The sun: light dark matter and sterile neutrinos

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Despite all the efforts made in the field of its research, Dark Matter (DM) continues to be an enigma in Physics.
This paper presents a model in which DM is described as a composite of a light DM (LDM) particle ϕ and a sterile neutrino $\boldsymbol{\nu}_s$. The motivation for this kind of model arises from the possibility to address some observational problems coming from cosmology, as well as to give an explanation to some of the observed anomalies found in short-baseline neutrino oscillation experiments. Under the hypothesis that the DM abundance today is constituted by the sum of both ϕ and $\boldsymbol{\nu}_s$ densities

$$\Omega_{\mathrm{DM}} h^2 = \Omega_\phi^2 h^2 + \Omega_{\nu_s}^2 h^2 \;,$$

the discussion is focused on how this LDM field modifies the neutrino flavor oscillations, and which constraints in the parameters of such models can be put by using the current sets of solar neutrino data.
The hypothesis that DM is made of very light particles leads to the description of ϕ in the DM halo of the Milky Way as a group of plane waves described as

$$\phi(\vec{r}, t) = \phi_o \cos\left(m_\phi t + \epsilon_o\right) \approx \phi_o \cos\left(m_\phi t\right),$$

where ϕ_o and ϵ_o are, respectively, the amplitude and the phase of $\phi(r,t)$. In presence of such LDM field, neutrino masses will receive a contribution δm_ν depending on a certain amplitude ϵ_ϕ, that will induce corrections on the mass differences and on the mixing angles: the Sun, immersed in this LDM halo, will experience this periodic perturbation due to the action of $\phi(r,t)$. The propagation of active neutrinos plus a sterile neutrino $\boldsymbol{\nu}_s$ through the solar plasma is described by:

$$i \frac{d\Psi}{dr} = \mathcal{H}\Psi = \frac{1}{2E}\left(\mathbf{U} M^2 \mathbf{U}^\dagger + 2E\mathcal{V}\right)\Psi,$$

where $\Psi = (\boldsymbol{\nu}_e, \boldsymbol{\nu}_\tau, \boldsymbol{\nu}_\mu, \boldsymbol{\nu}_s)$ and H is the Hamiltonian that, in presence of matter, is given by the sum of the neutrino propagation in vacuum plus the matter term describing the Mikheyev-Smirnov-Wolfenstein (MSW) effects. The matter potential depends on the generalised Fermi constant $G_{\boldsymbol{\nu} s\phi} = 4\sqrt{2} G_\phi G_F$, with G_ϕ being a free parameter of the model. The propagation of neutrinos away from resonances is well described by a two neutrino flavor oscillation model which, in the electron neutrino case, is dominated mostly by the ($\boldsymbol{\nu}_1$, $\boldsymbol{\nu}_2$) mass eigenstates. This split of the 3+1 neutrino model leads to an analytical solution for the time-dependent survival probability of electron neutrinos $P_{ee}(E,\phi)$. The effective survival probability $\langle P_{ee}(E)\rangle$ corresponds to an ensemble average of all the $P_{ee}(E,\phi)$:

$$\langle P_{ee}(E)\rangle = \int_0^{\tau_\phi} P_{ee}(E,\phi)\frac{dt}{\tau_\phi},$$

where $\tau_\phi = 2\pi/m_\phi$ is the period of ϕ. The ability of a solar neutrino detector to measure the impact of the time-dependent field $\phi(t)$ on the $P_{ee}(E,\phi)$ depends on three characteristic time scales: the neutrino flight time $\tau_{\boldsymbol{\nu}}$, the time between two consecutive neutrino detections $\tau_{e\boldsymbol{\nu}}$, and the total run time of the experiment τ_{ex}. Two regimes can be found for the time modulation of the survival probability of the electron neutrinos: when $\tau_\phi \geq \tau_{\boldsymbol{\nu}}$, the low-frequency (or low-mass) regime occurs. Here, the LDM field can induce an observable time variation in neutrino oscillation measurements as periodicity in the solar neutrino fluxes. When $\tau_\phi \leq \tau_{\boldsymbol{\nu}}$ instead, we fall in the high-frequency (or high-mass) regime: here the time average of the ensemble of oscillation probability $P_{ee}(E,\phi)$ can be distorted, inducing a shift in the observed values of $P_{ee}(E,\phi)$.

Both these regimes have been studied, by considering τ_ϕ varying from 4 µs to 13 yr or, equivalently, m_ϕ varying from 10^{-9}eV to 10^{-23}eV, which represents a reasonable range to be scanned by future detectors such as DUNE [1]. The proton-proton (pp) chain and the Carbon-Nitrogen-Oxygen (CNO) cycle also contribute to the time variability of $P_{ee}(E,\phi)$ because they occur at different distances from the center of the Sun and each one emits neutrinos in a well-defined energy range. This leads to a contribution to the overall variability of $P_{ee}(E,\phi)$ and $\langle P_{ee}(E,\phi)\rangle$.

In conclusion, it is already possible to put some constraints on these LDM models. It was found that LDM models with $G_{\phi}\approx 0$ must have a ϵ_{ϕ} smaller than 3% to be consistent with current solar neutrino measurements from the Borexino [2], SNO [3] and Super-Kamiokande [4] detectors (Fig1), and that models with a G_{ϕ}/m_{ϕ} smaller than $10^{30} G_F\, eV^{-1}$ agree with these experiments.

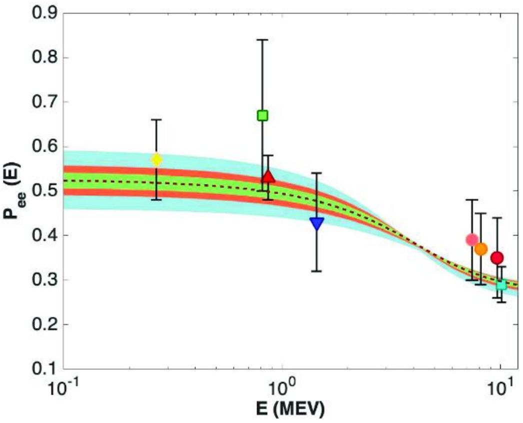

Fig1: The survival probability of the electron neutrinos for several solar nuclear reactions: pp (yellow diamond), ^{7}Be (green square), ^{7}Be (red upward triangle), pep (blue downward triangle) and ^{8}B HER (salmon circle), ^{8}B HER-I (orange circle), ^{8}B HER-II (magenta circle) and ^{8}B (cyan square). The diamond, triangle, and circles points use data from the Borexino [2] and the two square data points correspond to data obtained from SNO [3] and Super-Kamiokande [4] detectors. Each color band corresponds to an ensemble of $P_{ee}(E,\phi)$ in a 3+1 neutrino model with $G_{\phi}\approx 0$ and $\epsilon_{\phi}\approx 0$ (dashed curve), 1.5% (green), 3.0% (orange) and 6.0% (light blue).

References

[1] "Long-Baseline Neutrino Facility (LBNF) and Deep Underground Neutrino Experiment (DUNE) Conceptual Design Report Volume 2: The Physics Program for DUNE at LBNF". arXiv:1512.06148.

[2] "Solar Neutrino Detection Sensitivity in DARWIN via Electron Scattering". arXiv:2006.03114.

[3] "Combined analysis of all three phases of solar neutrino data from the Sudbury Neutrino Observatory". Phys. Rev. C, 88, 025501.

[4] "Solar neutrino measurements in Super-Kamiokande-IV". Phys. Rev. D, 94, 052010.