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Dark Matter candidates : Where do we stand?

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Abstract

The dark matter field has evolved tremendously in ten years. Many new particle candidates have been proposed by theoreticians while dark matter detection experiments have reached an unprecedented degree of precision that allows us to test accurately the WIMP paradigm. In these proceedings, I review the recent evolutions in the field and discuss possible directions in the near future.

1 Introduction

Since the observation of Supernovae of type Ia at 'large' redshift [1] and the results from Cosmological Microwave Background [2, 3], the Cosmology community has succeeded to determine the content of the Universe with an unprecedented degree of precision. While it appears that the Universe is mostly made of two unknown substances (dark matter and dark energy), the energy density associated with dark energy is about three times that of matter. Also it appears that dark matter represent about 80% of the matter content in the Universe. The nature of dark matter is unknown; It is likely to be made of massive neutral stable weakly interacting particles (WIMPs) but the community has now all the experimental tools to either find it or rule out a very important region of the parameter space.

In my opinion, three main changes happened during the last 10 years:

- The field is not 'relic density' driven anymore. Alternative scenarios to thermal Freeze-Out and non resonant self-annihilations have been proposed [4].
- Astrophysical data are now often guiding Particle dark matter model building, cf for example the PAMELA/HEAT anomaly [5, 6].
- Phenomenology overtook the Theory. Supersymmetry has long been seen as a very serious motivation to introduce Weakly Interacting Massive particles but with the lack of new Physics at LHC this is no longer the case (or not to the same extent at least) and models (rather than theories) were proposed.

In the following I will review the key changes in the field and will also discuss some important experimental results.

2 Light mass range

For many decades, the main argument which was used to test whether a particle could be a good dark matter candidate or not was to use the relic density argument. Whatever the nature of these new particles, their energy density today must not exceed the dark matter abundance that is observed.

With the present value of the dark matter cosmological parameter ($\Omega h^2 \simeq 0.1$) and the very small uncertainties (to be improved by the PLANCK experiment), such a constraint turns out to be a killer for many annihilating dark matter models. Indeed this typically implies that the annihilation cross section must have a very precise value which is difficult to achieve in most Particle Physics models, especially once one takes into account constraint from Particle Physics and Astrophysics (the annihilation cross section generally tends to be too small leading to an over abundance of dark matter).

As the relic density constraint enabled one to rule out a large fraction of the Supersymmetric parameter space, new mechanisms have been proposed to either 're-habilitate' some candidates/part of the parameter space [4, 7], making the notion of relic density less essential to model building.

However meanwhile several questions arose:

- Can we consider sub-10 GeV annihilating dark matter particles [8, 9]?
- Can dark matter particles be heavier than a few TeVs?
- Why is not there any signs of Weakly Interacting Massive Particles in the 10 GeV- TeV range?

Some of these questions are supported by anomalies in astrophysical data (the amount of which increased during the last few years). For example, the case for light particles was emphasised after that a 511 keV map was established by the SPectrometer for INTEGRAL on board of the INTEGRAL satellite [10]. The latter pointed out that the emission of 511 keV photons (due to positronium formation and the signature of low energy positrons in the Milky Way), was anomalously spherical. This emission was also found to be brighter than what is expected if the positrons originate from Astrophysical sources while the sphericity and brightness could be explained by light annihilating dark matter models [11]. Yet not all dark matter models work well: decaying particles fail to describe the morphology of the emission. In fact to fit the data these models require a dark matter halo profile which corresponds to a NFW profile with $\rho = 1.04 \pm 0.3$ [12], a feature which can in principle be used to test these types of models.

Exploring the light mass range implies to overcome the Hut and Lee-Weinberg limit which excludes annihilating dark matter particles lighter than a few GeVs. However this is possible if one considers e.g. either a fermion/scalar particles coupled to a (new) light gauge boson Z' or scalar particles coupled to heavy mediators. In the case of a scalar dark matter coupled to heavy fermions, the annihilation cross section is (almost) independent of the dark matter mass so imposing that such candidates have a relic density equal to the observed dark matter abundance constrains the mass of the mediator rather than the dark matter mass. It also constrains the mediator couplings to the dark matter and Standard Model particles.

