New neutrino physics and the altered shapes of solar neutrino spectra

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Neutrinos coming from the Sun’s core are now measured with a high precision, and fundamental neutrino oscillations parameters are determined with a good accuracy. In this work, we estimate the impact that a new neutrino physics model, the so-called generalized Mikheyev-Smirnov-Wolfenstein (MSW) oscillation mechanism, has on the shape of some of leading solar neutrino spectra, some of which will be partially tested by the next generation of solar neutrino experiments. In these calculations, we use a high-precision standard solar model in good agreement with helioseismology data. We found that the neutrino spectra of the different solar nuclear reactions of the proton-proton chains and carbon-nitrogen-oxygen cycle have quite distinct sensitivities to the new neutrino physics. The $HeP$ and $^{8}B$ neutrino spectra are the ones for which their shapes are more affected when neutrinos interact with quarks in addition to electrons. The shape of the $^{15}O$ and $^{17}F$ neutrino spectra are also modified, although in these cases the impact is much smaller. Finally, the impact in the shape of the $PP$ and $^{13}N$ neutrino spectra is practically negligible.

I. INTRODUCTION

Since their discovery in 1956, neutrinos have always surprised physicists due to their unexpected properties, often challenging our basic understanding of the standard model of particle physics (in the remainder of the article, it will be called simply the ‘standard model’) and the properties of elementary particles. In particular, the discovery of neutrino flavour oscillations stands as one of the most convincing proofs that the standard model is incomplete as it does not explain all the known experimental properties of the fundamental particles.

The neutrino research success has been made possible mostly due to many dedicated experiments performed during the last fifty years. It is worth highlighting the contributions of some pioneering experiments, among others, such as the Super-Kamiokande detector [1, 2] where the oscillation of atmospheric neutrinos was discovered, and the SNO detector [3] where the fluxes of all neutrino species produced in the Sun’s core were measured for the first time. Many other experiments done during the previous decades have contributed for the success of this story, in particular, the solar neutrino experiments. Despite their technical complexities, these experiments were able to measure the electron neutrino fluxes coming from the Sun and played a major role in the establishment of the so-called solar neutrino problem – a discrepancy between the theoretical prediction of neutrino fluxes and their experimental measurements: the experimental value being one third of the predicted value. This fact was evidenced for the first time by the Homestake Experiment of Ray Davis [4], and confirmed by many other experiments that followed. It was the solar neutrino problem that prompted the development of the neutrino flavour oscillation model.

If indeed the previous generation of solar neutrino detectors has been one of the beacons of particle physics, both by leading the way in uncovering the basic properties of particles, including the nature of neutrino flavour oscillations, and by being responsible for developing pioneering techniques in experimental neutrino detection [5], the next generation of detectors is equally promising in discovering new physics. Among various, some of which will be looking for evidence of neutrino new physics we can mention the following future detectors: the Low Energy Neutrino Astronomy [LENA, 6], the Jiangmen Underground Neutrino Observatory [JUNO, 7], the Deep Underground Neutrino Experiment [DUNE, 8], the NOvA Neutrino Experiment [NOvA, 9], and the Jinping Neutrino Experiment [Jinping, 10].

These detectors will measure with high precision the neutrino fluxes and neutrino spectra of a few key neutrino nuclear reactions, such as the $^{8}B$ electron-neutrino ($^{8}B\nu_{e}$) spectrum produced by the $\beta$-decay process in the $^{8}B$ solar (chain) reaction: $^7Be(p, \gamma)^8(e^+\nu_e)^8B^-(\alpha)^4He$ [11, 12]. This will allow us to probe in detail the Sun’s core, including the search for new neutrino physics interaction or even new physics processes. Moreover, the high quality of the data will enable the development of inversion techniques for determining basic properties of the solar plasma [e.g., 13]. Specific examples can be found in Balantekin et al. [14] and Lopes [15]. Equally, solar neutrino data can be used to find specific features associated with possible new physical processes present in the Sun’s interior [e.g., 16], such as the possibility of an isothermal solar core associated with the presence of dark matter [17].

