is far from being accurate and complete, there are still conservative choices of the parameters involved that do not result in ruling it out, namely thin halo models and large solar modulation potentials. [a]

[a] The authors of ref. [33] have also discussed the antiproton bounds. They find that the antiproton data can be marginally consistent with the GeV excess only if a very conservative propagation model with thin halo is used (a model roughly corresponding to our THN). The analysis in [32] differs from ref. [33] since: **1)** it considers a comprehensive set of propagation models, including several 'thin' models with different halo height, and models with high reacceleration or convection together with others where these effects are less important; **2)** it fully includes the subtleties associated to solar modulation: this turns out to be crucial since the more the Fisk potential for the antiprotons is allowed to vary the less stringent the bounds become.

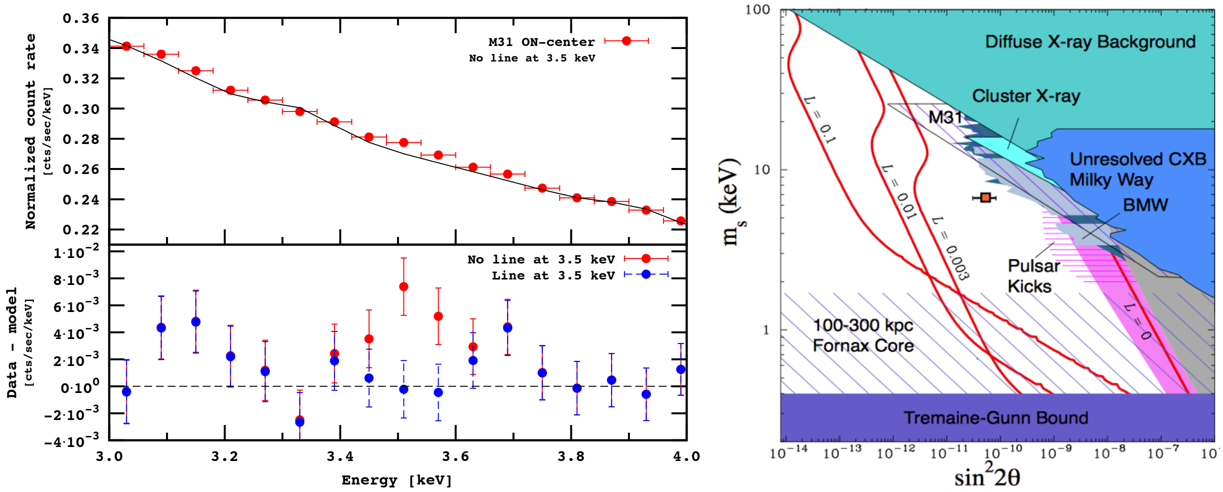


Figure 6 – Identification of the 3.5 KeV line in XMM-Newton data (left) and the parameter space of its interpretation in terms of a decaying sterile neutrino. From ref. [35] and ref. [34].

## 5 The 3.5 KeV X-ray line

One of the latest claims in the field of indirect detection comes from a different range of energies: X-rays. In datasets from the XMM-Newton satellite, two independent groups [34,35] have found evidence for an unexplained line at 3.5 KeV. The former group found it in observations of a set of 73 galaxy clusters with redshift between 0.01 and 0.35. The latter one in observations both of the Perseus cluster and of Andromeda, with no detection in "blank sky" measurements. Fig. 6, left, displays an extraction of the spectrum showing the line, from [35].

The complication is that the X-ray spectrum in this range of energies is crowded with atomic de-excitation lines from elements such as Cr, Mn, K, Fe, Ni, Ca, Cu... Ref. [36] has indeed very recently argued that previously-unaccounted-for potassium lines can well explain the signal. Ref. [37] reiterates, however, that data from Andromeda are instead solid and make the potassium interpretation problematic. On another side, ref. [38] has argued that no line is seen in Chandra data from the GC, although this conclusion depends on how one models the local background. The discussion is currently unfolding and probably more data from independent instruments will be needed.

If confirmed, however, the most straightforward explanation of the line in terms of new physics is of great interest for the field of DM indirect detection as it consists of a sterile neutrino of mass 7 KeV decaying into an ordinary neutrino and a photon (the detected X-ray). The decay rate turns out to be $\mathcal{O}(10^{-29})$ sec$^{-1}$. This, translated in terms of particle physics parameters by the effective mixing angle of the sterile and active neutrino, lies in a region of parameter space still allowed by other constraints, as illustrated by the right panel of fig. 6. The production mechanism of a population of sterile neutrinos in the early universe would involve active-sterile oscillations helped by the presence of a sizable leptonic asymmetry, quite uncompelling, but possible.

## 6 Conclusions

There are arguably no firm conclusions in this field at this moment in time. There are tantalizing hints (the positron and electron excess, the gamma-ray line, the GeV GC excess and the X-ray line) and there are stringent constraints. Such constraints, however, are often relaxed by appropriate assumptions, which can be extreme or not (the illustration with the antiproton constraints on the GeV excess in section 4 is exemplar). The only firm albeit generic conclusions seem to be that:

◇ current experiments are clearly reaching (and in some cases have already reached) the sensitivities for which they were designed, and hence they probe very promising regions of the parameter space;

◇ astrophysics, in different manifestations, is the main killjoy, introducing alternative compelling explanation, irreducible uncertainties, unbeatable background noise...;

◇ hence, it is important to pursue a multi-messenger approach in all instances, investigating associated signals in other channels, cross-checking constraints and confirmations from independent targets etc;

◇ in any case, the profusion of data from the recent experiments have spurred a remarkable proliferation of DM models, so that 'traditional' DM models (such as SuSy DM) have, for better or for worse, been joined by many other possibilities.

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