In addition, one has to take into account a constraint which comes from the gamma ray emission emanating from such candidates. In particular the exchange of a heavy fermion leads to a constant annihilation cross section into electron-positron that over predicts the gamma-ray emission by five order of magnitudes (if one assumes that one photon is emitted due to final state radiation each time an electron or positron is emitted). To avoid this, the product of the couplings of the heavy mediator to the Standard Model particles and dark matter must be significantly suppressed.

Since the same process is also responsible for the production of low energy positrons in the galaxy, the suppression of the couplings that is required to not over predict the gamma ray flux in the galaxy actually leads to a 511 keV flux prediction that agrees with SPI measurement. This could well be a coincidence but this is puzzling enough to make this model interesting. In this framework, the relic density is actually ensured by the exchange of a light vector boson. However a possible alternative is annihilations into neutrinos [13]. In this case, dark matter could give neutrinos a mass providing that they are Majorana particles, a condition which can be experimentally tested in neutrino experiments.

Going back to the model with a new light vector boson (to achieve the correct relic density) and a heavy mediator, it is important to notice that this can be tested by using the experimental value of the anomalous electron g-2 (δa_e). With the present value of δa_e (i.e. $\delta a_e = -0.4(0.88) \times 10^{-12}$) [14], one can exclude heavy mediators exchange as an explanation to the 511 keV line unless there is a compensation between the heavy mediator contribution and that of the Z' or if the dark matter only explains a fraction of the 511 keV emission [15]. Such a conclusion however assumes a certain dark matter velocity profile [12] and would probably deserve to be revisited.

3 Heavy mass range

The very heavy mass range has also received a lot of attention recently. In particular, since the observation by the PAMELA experiment of a positron excess in the 10-100 GeV range, many dark matter models with $m_{dm} = 100$ GeV have been proposed. The difficulty in this mass range is to obtain a 'visible' signal in dark matter indirect detection experiments: due to the large mass the dark matter number density is very suppressed and as a consequence one needs to boost the annihilation rate. The resulting boost factor can originate from astrophysical considerations (such as the presence of dark matter clumps near us) or from Particle Physics arguments (such as a Sommerfeld enhancement). Among the most 'successful models' to explain the PAMELA excess, 'leptophilic' dark matter models [16] (which are dominantly coupled to leptons) have received a lot of attention. Those seem to explain successfully the positron excess but they are strongly constrained by the lack of anomaly in the anti-proton data (also collected by the PAMELA experiment) [17, 18].

As a byproduct of these anomalies, there has been many efforts to improve the predictions for positron energy and spatial propagation. Both semi-analytical and numerical methods have been used to make predictions of the flux emission expected in dark matter models. The semi-analytical method solves the diffusion equation in a 'vertical' cylinder (with radius R_{gal} that is large enough to englobe the whole 'visible' galaxy plane) with the help of Bessel and Fourier decomposition. The thickness (height) of the cylinder has direct consequences on the brightness of the signal. A small thickness generally leads to a small flux while, conversely, a large thickness tends to predict very large values of the flux.

While the spatial and energy propagation of cosmic ray has been improved over the last few years, an important issue came up with the problem of subtracting the backgrounds and foregrounds [21]. In particular discrepancies in gamma ray (the so-called FERMI bubbles) and submillimetre wavelengths (the so-called 'WMAP haze') have focussed a lot attention and ask the question of whether or not these anomalies could be explained by dark matter particles e.g. [22] (despite constraints from radio emission in the galactic centre [19, 20]). At the same time, providing that one knows the background and foregrounds to a high degree of accuracy and an anomaly does exist, the study of the morphology of the 'dark' emission should provide essential information such as whether dark matter is made of annihilating or decaying particles [23] and what is the value of its mass [24].

4 Intermediate mass range

In absence of strong evidence for dark matter particles in indirect detection experiments, direct detection provides strong constraints on the Vanilla 'WIMP' hypothesis. The XENON100 experiment [25] in particular (along with EDEL-

WEISS [26], CDMS [27] and many other experiments) has unabled to set stringent limits on the dark matter elastic scattering cross section with nucleons. It was found that heavy dark matter (with a mass in the GeV-TeV range) interacts with a cross section that is less than 2 10^{-45} cm^2 if its mass is about 50 GeV, a value which is about ten order of magnitude below expectations if one assumes that the annihilation and elastic scattering cross sections are not too different and which clearly illustrates the experimental breakthrough performed by direct detection experiments.