Today, the basic principles of neutrino physics are firmly established, neutrinos are massive particles with a lepton flavours mix. The parameters describing neutrino flavour oscillations are measured with great accuracy and precision, which has been possible due to the extensive studies made by many different types of neutrino experiments: solar and atmospheric neutrino observatories, nuclear reactors and experimental particle accelerators [e.g., 18–20]. Section III C presents the status of the current neutrino oscillation parameters obtained from up-to-date experimental data.

Even if many properties of neutrinos are known, many others are still a mystery:
- firstly, are neutrinos Majorana or Dirac fermions ? i.e., are neutrinos their own anti-particle ? Although the theoretical expectation favours the first option, only experimental ev-

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idence can settle this question;
- secondly, what is the mass hierarchy of neutrinos? In other words, does the order of neutrino masses between the different particle families follow a normal hierarchy – two light neutrinos followed by a heavier one, or an inverted hierarchy – one light neutrino follow by two heavier ones?

Together with the CP violation in the lepton sector, these are the most important questions of neutrino physics. Some of these questions will be answered by the next generation of neutrino experiments – the long baseline neutrino experiments and solar neutrino telescopes. Nevertheless, it is necessary to improve the current neutrino flavour model to take full advantage of the forthcoming experimental data.

Despite the success of the current neutrino physics model in explaining most of the neutrino’s known observed properties, the solution encountered clearly indicate the existence of new physics beyond the standard model. As such, this implies that within the current particle physics theoretical framework, experiments can study neutrinos in other types of interactions. When such processes occur, these lead to important modifications of the physical mechanisms by which neutrinos are created, propagate and interact with other particles of the standard model. This new class of neutrino interactions is usually known as non-standard interactions (nsi).

The non-standard interactions of neutrinos have been extensively studied in the literature, among others reviews on this topic, see for instance Miranda and Nunokawa [21], Ohlsson [22]. Moreover, the constraints on the nsi parameters and their effects for low energy neutrinos have been derived from a great variety of experimental results. Until now no definitive evidence of non-standard interactions has been provided by the experimental data. Actually, all observations made as yet can be explained in terms of the standard interactions of the three known neutrinos, although some of them need the help of sterile neutrinos. Nevertheless, in some cases the non-standard interactions of neutrinos provide an interesting and valid alternative [e.g., 23]

In this work we are mostly concerned with the non-standard interactions of solar neutrinos. These interactions can affect the neutrino production inside the Sun, the detection of neutrinos by experimental detectors and the neutrino propagation in the Earth’s and Sun’s interiors. In particular, our study focus on the propagation of neutrinos through baryonic matter in the Sun’s interior, a process usually known as the generalized Mikheyev-Smirnov-Wolfenstein (MSW) oscillation mechanism, or generalized matter effect oscillations. Our goal is to make predictions about the modifications imprinted by this new generalized MSW on the shape of the solar neutrino spectrum produced by some of the (pp) and carbon-nitrogen-oxygen (CNO) key nuclear reactions, like HeP and 8B neutrino spectra.

The high-quality of the standard solar model in reproducing the measured solar neutrino fluxes, and the observed acoustic frequency oscillations, make it a privileged tool to look for the new interactions within a generalized Mikheyev-Smirnov-Wolfenstein mechanism occurring in the Sun’s interior. The standard solar model [SSM, 24] partly validated by helioseismology, predicts that the density inside the Sun varies from about 150 g cm⁻³ in the centre of the star, to 1 g cm⁻³ at half of the solar radius. The variation of density of matter with the solar radius is followed by identical variations on the local quantities of electrons and quarks. Moreover, the different type of quarks will also be affected by the local distribution of chemical elements (most noticeably Hydrogen and Helium) which lead to a not obvious distribution of up- and down-quarks. Therefore, we can anticipate that the current standard solar model combined with data coming from the next generation of the solar neutrino detections, will allow us to put much stronger constraints in the non-standard interactions of neutrinos.

