Light Asymmetric Dark Matter

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Stable relic particles of mass around 5 GeV with an intrinsic matter-antimatter asymmetry would naturally provide the dark matter. They do not annihilate after being captured by the Sun and the capture rate is exponentially enhanced if they have self-interactions (of the right order to solve the excessive substructure problem of collisionless cold dark matter). Such particles can significantly affect heat transport in the Sun and may solve the 'Solar composition problem' — the predicted small changes in low energy neutrino fluxes are potentially measurable by Borexino and the proposed SNO+ and LENS experiments.

1 Asymmetric Dark Matter

An asymmetry in dark matter similar to that in baryons would naturally explain why their observed abundances are of the same order of magnitude [1]. Technicolour models of electroweak symmetry breaking [2] provide a TeV mass candidate for asymmetric Dark Matter (ADM) in the form of the lightest neutral technibaryon [3, 4]. Other stable Techni-Interacting Massive Particles (TIMPs) may be pseudo Nambu-Goldstone bosons of 'walking' technicolour interactions and thus much lighter [5]. There has recently been renewed interest in GeV-scale ADM from new strong dynamics [6, 7], motivated by putative signals in dark matter detectors [8].

If the dark matter is sufficiently strongly self-interacting that there is no significant *symmetric* relic abundance today (as for baryons), the relic density of the dark matter χ is given simply by $\Omega_\chi \sim (m_\chi \mathcal{N}_\chi / m_{\rm B} \mathcal{N}_{\rm B}) \Omega_B$ where $\mathcal{N}_{{\rm B},\chi}$ are the respective asymmetries. If $\mathcal{N}_{\rm B} \sim \mathcal{N}_\chi$ (e.g. if both asymmetries are created by leptogenesis) then the required abundance is obtained for a 5 GeV particle as shown in Fig.1 — this also shows how the required relic abundance is achieved again for $\sim$ TeV mass ADM due to the Boltzmann suppression factor [3, 4].

If ADM arises from a strongly coupled gauge theory, then there is naturally a conserved $U(1)$ global symmetry (like B number in QCD) which guarantees stability of the lightest $U(1)$ charged object. A 'dark baryon' from a QCD-like strongly interacting sector but with a mass of about 5 GeV is thus a natural candidate for ADM. The self-interaction cross-section of such a neutral particle can be estimated by scaling up the neutron self-scattering cross-section of $\sim 10^{-23}$ cm^2 as: $\sigma_{\chi\chi} = (m_{\rm n}/m_\chi)^2 \sigma_{\rm nn}$. The self-annihilation cross-section will be of the same order which ensures that the relic thermal (symmetric) abundance is negligible.

2 ADM and the Sun

In contrast to candidates for cold dark matter (CDM) which have a relic thermal abundance determined by 'freeze-out' from chemical equilibrium, ADM does not annihilate upon capture in astrophysical bodies such as the Sun, leading to a build up of its concentration. In particular, self-interactions of the order above can lead to an *exponential* increase of the ADM abundance in the Sun as it orbits around the Galaxy, accreting dark matter [9, 10].

ADM does not have the usual indirect signatures e.g. there will be no high energy neutrino signal from annihilations in the Sun. Instead ADM will alter heat transport in the Sun thus affecting low energy neutrino fluxes. This had been proposed as a solution to the 'Solar neutrino problem' [11, 12, 13]. Although the solution is now understood to be neutrino oscillations [14], small changes induced by accreted CDM particles may account [10, 15] for the current discrepancy [16] between helioseismological data and the revised 'Standard Solar Model' (SSM).

2.1 Capture of self-interacting ADM by the Sun

The capture rate for χ particles with *both* an asymmetry and self-interactions is governed by $\mathrm{d}N_\chi/\mathrm{d}t = C_{\chi\mathrm{N}} + C_{\chi\chi}N_\chi$, where $C_{\chi\mathcal{N}}$ is the usual rate of capture of CDM particles by scattering off nuclei (dominantly protons) within the Sun, while $C_{\chi\chi}$ is the rate of self-capture through scattering off already captured χ particles. Hence the number of captured particles grows exponentially for $t \gtrsim C_{\chi\chi}^{-1}$. However the effective cross-section for self-captures cannot increase beyond πr_χ^2 where $r_\chi \simeq 0.13 R_\odot \sqrt{m_\mathrm{N}/m_\chi}$ is the scale-height of the region where they are gravitationally trapped [11]. The linear growth by contrast can continue up to the 'black disk' limit i.e. $\pi R_\odot^2$, as seen in Fig.1. In both cases there is an additional enhancement due to 'gravitational focussing' [11, 17]. Ejection of captured particles by recoil effects in the self-scattering can be neglected [9] and 'evaporation' is negligible for $m_\chi \gtrsim 3.7$ GeV [17].

