PROCEEDINGS OF SCIENCE

Minimal Dark Matter (15’+5’)

Marco Cirelli[∗ †]
Institut de Physique Théorique, CNRS, URA 2306 & CEA/Saclay,
F-91191 Gif-sur-Yvette, France
E-mail: marco.cirelli@cea.fr

Alessandro Strumia
Dipartimento di Fisica dell’Università di Pisa & INFN, Italia
E-mail: astrumia@df.unipi.it

We present Minimal Dark Matter and its univocal predictions for Dark Matter observables. During the idm08 conference, PAMELA presented preliminary results showing an anomaly in the positron fraction: we find a good agreement, with a modest astrophysical boost factor.

Identification of dark matter 2008
August 18-22, 2008
Stockholm, Sweden
–
Preprint number: SACLAY–t08/163

PoS(idm2008)089

[∗] Speaker.

[†] We are indebted to Gianfranco Bertone, Torsten Bringmann, Pierre Brun and Nicolao Fornengo for very useful discussions and we thank the organizers of the idm08 conference for the very stimulating atmosphere. The work of M.C. is partially supported by the french ANR grants DARKPHYS and PHYS@COL&COS. We thank the EU Marie Curie Research & Training network "UniverseNet" (MRTN-CT-2006-035863) for support.

1. Introduction

The quest for the identification of the missing mass of the Universe has been with us since many decades now [1]. While explanations in terms of modifications of Newtonian gravity or GR become more and more contrived, evidence for the particle nature of such Dark Matter now comes from many astrophysical and cosmological observations. Non-baryonic new particles that may fulfill the rôle of DM have emerged in the latest decades within many Beyond the SM theories, most notably SuSy. These constructions try to naturally explain the hierarchy between the EW scale and the Planck scale and, in doing so, introduce a host of new particles with EW masses and interactions. Some of these particles can be good DM candidates (e.g. the lightest neutralino). DM stability is the result of extra features introduced by hand (e.g. R-parity), usually necessary also to recover good properties of the SM that are lost in these extensions (automatic conservation of baryon number, lepton number, etc). Finally, the richness of these theories implies many unknown new parameters (e.g. all sparticle masses), so that the phenomenology of the DM candidate is often unclear. The Minimal Dark Matter (MDM) proposal [2] originates from the following motivations: focussing on the DM problem only, we add to the SM the minimal amount of new physics (just one extra EW multiplet χ) and search for the minimal assignments of its quantum numbers (spin, isospin and hypercharge) that make it a DM candidate without ad hoc extra features, and without ruining the good features of the SM. As detailed in the following section, we do find one optimal candidate, and we here focus on it. Its only free parameter (the DM mass) is fixed from the cosmological DM abundance, so that any DM observable can be univocally predicted. Indirect searches are one of the most promising ways to detect DM. DM particles in the galactic halo are expected to annihilate and produce fluxes of cosmic rays that propagate through the galaxy and reach the Earth. Their energy spectra carry important information on the nature of the DM particle (mass and primary annihilations). Many experiments searched for signatures of DM annihilations in the fluxes of γ rays, e^+ and $\bar{p}$. At the idm08 conference, the PAMELA experiment [3] reported preliminary results that seem to be the first strong hint for a DM indirect signal. We here assume that PAMELA data will be confirmed and that on-going re-evaluations of the astrophysical backgrounds will confirm previous studies, such that the PAMELA excess implies WIMP DM (non-WIMP DM candidates such as the gravitino may remain viable if unstable [4]; DM candidates with a relic density due to a baryon-like asymmetry are disfavored). After introducing the MDM model we compare its predictions, as previously computed in [5], with the PAMELA results.

2. Minimal Dark Matter

The MDM model is constructed by adding on top of the SM a single multiplet $\chi \oplus \bar{\chi}$ with weak interactions, fully determined by its hypercharge Y and by the number of its $\mathrm{SU}(2)_L$ components, $n = \{2,3,4,5,\ldots\}$. The Lagrangian is therefore 'minimal': $\mathscr{L} = \mathscr{L}_{\rm SM} + \frac{1}{2}\bar{\chi}(i\not{D} + M)\chi$ for fermionic χ, $\frac{1}{2}(|D_\mu \chi|^2 - M^2|\chi|^2)$ for scalar χ, where D_μ contains the usual EW gauge couplings and vectors, M is a tree level mass term (the only free parameter). Any additional term (such as Yukawa couplings with SM fields) will be forbidden by gauge and Lorentz invariance, as detailed below. For a given assignment of n there are few assignments of Y such that one component of the χ multiplet has electric charge $Q = T_3 + Y = 0$, as needed for a DM candidate. For instance, for

