A possible indication of momentum-dependent asymmetric dark matter in the Sun

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Broad disagreement persists between helioseismological observables and predictions of solar models computed with the latest surface abundances. Here we show that most of these problems can be solved by the presence of asymmetric dark matter coupling to nucleons as the square of the momentum exchanged in the collision. We compute neutrino fluxes, small frequency separations, surface helium abundances, sound speed profiles and convective zone depths for a number of models, showing more than a 6σ preference for q² models over others, and over the Standard Solar Model. The preferred mass (3 GeV) and reference dark matter-nucleon cross-section (10⁻³⁷ cm² at q₀ = 40 MeV) are within the region of parameter space allowed by both direct detection and collider searches.

Introduction.— Since the downwards revision of the solar photospheric metallicity [1], a number of discrepancies have appeared between models of the solar interior and helioseismology. Models computed with the revised photospheric abundances show poor agreement with the observed depth of the convection zone, sound speed profile, surface helium abundance and small frequency separations [2]. A number of explanations have been proposed [3, 4], some based on axion-like particles [5] or modified energy transport in the solar interior due to dark matter (DM) [6, 7], but none has proven compelling.

Here we demonstrate that the existence of weakly-interacting asymmetric dark matter (ADM; [8]) with a mass of a few GeV can explain most of these anomalies, if (and only if) the strength of the interaction between DM and nucleons depends on the momentum q exchanged between them. In particular, we find a more than 6σ preference for a coupling proportional to q².

Momentum-dependent dark matter.— The scattering cross-section between DM and nucleons can depend on both the relative velocity of the colliding particles (v_rel) and the momentum that they exchange (q). The first term in series expansions of the cross-section is independent of both v_rel and q, and dominates in models such as supersymmetry. In other models, this term is suppressed, and the leading contribution comes from terms with a non-trivial dependence on v_rel or q [9]. At low masses, such a dependence has been one of the theoretical mechanisms proposed to reconcile various anomalies in direct searches for dark matter [10].

Here we focus on an effective spin-independent (SI) elastic cross-section between DM χ and nucleons of the form

$$\sigma_{\chi-nuc} = \sigma_0 \left( \frac{q}{q_0} \right)^2,$$

where q₀ is a reference momentum used to normalise the scattering cross-section; we choose q₀ = 40 MeV, which corresponds to a typical nuclear recoil energy of ~10 keV in direct detection experiments. Such a q² SI form to the cross-section can arise from, e.g. effective DM-quark operators like $\bar{\chi} \gamma_\mu q \bar{q} q$ and $\chi \sigma_{\mu\nu} \gamma_\mu \bar{q} q \gamma_\nu q$ [11]. The former operator is particularly appealing in its simplicity, arising from the exchange of a pseudoscalar mediator.

Helioseismology and dark matter.— The impacts of DM-nucleon scattering on helioseismology and stellar structure have been well studied [6, 7, 12, 13]. Weakly-interacting DM from the Galactic halo is captured when it passes through the Sun, scatters onto a bound orbit [14], undergoes repeated additional scattering and energy loss, and eventually settles into the solar core. DM-nucleon scattering provides an additional means of conductive energy transport: DM particles absorb energy in the hottest, central part of the core, then travel to a cooler, more distal region before scattering again and redepositing their energy [15]. This decreases the temperature contrast over the core region and reduces the central temperature. The cooler core produces less neutrinos from the most temperature-sensitive fusion reactions, so the ⁸B and ⁷Be neutrino fluxes observed at Earth can be noticeably reduced. This is accompanied by a smaller increase in the pp and pcp fluxes, as required by the constancy of the solar luminosity.

The structural changes in the core shift the balance between gravity and pressure elsewhere, leading to global readjustments in models constrained to fit the solar radius $R_\odot$, luminosity $L_\odot$ and metal to hydrogen abundance ratio $(Z/X)_\odot$ at the solar system age $t_\odot$. A widely used seismic diagnostic, the depth of the solar convective envelope $R_{CZ}$, is determined by the temperature gradient immediately below the convective envelope. In our DM models, the gradient in this region is slightly steeper than in the Standard Solar Model (SSM), leading to a modest but measurable deepening of the convective envelope. The lower core temperature leads to lower nuclear fusion rates, which must be compensated for by increasing the
hydrogen abundance so that the integrated nuclear energy release accounts for $L_\odot$. The initial helium mass fraction and the present day surface value $Y_*$ are thus lower in models where DM contributes to energy transport. In general, helioseismic diagnostics are affected by changes in temperature ($T$), mean molecular weight ($\bar{\mu}$), and their gradients, as the solar sound speed varies as $\delta c_s / c_s = \frac{1}{2} \delta T / T - \frac{1}{2} \delta \bar{\mu} / \bar{\mu}$ (neglecting here a small term from variation of the adiabatic index $\Gamma_1$). If $\nu_{n,\ell}$ is the frequency corresponding to the eigenmode of radial order $n$ and angular degree $\ell$, then the so-called frequency ratios