The XENON100 experiment initially suffered from one drawback due the fact that the response of the detector to dark matter particles strongly depends on the scintillation function (L_{eff}) of liquid Xenon, for which there is no analytical expression. An interpolation to the 'calibration' data has enabled the XENON100 collaboration to establish the recoil energy associated with the primary scintillation signal in the liquid part of the detector but the absence of data below 3 keVnr prevents to accurately model L_{eff} at low energy, while this range is particularly relevant to constrain light WIMPs. To circumvent this problem, XENON100 extrapolated the data at high energy down to lower energies and also 'cut' the too low energies. However uncertainties due to the interpolation should still be present and are not reflected on the corresponding exclusion curve.

While this does not affect the quality of the experiment, the fact that uncertainties are not shown prevents to use these data to accurately constrain light dark matter models (such as those arising from Supersymmetric theories). Also this questions the compatibility between the XENON100 exclusion curve and the CoGeNT [28] and DAMA/LIBRA [29] claims.

However one can reconstruct the experimental uncertainties by repeating a similar analysis as that performed by the XENON100 experiment and not marginalising over L_{eff}. Such a procedure shows that the uncertainties on L_{eff} are large. Hence improving L_{eff} at low energy should really enable the collaboration to obtain very strong constraints on light candidate [30]. An additional improvement that one can do to help theorists using the XENON100 data in a more consistent way is to exploit all the information contained in the data. For this one can grid the background events in the plane $(S1, log(S_2/S_1))$ (instead of using bands) as the collaboration did [31]. This enables one to improve the constraint by a factor 3-10 (and even more at low energy), using the 100days data and we expect this method to be still very useful using the 225days data.

This has a direct impact on model building. For example in the NMSSM, one finds many dark matter models with a low mass (below 10 GeV) [32]. Those are hard to constrain using direct detection experiments but XENON100 does have the potential to exclude them. A proper analysis that would take into account the astrophysical uncertainties is nevertheless still required.

In the 10 GeV-TeV region, the thermal 'freeze-out' relic density argument sets very strong constraints on the parameter space. However it was suggested recently that one could reduce the thermal candidate relic density to a very large degree and nevertheless regenerate the dark matter at a later stage. Such a scenario favours large annihilation cross section but in [33] it was shown that if the cross section is too large, one would actually overproduce gamma rays in the Milky Way. Typically cross section values which are at least thousand times larger than the canonical value ($\sigma v = 3\ 10^{-26}\mathrm{cm}^3/\mathrm{s}$) are excluded.

Yet there was also a very interesting proposal in this mass range that dark matter can annihilate and produce Higgs bosons in our dark matter halo [34, 35, 36]. In particular if the dark matter mass has very specific values (for example $m_{dm} = m_H/2$), one expects the Higgs boson to be produced at rest in the Milky Way [35]. The corresponding signature will be the Higgs boson decay into two gammas which in some circumstances can actually be detected. While this applies to the Standard Model Higgs boson, such a technique could be used to exclude light Higgs bosons, such as those predicted in the Next-to-Minimal Supersymmetric extension of the Standard Model.

5 Conclusion

The dark matter field has considerably evolved during the last ten years. While the relic density argument has set very strong constraints on the dark matter annihilation cross section, new directions have been explored where the dark matter could be lighter than a proton or much heavier than a few TeV. Meanwhile indirect detection experiments have collected an impressive amount of data and some anomalies appeared. Those might be indications of dark matter but they could also be related to astrophysical sources. Whatever the origin of these anomalies, these have encouraged the community to propose new dark matter models (including with interactions with leptons only) and explore new directions far away from supersymmetric theories. Since no sign of dark matter particles has been found yet, despite intensive searches at LHC nor in direct detection experiments, it is likely that the dark matter quest continues for at least a few more years. But with the results of the LHC, PLANCK, FERMI-LAT,AMS II, XENON100 and many other experiments delivering their results in the near future, the next ten years should be fascinating!

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