$n = 2$, since $T_3 = \pm 1/2$, the only possibility is $Y = \mp 1/2$. For $n = 5$ one can have $Y = \{0, \pm 1, \pm 2\}$, and so on. But MDM candidates with $Y \neq 0$ interact with the nuclei of direct detection experiments via exchange of a Z boson, giving rise to an effect not seen by the Xenon and CDMS [6] experiments. Thus we restrict to candidates with $Y = 0$, and therefore to odd n multiplets. Also, the list of possible MDM candidates has to stop at $n \leq 5$ (8) for fermions (scalars) because larger multiplets would cause the running of g_2 to hit a Landau pole below $M_{\rm Pl}$. Next we inspect which remaining candidates are stable against decay into SM particles. For instance, the fermionic 3-plet with $Y = 0$ would couple with a Yukawa operator $\chi L H$ with a SM lepton doublet L and a Higgs field H and decay. This is not a viable DM candidate, unless the operator is eliminated by some ad hoc symmetry. For another instance, the scalar 5-plet with $Y = 0$ would couple to four Higgs fields with a dimension 5 operator $\chi H H H^* H^* / M_{\rm Pl}$, suppressed by one power of $M_{\rm Pl}$. Despite the suppression, the resulting life-time is shorter than the age of the Universe, so that this is not a viable DM candidate. Now, the crucial observation is that, given the known SM particle content, there are multiplets that cannot couple to SM fields and are therefore automatically stable DM candidates. Only two possibilities emerge: a $n = 5$ fermion, or a $n = 7$ scalar. But since the latter may have non-minimal quartic couplings with the Higgs field, we will set it aside and focus here on the former for minimality. Quantum corrections due to a loop of gauge bosons generate a small mass splitting between the components of χ. The lightest component turns out to be the neutral one (as required by DM phenomenology), and the $Q = \pm 1$ partners are 166 MeV heavier [2]. We can now compute the DM cosmological abundance as a function of the only free parameter, the mass M. The abundance measured by cosmology, $\Omega_{\rm DM} h^2 = 0.110 \pm 0.005$ [7], is matched for $M = (9.6 \pm 0.2)$ TeV [8]. This result is obtained solving the relevant Boltzmann equation taking into account all co-annihilations and, importantly, electroweak Sommerfeld corrections [9]. This non-perturbative phenomenon significantly enhances non-relativistic annihilations of particles with mass $M \gtrsim M_W/\alpha_2$. As a result the (co)-annihilation cross section σv grows as $v \to 0$, so that astrophysical signals ($v \sim 10^{-3}$ in our galaxy), being much more enhanced than DM annihilations in cosmology ($v \sim 0.2$ at freeze-out), are detectably large despite the large multi-TeV DM mass M. Elastic scattering of χ on nuclei occurs at 1-loop via the exchange of W's and Higgs [2, 8], giving rise to a negligible spin-dependent cross section and to a spin-independent cross section $\sigma_{\rm SI}(\text{DM N}) \approx 10^{-44}\text{cm}^2$ (up to reducible uncertainties due to QCD and to the unknown Higgs mass), within the reach of the next generation of direct detection experiments [6]. In summary, the MDM construction singles out a **fermionic SU(2)$_L$ 5-plet with zero hypercharge** as providing a fully viable, automatically stable DM candidate. It is called 'Minimal Dark Matter' since it is described by the minimal gauge-covariant Lagrangian. Its mass is fixed at (9.6 ± 0.2) TeV and its phenomenology is fully computable with no free particle-physics parameters.