$$ r_{0,2} = \frac{\nu_{n,0} - \nu_{n-1,2}}{\nu_{n,1} - \nu_{n-1,1}} \quad \text{and} \quad r_{1,3} = \frac{\nu_{n,1} - \nu_{n-1,3}}{\nu_{n+1,0} - \nu_{n,0}}, $$

are given by

$$ r_{\ell,\ell+2}(n) \approx -(4\ell + 6) \frac{1}{4\pi^2 \nu_{n,\ell}} \int_0^{R_\odot} dc_s \frac{dR}{dR}, $$

for $n \gg 1$. These are weighted towards the core, so give information on the central region of the Sun [16]. In this work we use solar data from BiSON [17], from which ratios can be computed for $n > 8$.

The major technical advance here over earlier work [6, 7, 12] is that we compute solar models using an accurate treatment of energy transport and solar capture by momentum-dependent DM-nucleon interactions. The correct transport treatment is quite involved [18]. The capture rate of $q^2$-dependent DM by the Sun is [19]

$$ C_\odot(t) = 4\pi \int_0^{R_\odot} R^2 \int_0^\infty f_0(u) \frac{w^2}{u^2} \sum_i \sigma_{N,i} n_i(R,t) \frac{\mu_i^2}{\mu_i^*} \times \Theta \left( \frac{\mu_i v_{esc}^2(R,t)}{\mu_i^*} - u^2 \right) \left( \frac{m_\chi w}{u_0} \right)^2 I_{FF} \frac{d\mu_i^*}{dR}, $$

where $R_\odot$ is the solar radius, $m_\chi$ the DM mass, $v_{esc}(R,t)$ the local escape speed at height $R$ in the Sun, $f_0(u)$ the distribution of halo DM particle speeds $u$ in the solar frame, $w \equiv \sqrt{u^2 + v_{esc}^2}$, $\sigma_{N,i}$ and $n_i$ are the DM-nucleus scattering cross-section and local number density respectively for nuclear species $i$, $\mu_i \equiv m_\chi/m_{N,i}$, $\mu_{i\pm} \equiv (\mu_i \pm 1)/2$, and $I_{FF}$ is the form factor integral. For hydrogen,

$$ I_{FF} = \frac{\mu_{H,+}^2}{2\mu_{H}^*} \left[ \frac{\mu_{H}^2}{\mu_{H,+}^2} - \frac{u^4}{w^4} \right]. $$

For heavier elements, assuming a Helm form factor gives

$$ I_{FF} = \frac{\mu_i}{(B_{iH}\mu_{iH})} \left[ \Gamma \left( 2, B_{iH} \frac{u^2}{w^2} \right) - \Gamma \left( 2, B_i \frac{\mu_i}{\mu_{iH}^*} \right) \right], $$

with $\Gamma(m,x)$ the upper incomplete gamma function. Here $B_i \equiv \frac{1}{2} m_\chi w^2 / E_i$, where $E_i$ is a constant given in [14] for each nuclear species.

**FIG. 1.** Deviation of the radial sound speed profile (Sun − model) in the solar interior from the values inferred from helioseismological data, for the Standard Solar Model (SSM) and three models of asymmetric dark matter (ADM). Coloured regions indicate $1$ and $2\sigma$ errors in modelling (thick blue band) and on helioseismological inversions (thinner green band). The combination ($m_\chi,\sigma_{X-nuc}$) for each model is chosen to give the best overall improvement with respect to the SSM.

**Simulations of $q^2$ ADM in the Sun.**— To study the impact of $q^2$ ADM on solar observables, we merged the solar structure and dark stellar evolution codes GARSTEC [4, 20] and DarkStec [21], then implemented momentum-dependent transfer as per [18] and capture as in Eq. 4, creating a precision dark solar evolution package DarkStec. We computed solar models matching $(Z/X)_{SSM}$, $L_\odot$ and $L_\odot$ at the solar age $t_\odot$ over a grid of ADM masses and cross-sections $\sigma_0$, for regular SI and SD (spin-dependent) ADM, as well as $q^2$ momentum-dependent SI ADM. We assumed passage of the Sun at $220\text{ km s}^{-1}$ through a standard Maxwell-Boltzmann halo with velocity dispersion $270\text{ km s}^{-1}$ and local DM density $0.38\text{ GeV cm}^{-3}$. On the basis of the observed $^8\text{B}$ and $^7\text{Be}$ neutrino fluxes, depth of the convection zone, surface helium fraction and sound speed profile, we selected the best-fit model within each of these grids: for {SD, SI, $q^2$ SI} models, $m_\chi = \{5,10,3\}$ GeV and $\sigma_0 = \{10^{-36},10^{-37},10^{-37}\}$ cm$^2$.