The ADM capture rate is proportional to the χ-nucleon cross-section which is constrained by direct detection experiments such as CDMS-II [18], XENON10/100 [19] and CoGeNT [20] to be $\sigma_{\chi\mathrm{N}}^{\mathrm{SI}} \lesssim 2 \times 10^{-40}$ cm^2 for spin-independent interactions and $m_\chi = 5$ GeV. For spin-dependent interactions the constraints are considerably weaker, and the strongest bound of $\sigma_{\chi\mathrm{N}}^{\mathrm{SD}} \lesssim 10^{-36}$ cm^2 for this mass is set by PICASSO [21]. The self-capture rate in the Sun is proportional to the self-interaction cross-section which is unconstrained by direct detection.

Self-interacting CDM was proposed [22] to account for observations of galactic and subgalactic structure on scales $\lesssim$ a few Mpc which are not in accord with numerical simulations using collisionless cold particles. The discrepancy can be solved if CDM has a mean free path against self-interactions of $\lambda \sim 1$ kpc $-$ 1 Mpc corresponding to a self-scattering cross-section between $s_{\chi\chi} \sim 8 \times 10^{-22}$ and $\sim 8 \times 10^{-25}$ cm^{2}GeV^{-1} [22]. A detailed analysis sets an upper limit of $s_{\chi\chi} \lesssim 10^{-23}$ cm^{2}GeV^{-1} [23], while a study [24] of the colliding 'Bullet cluster' of galaxies implies a stronger bound of $\sim 2 \times 10^{-24}$ cm^{2}GeV^{-1}, which we adopt for our calculations below.

If χ has a magnetic moment, photon exchange will give rise to both spin-independent and spin-dependent interactions with nucleons as has been investigated in a model of a 5 GeV 'hidden baryon' interacting with the photon through mixing with a hidden photon [7]. Since the photon couples *only* to the proton in direct detection experiments, the experimental limit on $\sigma_{\chi\mathrm{N}}^{\mathrm{SI}}$ is degraded for this model to $\sim 8 \times 10^{-40}$ cm^2 [10]. Such a cross-section can easily be achieved in this model and will moreover be accompanied by spin-*dependent* interactions which can be bigger and would be particularly relevant for heat transport in the Sun. Hence we adopt a cross-section of $\sigma_{\chi\mathrm{N}}^{\mathrm{SD}} \sim 4 \times 10^{-39}$ cm^2 as an example.

3 Helioseismology and Solar neutrinos

Fig. 1 shows the growth of the number of captured ADM particles in ratio to the number of baryons in the Sun, including the 'gravitational focussing' factor of $(v_{\rm esc}(r)/\bar{v})^2$ [17] and setting $r = R_\odot$ or r_χ ($\simeq 0.07R_\odot$ for $m_\chi = 5$ GeV) as appropriate.

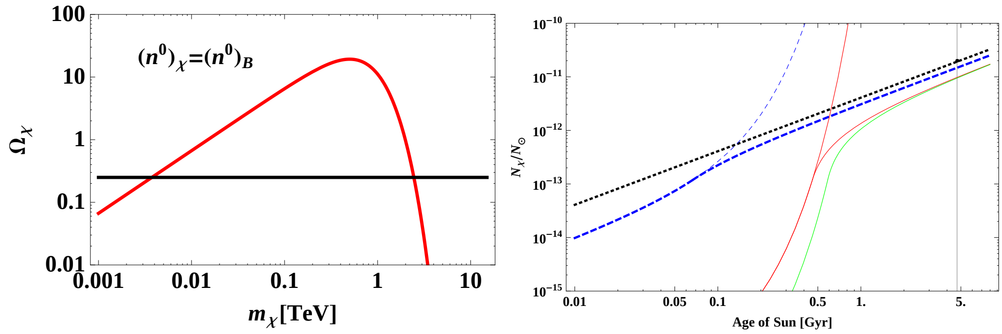

Figure 1: Left: The relic density of ADM as a function of its mass. Right: Growth of the relative abundance of 5 GeV mass ADM particles in the Sun until its present age (vertical line) for $s_{\chi\chi} = 2 \times 10^{-24}{\rm cm}^2{\rm GeV}^{-1}$ and $\sigma_{\chi N}/{\rm cm}^2 = 2 \times 10^{-40}$ (green line), 10^{-39} (red line) and 10^{-36} (blue line); also shown is the 'black disk' limit (dotted line) for the Sun.