3. Indirect signatures and the PAMELA positron excess

The MDM fermionic 5-plet annihilates at tree level into W^+W^-, and into $\gamma\gamma$, γZ and ZZ at 1-loop. We neglected 3-body primary final states. The annihilation cross sections at $v \sim 10^{-3}$ are large thanks to the Sommerfeld enhancement: for $M = 9.6$ TeV one has $\langle \sigma v \rangle_{WW} = 1.1 \cdot 10^{-23}\ \frac{\text{cm}^3}{\text{sec}}$, $\langle \sigma v \rangle_{\gamma\gamma} = \langle \sigma v \rangle_{\gamma Z} \frac{\tan^2 \theta_w}{2} = \langle \sigma v \rangle_{ZZ} \tan^4 \theta_w = 3 \cdot 10^{-25}\ \frac{\text{cm}^3}{\text{sec}}$. The Sommerfeld corrections also introduce a strong dependence on M, such that, within 3σ, the σv's change by one order of

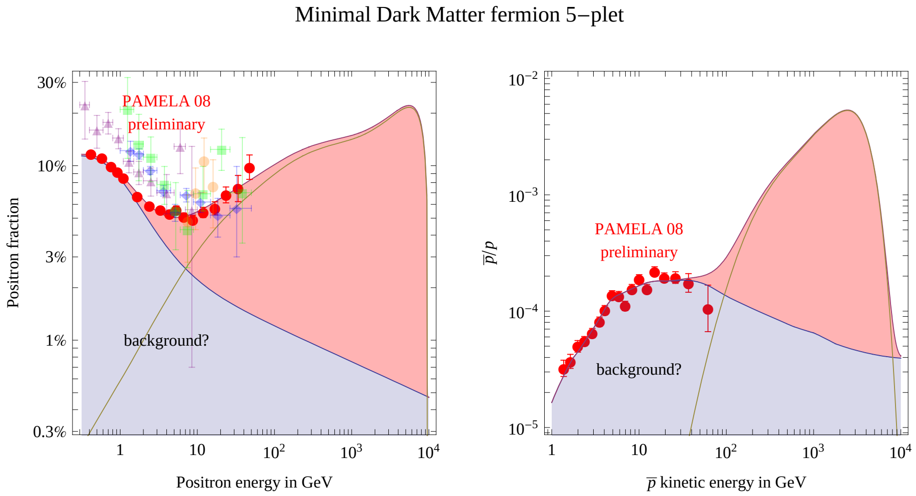

Figure 1: *The PAMELA preliminary data [3] compared with the fermion 5-plet MDM prediction, at the best-fit point for the astrophysical parameters.*

magnitude around these central values. The resulting spectra of e^+ and $\bar{p}$, plotted in fig. 1, are obtained from the primary spectra computed taking into account spin-correlations and propagated in the galactic halo [5]. PAMELA presented preliminary results [3] for the fluxes of $\bar{p}$ and e^+ in the cosmic rays. The latters show an excess at $E_{e^+} = (10-60)$ GeV with respect to the expected background, compatibly with hints that previous experiments (e.g. HEAT) had already suggested with a much lower significance. The $\bar{p}$ data show no anomaly. We tried to perform a preliminary fit of the preliminary PAMELA data to have a feeling of which set of astrophysical assumptions allows to reproduce the data and how well. We have taken the e^+ and $\bar{p}$ astrophysical backgrounds from [11], and multiplied each one of them times a free factor and a spectral correction E^p with $p = 0 \pm 0.1$. This conservatively mimics the estimated uncertainties. Concerning the DM signal, we smoothly vary between the possible halo models and the propagation configurations considered in [5], assuming that they are the same for e^+ and $\bar{p}$: this should reasonably approximate a precise fit where galactic parameters are extracted from CR data. Uncertainties on $\bar{p}$ propagation mainly affect the overall $\bar{p}$ flux, and we anyway assume different E-independent boost factors B_p and B_e for $\bar{p}$ and e^+. We neglect possible statistical correlations among the PAMELA points. Under these assumptions, the best MDM fit is at $B_e \cdot \sigma v = 4\ 10^{-22}\,\mathrm{cm}^3/\mathrm{sec}$ (i.e. $3 \lesssim B_e \lesssim 100$) and for a propagation model intermediate between 'MED' and 'MAX'; the halo model is not significantly constrained. Fig. 1 shows the MDM fit superimposed to the preliminary PAMELA data; we here used $B_p = 3$, and this fit does not significantly deteriorate until much larger values. For the moment uncertainties can only be estimated, so that the fact that this fit has $\chi^2/\mathrm{dof} \sim 1$ is encouraging but cannot be taken as an overall quality indicator. Alternative tools can be employed. We varied M in order to see if the MDM value $M \sim 10\,\mathrm{TeV}$ is preferred by data. We find that increasing the DM mass above 10 TeV starts to give a poorer fit of the e^+ spectrum. Lowering the DM mass, one needs to increasingly reduce free parameters such as B_p/B_e in order to generate the e^+ excess without giving at the same time an unseen $\bar{p}$ excess. The e^+ and $\bar{p}$ spectra will be measured by PAMELA (possibly up to 270 GeV for e^+ and 150 GeV for $\bar{p}$) and later by AMS-08 (up to about 1 TeV). MDM predicts that the positron fraction should continue to grow, and that an anomaly should appear in the $\bar{p}$ spectrum, unless $\bar{p}$ have an unfavorable boost factor or propagation in our galaxy. Collateral constraints must be considered. The $e^\pm$ from DM annihilations lead to a synchrotron radiation [5] at the level of 'WMAP haze' anomaly [12]. Ref. [10] claims that very strong bounds on the DM annihilation cross section can be inferred from infrared and X-ray observations of the GC region, modeled assuming a certain magnetic field and DM density, that gets extremely high close to the central black hole leading to a high rate of DM annihilations. In this region DM becomes relativistic, and in the MDM case this means that the Sommerfeld enhancement disappears, leaving a small annihilation cross section, $\sigma \sim \alpha_2^2/M^2 \sim 10^{-28}\,\mathrm{cm}^3/\mathrm{sec}$ that would not contradict the strong bounds of [10]. A dedicated computation of the MDM prediction together with a precise description of the galactic center is necessary to quantitatively clarify this issue. To conclude: we presented Minimal Dark Matter. Like string theory, MDM has no free parameters, and thereby makes univocal predictions, falsifiable by any single experimental result. The preliminary data from PAMELA, presented at idm08, show an excess in the flux of cosmic ray positrons at 10-60 GeV which matches the MDM prediction. Let us compare with SuSy, the theoretically favored scenario: slepton masses can be fine-tuned to be quasi-degenerate with the lightest neutralino in order to enhance 3-body annihilations obtaining the correct relic abundance and a e^+ spectrum that, with a boost factor of $\gtrsim 10^4$, can be compatible with the PAMELA excess [13]: in such a case the e^+ fraction should decrease at higher energy. MDM predicts the continuing rise of fig. 1a. The PAMELA results recently published on the arXiv [3] have one extra data-point at 80 GeV, still consistent with MDM predictions [5]. The nearby pulsars Geminga or B0656+14 could also produce a rising e^+ fraction, together with an angular anisotropy [14].

