SCALAR DARK MATTER AND DAMA

S. ANDREAS
Service de Physique Théorique, Université Libre de Bruxelles, B-1050 Brussels, Belgium
Institut für Theoretische Physik E, RWTH Aachen University, D-52056 Aachen, Germany
Sarah.Andreas@rwth-aachen.de

A light scalar WIMP is studied in view of the recent results of the DAMA collaboration. In a scenario where both the WIMP's annihilation and its elastic scattering on nuclei occur dominantly through Higgs exchange, a one-to-one relation between the WIMP's relic density and its spin-independent direct detection rate is established. The ratio of the relevant cross sections depends only on the dark matter mass if the range allowed by the DAMA results (m < 10 GeV) is considered. We show that if such a light scalar WIMP possesses a direct detection rate compatible with DAMA, it naturally obtains a relic abundance in agreement with WMAP. Indirect detection both with gammas from the Galactic centre and neutrinos from the Sun opens possibilities to test this light dark matter scenario.

1 Introduction

The recent observation of an annual modulation in the nuclear recoil rate by the DAMA collaboration [1] can be reconciled with null results of other direct detection searches [2] for a spin-independent (SI) scattering cross section and dark matter (DM) mass in the ranges

$$3 \times 10^{-41}\ \mathrm{cm}^2 \lesssim \sigma_p^{SI} \lesssim 5 \times 10^{-39}\ \mathrm{cm}^2 \qquad \text{and} \qquad 3\ \mathrm{GeV} \lesssim m_{DM} \lesssim 8\ \mathrm{GeV} \tag{1}$$

when taking into account the channeling effect [3]. These results have already been studied in various specific models [4,5,6,7] and are discussed in the following in view of a light scalar WIMP [a]. For this DM candidate we also present the signature in indirect detection through gammas from the Galactic centre (GC) [7] and neutrinos from the Sun [8].

[a] The WIMP relic density is determined by thermal freeze-out assuming a mundane, radiation dominated expansion of the universe. We use general assumptions on abundance and velocity of the DM distribution in our neighbourhood.

2 Light scalar Dark Matter

Assuming only one Higgs boson, such a scenario is of interest since for a light scalar DM candidate, a natural one-to-one relation between the annihilation cross section and the one for SI scattering on a nucleon $\mathcal{N}$ arises as both processes occur in a Higgs-channel and connects the DM abundance to the direct detection rate. The sole possible tree level annihilation process (figure 1a) is through a Higgs boson in a s-channel into a pair of fermions, among which only $b\bar{b}$, $c\bar{c}$ and $\tau\bar{\tau}$ are relevant, since all other SM fermions have small Yukawa couplings [b]. The SI elastic scattering occurs exclusively through a Higgs in the t-channel (figure 1b) and is induced by the same DM-Higgs coupling.

The scalar DM candidate is introduced in the simplest way as a real scalar singlet S, odd under a Z_2 symmetry, by adding the four following renormalizable terms to the SM lagrangian:

$$\mathcal{L} \ni \frac{1}{2}\partial^\mu S \partial_\mu S - \frac{1}{2}\mu_S^2\, S^2 - \frac{\lambda_S}{4} S^4 - \lambda_L\, H^\dagger H\, S^2 \tag{2}$$

with the Higgs doublet $H = (h^+ \, (h + iG_0)/\sqrt{2})^T$. The mass of S is thus given by $m_S^2 = \mu_S^2 + \lambda_L \mathrm{v}^2$ where $\mathrm{v} = 246$ GeV. In this model, the sole coupling which allows S to annihilate into SM particles and to interact with nucleons is λ_L. For the annihilation and the elastic scattering cross section (normalized to one nucleon), we obtain

$$\sigma(SS \to \bar{f}f)v_{rel} = n_c \frac{\lambda_L^2}{\pi} \frac{m_f^2}{m_h^4 m_S^3} (m_S^2 - m_f^2)^{3/2} \tag{3}$$

$$\sigma(S\mathcal{N} \to S\mathcal{N}) = \frac{\lambda_L^2}{\pi} \frac{m_\mathcal{N}^4}{m_h^4\, (m_S + m_\mathcal{N})^2} f^2, \tag{4}$$

where $n_c = 3(1)$ for quarks (leptons) and $v_{rel} = (s - 4m_S^2)^{1/2}/m_S$ is the centre of mass relative velocity between both S. The factor f parametrizes the Higgs to nucleons coupling from the trace anomaly, $f m_\mathcal{N} \equiv \langle \mathcal{N} | \sum_q m_q \bar{q} q | \mathcal{N} \rangle = g_{h\mathcal{N}\mathcal{N}} \mathrm{v}$. Reflecting the uncertainty in f we consider the range $0.14 < f < 0.66$ with $f = 0.30$ as central value [6]. As for the Yukawa couplings [c], $Y_i = \sqrt{2} m_i/\mathrm{v}$, we consider the pole masses $m_b = 4.23$ GeV, $m_c = 1.2$ GeV and $m_\tau = 1.77$ GeV.