In the next section, we review the current status of the standard solar model and neutrino production in the Sun’s core. In Section III, we present a summarised discussion about the current standard neutrino oscillation flavour model, and a generalized model for which neutrinos have new types of interactions with standard particles. In Section IV, we compute the neutrino spectra resulting from these new types of interactions. In the final section we discuss the results and their implications for the future neutrino experiments.
II. NEUTRINO PRODUCTION IN THE SUN’S CORE

A. Helioseismology and the standard solar model

During the last three decades helioseismology has provided solar physics with a tool that describes with unprecedented quality the internal structure of the Sun from its surface up to the deepest layers of the Sun’s interior. This has allowed astronomers to characterise with great precision the different solar neutrino sources. Equally, this discipline has stimulated the development of inversion techniques to probe the internal solar dynamics. Today an impressive agreement has been reached between the neutrino flux predictions and the neutrino flux measurements made by the existing neutrino detectors. The high quality of the helioseismology data has allowed to compute an exceptionally accurate model of the Sun’s interior - the standard solar model. The neutrino fluxes predictions of the solar model have an accuracy comparable to the current measurements made by particle accelerators or nuclear reactors.

The standard solar model in this study is obtained using a version of the one-dimensional stellar evolution code CESAM [25]. The code has an up-to-date and very refined microscopic physics (updated equation of state, opacities, nuclear reactions rates, and an accurate treatment of the microscopic diffusion of heavy elements), including the solar mixture of Asplund et al. [26, 27]. This solar model is calibrated for the present day solar data with a high accuracy. Therefore slightly different physical assumptions, will lead to different radial profiles of temperature, density and chemical composition, among other quantities. These changes result from readjustments of the Sun’s internal structure caused by the need to obtain the same total luminosity. In particular, the neutrino fluxes and sound speed profile will be very sensitive to the radial distributions of the previous quantities. As such, using the high precision data from helioseismology, it is possible to put strong constraints to the internal structure of the Sun and its neutrino fluxes [28, 35].

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The current uncertainty between the square of the sound speed profile inferred from helioseismology acoustic data and the one obtained from the standard solar model using the up-to-date photospheric abundances Asplund et al. [27] is smaller than 3% for any layer of the Sun’s interior. Although there is a difference between the sound speed profile computed using an older mixture of abundances by Grevesse and Sauval [36] or the new mixture of Asplund et al. [27], for this study these effects are negligible on the radial variation of electrons, protons and neutrons. This is even more so, since recent measurements of the solar metallicity abundances suggest that the sound speed difference of helioseismic data and standard solar model is reduced further [37].

Particularly relevant for our study is the radial profile of the electron, proton and neutron densities inside the Sun, since these quantities are fundamental ingredients to test the non-standard neutrino physics theories.

B. The solar neutrino sources

The neutrino fluxes produced in the nuclear reactions of the pp chains and CNO cycle have been computed for an updated version of the solar standard model, as discussed in the previous section. Figure 1 shows the location of the different neutrino emission regions of the nuclear reactions for an up-to-date SSM. In the Sun’s core, the neutrino emission regions occur in a sequence of shells, following closely the location of nuclear reactions, orderly arranged in a sequence dependent on their temperature. The helioseismology data and solar neutrino fluxes guaranties that such neutrino shells are known with a great accuracy. The leading source of the energy in the present Sun are the pp chains nuclear reactions, since the CNO cycle nuclear reactions contribute with less than 2%. The first reaction of the pp chains is the $^{\text{PP}}\nu$ reaction which has the largest neutrino emission shell, a region that extends from the centre to 0.30 $R_\odot$. The $^{\text{PeP}}\nu$ reaction has a neutrino emission shell which is similar to the $^{\text{PP}}\nu$ reaction, but with a shell of 0.25 $R_\odot$. These nuclear reactions are strongly dependent on the total luminosity of the star. Alternatively, the neutrino emission shells of $^{8}B-\nu$ and $^{7}Be-\nu$ extend up to 0.15 $R_\odot$ and 0.22$R_\odot$. It is interesting to notice that the maximum emission of neutrinos for the pp chains nuclear reactions, follows an ordered sequence (see figure 1): $^{8}B-\nu,^{7}Be-\nu, PeP-\nu$ and $^{PP}$-
v with the maximum emission located at 0.05, 0.06, 0.08 and 0.10 \( R_\odot \). The known neutrino emission shells of the different CNO cycle nuclear reactions are the following ones: \(^{15}\text{O} \nu\), \(^{17}\text{F} \nu\) and \(^{13}\text{N} \nu\). These shells are similar to the 8 \( B \nu\) emission shell. The \(^{13}\text{N} \nu\) have two independent shells: one in the Sun’s deepest layers of the core and a second shell located between 0.12 and 0.25 of \( R_\odot \). The emission of neutrinos for \(^{15}\text{O} \nu\), \(^{17}\text{F} \nu\) and \(^{13}\text{N} \nu\) shells is maximal at 0.04 – 0.05 of \( R_\odot \). The \(^{13}\text{N} \nu\) neutrinos have a second emission maximum which is located at 0.16 \( R_\odot \).