In Fig. 1 we compare the sound speed profile predicted by each of the three best-fit models to that inferred from helioseismic inversions and presented in [2]. We also show the profile of the SSM, as computed with the latest abundances [1, 4]. SI and SD ADM provide little improvement over the SSM. Momentum-dependent ADM significantly improves agreement with the observed sound speed profile, both at the base of the convection zone and in the outer part of the core, bringing the discrepancy down to
little more than \( \sim 2\sigma \). Momentum-dependent ADM evacuates energy from the solar core, causing it to become cooler, in turn increasing the central hydrogen fraction and reducing the mean molecular weight of the core material. The net effect is a decrease in the sound speed. At intermediate regions, where DM deposits energy, the temperature is slightly higher, forcing a steeper temperature gradient towards the bottom of the convective envelope, and therefore a deeper \( R_{\text{CZ}} \).

We also computed the small frequency separations \( r_{02} \) and \( r_{13} \) (Fig. 2). The agreement of predictions from momentum-dependent DM with the observed ratios is remarkable, barely passing beyond a single standard deviation for any ratio. None of the other models is able to produce a remotely competitive fit.

In Table I we give the neutrino fluxes, \( R_{\text{CZ}} \) and \( Y_s \) predicted by all models, along with contributions to a global \( \chi^2 \) statistic from each. We see that although the \( q^2 \) model gives slightly worse agreement with the observed neutrino fluxes and \( Y_s \) than the SSM, the worsening of the fit is fairly benign in a statistical sense – and the fit to \( R_{\text{CZ}} \) is improved from a 2.2\( \sigma \) discrepancy in the SSM to little more than a standard deviation. The largest contributor to the global \( \chi^2 \) of the \( q^2 \) model is \( Y_s \), which changes from the SSM as 0.2356 \( \rightarrow \) 0.2327 (a 2.6\( \sigma \) \( \rightarrow \) 3.2\( \sigma \) discrepancy). Assuming Gaussian errors, \( p = 0.85 \) for the \( q^2 \) model, indicating an excellent overall fit to data. All the other models have \( p < 10^{-10} \), indicating that they are ruled out with greater than 6\( \sigma \) confidence.

We include \( r_{\ell,\ell+2} \) but not \( c_s \) in the \( \chi^2 \), as the former is more precise, and the two datasets are strongly correlated. Different \( r_{\ell,\ell+2} \) values are also correlated. For the data that we use, however, the correlation is < 1% between different \( n \) and < 8% between \( r_{02} \) and \( r_{13} \). We hence include all points in the \( \chi^2 \). Using e.g. \( r_{02} \) only (which gives a worse fit than \( r_{13} \)) would only reduce \( p \) to 0.18 – still an excellent fit.

In general, the \( q^2 \) SI coupling produces the best results because it allows the capture rate to be maximised at values of \( m_\chi \) and \( \sigma_0 \) that make transport by DM both effective and long-range [18, 19].

**Discussion.**— This is the first real exploration of the effects of momentum-dependent dark matter on solar physics. Previous papers dealt with regular SI and SD couplings [6, 7, 13], but of those only [6] included the correct treatment of conductive energy transport by DM. Accounting for (small) improvements in the underlying solar modelling here relative to [6], our SI and SD results are in good agreement with their findings. The only other investigations to date of non-standard couplings in the context of helioseismology [12] involved approximate treatments of mixed \( q-v_{\text{rel}} \)-dependent cross-sections as purely \( v_{\text{rel}} \), without proper capture or transport calculations, nor consideration of all observational conse-
quenches. A $v^2$ SD cross-section, for example, can indeed provide improvements over the SSM in terms of $c_s$ and $R_{CCz}$, but these are outweighed by more severe decreases in the $^8$B and $^7$Be neutrino fluxes [19].

The mass (3 GeV) and cross-section ($10^{-37}$ cm$^2$) of $q^2$ momentum-dependent DM preferred by solar physics are in agreement with all direct searches performed to date [20], and are even tantalisingly close to some of the preferred regions in analyses of direct detection anomalies [11]. Models with appropriate couplings (e.g. $\bar{\chi}\gamma\chi q\bar{q}$) are also still allowed by collider searches [22], so the prospects for soon confirming or refuting the existence of $q^2$ ADM resembling our best-fit model appear favourable.

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