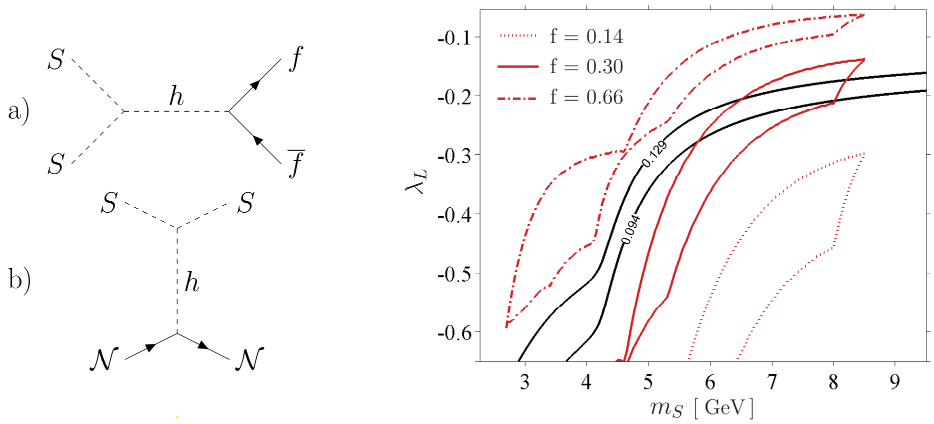

Figure 1: *left*: Higgs exchange diagrams for the DM annihilation (a) and scattering with a nucleon $\mathcal{N}$ (b). *right*: The abundance is in agreement with WMAP ($0.094 < \Omega_{DM}h^2 < 0.129$) between the black solid lines. Direct detection constraints are met in the regions surrounded by the red lines for $f = 0.14$ (dotted lines), $f = 0.30$ (solid lines) and $f = 0.66$ (dash-dotted lines). ($m_h = 120$ GeV)

[b] Annihilation through the SM Z boson is excluded because the DM would contribute to the Z invisible width [9].
[c] We neglect the effects of the running of the Yukawa couplings which are expected to be quite moderate.

3 DAMA and WMAP

In function of the two free parameters m_S and λ_L and for a Higgs mass $m_h = 120$ GeV, we check whether or not agreement with both experiments can be obtained. For the parameter space between the two black lines (figure 1), the relic density, computed with MICROMEGAs [11], with respect to the critical density lies within the WMAP density range $0.094 < \Omega_{DM} h^2 < 0.129$[10]. In the red regions σ_p^{SI} and m_S are in agreement with DAMA and allowed by other direct detection experiments [3] (taking into account the channeling effect [d]). We find that the regions of m_S and λ_L which are consistent with WMAP and direct detection constraints nicely overlap [e]. For the central value $f = 0.30$, the overlap ranges over $m_S \approx 6 - 8$ GeV while for $0.14 < f < 0.66$ regions overlap for 3.5 GeV $< m_S <$ 8.4 GeV. For f smaller than 0.20 no overlap exists.

Those results are shown for $m_h = 120$ GeV but agreement may be obtained for other Higgs masses provided the ratio λ_L/m_h^2 is kept fixed, typically at a value $\lambda_L/m_h^2 \simeq 10^{-5}$ GeV^{-2}. To keep the result perturbative ($\lambda_L \lesssim 2\pi$) we need that $m_h \lesssim 800$ GeV.

4 Indirect Detection and LHC

For the parameter range of interest, we make predictions regarding possible indirect detection from DM annihilation through gamma rays from the GC and neutrinos from the Sun.

The gamma fluxes from the GC for a NFW profile are shown in figure 2 for three parameter sets consistent with DAMA and WMAP and $m_h = 120$ GeV. Since those gammas have an energy in the range of the EGRET (and the forthcoming FERMI/GLAST) data we give for comparison the flux seen by EGRET [15]. The predicted flux is of the same order of magnitude and may even be larger than the one observed. We have however refrained from putting constraints on model parameters, given the large uncertainties on the DM density at the GC.