Due to the self-captures the limiting abundance $N_\chi/N_\odot \sim 10^{-11}$ is almost independent of the actual scattering cross-section as seen in Fig.1. Such an ADM fraction in the Sun can affect the thermal transport and Solar neutrino fluxes [11, 12] which are in fact well accounted for (taking neutrino oscillations into account) by the Standard Solar Model (SSM) [26] with the 'standard' Solar composition [27]. The SSM used to be in excellent agreement with helioseismology [28], however the recent revision of the Solar composition [29] means that it no longer reproduces the sound speed and density profile, resulting in a 'Solar composition problem' [16]. We find that the presence of ADM in the Sun can alleviate this problem and precision measurements of Solar neutrino fluxes can constrain the properties of self-interacting ADM [10].

A simple scaling argument gives for the luminosity carried by the ADM [11]:

$$L_\chi \sim 4 \times 10^{12} L_\odot \frac{N_\chi}{N_\odot} \frac{\sigma_{\chi{\rm N}}}{\sigma_\odot} \sqrt{\frac{m_{\rm N}}{m_\chi}} \,, \tag{1}$$

where $L_\odot \sim 4\times10^{33}{\rm ergs\,s}^{-1}$. When the ADM mean free path $\lambda_\chi(= 1/n_\odot\sigma_{\chi{\rm N}})$ is large compared to the scale-height r_χ then the energy transfer is *non-local* [11]. This is the case when $\sigma_{\chi{\rm N}} \ll \sigma_\odot$ where $\sigma_\odot \equiv (m_{\rm N}/M_\odot)R_\odot^2 \sim 4 \times 10^{-36}$ cm^2 is a critical scattering cross-section. The resulting variation of the Solar luminosity $\delta L(r) \equiv L_\chi(r)/L_\odot(r)$ is shown in Fig.2 assuming $\sigma_{\chi{\rm N}} = 4 \times 10^{-39}$ cm^2 (i.e. $10^{-3}\sigma_\odot$) and $N_\chi = 2 \times 10^{-11} N_\odot$ from Fig. 1. Note that the luminosity scales linearly with both $\sigma_{\chi{\rm N}}$ and $N_\chi/N_\odot$.

The ADM temperature T_χ is fixed by requiring that the energy absorbed in the inner region ($T(r) > T_\chi$) is equal to that released in the outer region ($T(r) < T_\chi$), such that $L_\chi(R_\odot) = 0$. This approximation overestimates the energy transfer by a small factor [30, 31] but is sufficiently accurate for the present study. From the radiative transport equation it follows that a small variation of the Solar luminosity is equivalent to an *opposite* small variation in the effective

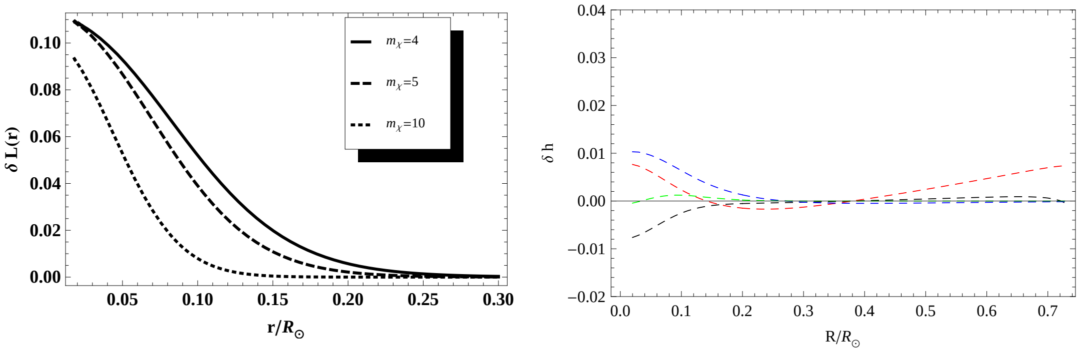

Figure 2: Left: Radial variation of $\delta L(r) \equiv L_\chi(r)/L_\odot(r)$ due to ADM. Right: Effect of 5 GeV ADM with $\sigma_{\chi\mathrm{N}} = 4 \times 10^{-39}$ cm^2 on the Solar temperature (black), pressure (red), mass fraction (blue), and luminosity (green), as computed using the linear Solar model [34].