References

[1] Talk by P. Gondolo at the idm08 conference.

[2] M. Cirelli, N. Fornengo, A. Strumia, Nucl. Phys. B753 (2006) 178 [hep-ph/0512090].

[3] Talk by M. Boezio at idm08. In order to comply with the publication policy, the preliminary data points for positron and antiproton fluxes plotted in our figures have been extracted from a photo of the slides taken during the talk. $\bar{p}$ data in [5] were extracted from a talk by R. Sparvoli, Pisa, 10/6/08. The PAMELA data have been later published in arXiv:0810.4994 and 0810.4995, confirming the preliminary ones. PAMELA web page: PAMELA.roma2.infn.it.

[4] A. Ibarra and D. Tran, JCAP 0807 (2008) 002 [0804.4596].

[5] M. Cirelli, R. Franceschini, A. Strumia, Nucl. Phys. B800 (2008) 204 [0802.3378].

[6] Talks by E. Aprile, L. Baudis and J. Hall at the idm08 conference.

[7] Talks by A. Riess and M. Tegmark at the idm08 conference.

[8] M. Cirelli, A. Strumia, M. Tamburini, Nucl. Phys. B787 (2007) 152 [0706.4071].

[9] J. Hisano et al. Phys. Rev. Lett. **92** (2004) 031303; Phys. Rev. D **71** (2005) 063528

[10] Talk by M. Regis at the idm08 conference.

[11] e^+: E. A. Baltz and J. Edsjo, Phys. Rev. D59 (1999) 023511 [astro-ph/9808243]. $\bar{p}$: T. Bringmann and P. Salati, Phys. Rev. D 75 (2007) 083006 [astro-ph/0612514]. The p flux is taken from PAMELA data as reported by R. Sparvoli, talk at Pisa U., June 2008. See also the talk by A. Morselli at idm08.

[12] D. P. Finkbeiner, astro-ph/0409027.

[13] Talk by T. Bringmann at the idm08 conference. L. Bergström, T. Bringmann, J. Edsjö, 0808.3725.

[14] A. M. Atoian et al., Phys. Rev. D 52 (1995) 3265. I. Büshing et al., 0804.0220.