Dark matter which has been captured in the Sun [12] annihilates and produces neutrinos that can be observed at the Earth after converting into muons close to the detector volume. The expected flux of neutrino induced muons from the Sun for $m_h = 120$ GeV is presented in figure 2 together with the WMAP and DAMA regions from figure 1 as well as the CDMS and XENON limits. With our horizontally from higher [14] to lower DM masses conservatively extrapolated Super-Kamiokande sensitivity [f] (blue line) it can be seen that Super-Kamiokande is potentially able to test the light scalar DM and a part of the DAMA allowed region ($3 - 4.8$ GeV) [8].

Additionally, in this framework, the Higgs boson is predicted to be basically invisible at LHC for $m_h = 120$ GeV. The large coupling to the Higgs leads to its large decay rate into a pair of scalar WIMPs, e.g. for $m_S = 7$ GeV, $BR_{h\to SS} = 99.5\,\%$ for $\lambda_L = -0.2$, $m_h = 120$ GeV and $BR_{h\to SS} \simeq 70\,\%$ for $\lambda_L = -0.55$, $m_h = 200$ GeV [7].

5 Conclusions

Light scalar DM has a one-to-one relation between SI direct detection rate and relic abundance since both processes occur in a Higgs channel. We show that this model can at the same time give the correct WMAP abundance and account for the DAMA results without contradicting other direct searches. The presented signatures in indirect detection show potential to further test this model. Gamma rays from the GC might be in reach of the upcoming FERMI/GLAST

[d] There is no region allowed by all experiments if no channeling effect is assumed.

[e] A DM mass in the relevant range demands some fine tuning, which is in our opinion not unbearable nor surprising, given the minimal number of parameters of the model. To obtain the quite large SI cross section needed to fit the DAMA data a large, albeit still perturbative coupling is required.

[f] The low energetic neutrinos from light DM might be observed with Super-Kamiokande if its sensitivity is extended down to 2 GeV by including stopped, partially contained or fully contained muons [13].

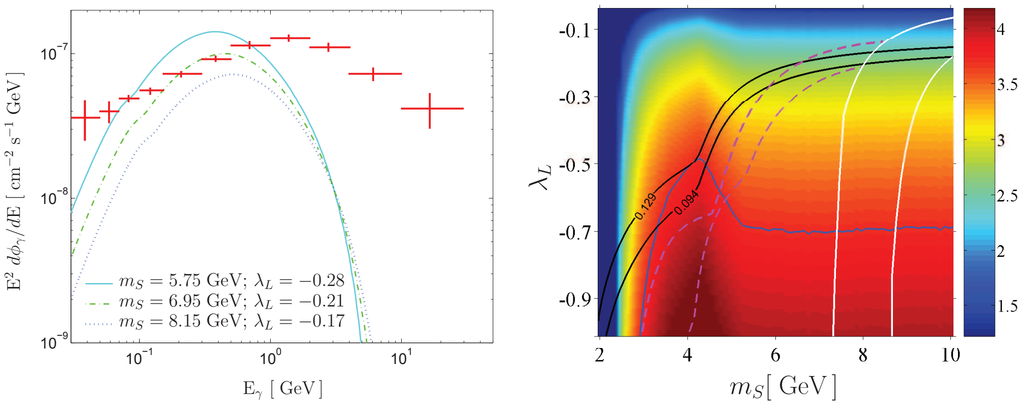

Figure 2: *left*: Flux of gammas from DM-annihilation at the GC for three examples of m_S, λ_L consistent with DAMA, compared to EGRET data (red crosses). *right*: Expected neutrino induced muon flux ($\log_{10} \phi_\mu$) from the Sun, for 2 GeV neutrino energy threshold, together with estimated Super-Kamiokande sensitivity conservatively extrapolated to light WIMPs (blue line, sensitive below), XENON and CDMS exclusion limits (white lines, from left to right), DAMA (magenta dashed lines) and WMAP (black lines) regions.

satellite and Super-Kamiokande might set constraints through neutrinos from the Sun. A striking consequence for LHC Higgs searches is the severe reduction of the visible branching ratio.[g]

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[g] The results discussed here apply for any scalar DM model (like the inert doublet or Higgs portal models) for which annihilation and SI scattering would be dominated by the diagrams of figure 1a,b. For a fermionic DM candidate we find that other channels must be present in order to match the WMAP and DAMA observations [7].