radiative opacity: $\delta L(r) \sim -\delta\kappa_\gamma(r) \equiv -\kappa_\chi(r)/\kappa_\gamma(r)$ [32]. The effect of such a localised opacity variation in the region $r \lesssim 0.2R_\odot$ has been studied by a Monte Carlo simulation [33] and results in excellent agreement obtained using a linear approximation to the solar structure equations [34]. Fig. 2 shows that the opacity modification due to a 5 GeV ADM with a relative concentration of 10^{-11} is roughly equivalent to the effect of a 10% opacity variation. In general, to have an observable effect on neutrino fluxes requires $\sigma_{\chi\mathrm{N}} N_\chi/\sigma_\odot N_\odot \gtrsim 10^{-14}$.

It is possible through helioseismology to determine the mean variations of the sound speed profile $\langle \delta c/c \rangle$ as well as the boundary of the convective zone R_{CZ} which is determined to be $(0.713 \pm 0.001)R_\odot$, while the SSM with the revised composition [29] predicts a significantly higher value. Lowering the opacity in the central region of the Sun with ADM also lowers the convective boundary. The 10% opacity variation shown in Fig. 2 leads to a $\sim 0.7\%$ reduction in R_{CZ} [34] and thus *restores* the agreement with helioseismology. The sound speed and density profiles, which are presently underestimated in the region $0.2R_\odot \lesssim r \lesssim R_{\mathrm{CZ}}$, would also be corrected by the opacity modification displayed in Fig. 2.

The modification of the luminosity profile extends into the neutrino producing region. Precision measurements of different neutrino fluxes can thus test the ADM model and determine its parameters. The ADM mass determines the scale height r_χ, hence the relative modifications of individual neutrino fluxes, while the cross-section determines the capture rate and thereby the overall modification. Both Monte Carlo simulations [33] and the 'linear solar model' [34] show that the variation of neutrino fluxes with respect to localised opacity changes in the neutrino producing region ($r \lesssim 0.2R_\odot$) scales approximately as $\delta\Phi_{\mathrm{B}} \sim 1.5\delta\kappa$ and $\delta\Phi_{\mathrm{Be}} \sim 0.7\delta\kappa$. The opacity variation in Fig. 2 leads to variations $\delta\Phi_{\mathrm{B}} = -17\%, \delta\Phi_{\mathrm{Be}} = -6.7\%$ and $\delta\Phi_{\mathrm{N}} = -10\%, \delta\Phi_{\mathrm{O}} = -14\%$ [34]. Measurements of the ^{8}B flux by Super-Kamiokande [35], SNO [36] and Borexino [37] are precise to 10% while the expectations vary by up to 20% depending on whether the old [27] or the new [29] composition is used [28]. For the ^{7}Be flux, the theoretical uncertainty is 10%, while Borexino aims to make a measurement precise to 3% [38]. SNO+ aims to make a first measurement of the pep and CN-cycle fluxes [39], while LENS may be sensitive to the commensurate small increase in the pp neutrino flux [40].

Numerical simulations of Solar evolution with ADM [41, 42] indicate similar reductions of the neutrino fluxes but smaller effects on helioseismology. This is under investigation.

4 Conclusions

Intriguingly a 5 GeV 'dark baryon' would naturally a) have the required relic abundance if it has an initial asymmetry similar to that of baryons, b) have a self-interaction cross-section of the right order to suppress excessive sub-structure on galactic scales, c) modify the deep interior of the Sun, restoring agreement between the standard Solar model and helioseismology, and d) be consistent with recent hints of signals in direct detection experiments. Such a 5 GeV ADM particle would lower the Solar neutrino fluxes which ought to be measurable by the Borexino and (forthcoming) SNO+ and LENS experiments. Thus this model is predictive and falsifiable.

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