C. Neutrinos, Electrons and Quarks

The electron density \( n_e(r) = N_e \rho(r)/\mu_e(r) \) where \( \mu_e \) is the mean molecular weight per electron, \( \rho(r) \) the density of matter and \( N_e \), the Avogadro’s number. In the model we will consider the impact on the quarks up and down. Accordingly, the density of up and down quarks will be computed from a relation analogous to \( n_e(r), n_i(r) = N_i \rho(r)/\mu_i(r) \) (with \( i = u, d \)) where \( \mu_i(r) \) is the mean molecular weight per quark given by

\[
\mu_i(r) = \left[ (1 + \delta_{iu}) X(r) + \frac{3}{2} Y(r) + \frac{3}{2} Z(r) \right]^{-1}
\]

where \( i = u, d \) with \( X + Y + Z = 1 \). The distribution of electrons and up and down quarks, as a function of the radius of the Sun for the standard solar model, is shown in figure 2. The mean molecular weight per quark is dominated by Hydrogen and Helium since the only other elements included in \( Z \) like Carbon, Nitrogen, Oxygen and heavier elements contribute with a very small fraction to the solar plasma. Although the Z-variation can affect the evolution of the star in the way it affects the radiative transport [37], its impact on the \( si \) and \( ns \) MSW interactions for \( \mu_i(r), i = u, d \) is small since the relative radial variation between up- and down-quarks due to Z-variation is not significant.

III. MODEL OF NEUTRINO PHYSICS OSCILLATIONS

A. Basic neutrino physics

In the Standard Model, neutrinos interact with other particles only via weak standard interactions (\( si \)), which are described by the Lagrangian \( \mathcal{L}_{si} \) which can be decomposed into components describing the charged and neutral interactions [38–40]. Nevertheless, in the current study, we choose to write the Lagrangian \( \mathcal{L}_{si} \) as an effective interaction Lagrangian [40, 41], which at low and intermediate neutrino energies reads

\[
\mathcal{L}_{si} = -2\sqrt{2} G_F g^f_p \bar{\nu}_e \gamma_\mu L \nu_\alpha \left( \bar{f} \gamma^\mu P f \right)
\]

where \( f \) denotes a lepton or a quark, such as the \( u \)-quark and the \( d \)-quark, \( \nu_\alpha \) are the three light neutrinos (with the subscript \( \alpha = e, \mu, \tau \)), \( P \) is the chiral projector (is equal to \( R \) or \( L \) such that \( R, L \equiv (1 \pm \gamma^5)/2 \)) and \( g^f_p \) denotes the strength of the interaction (\( ns \)) as defined in the standard model between neutrinos of flavours \( \alpha \) and \( \beta \) and the \( P \)-handed component of the fermion \( f \). Specifically, the \( g^f_p \) coupling (left- and right-handed coupling, i.e., \( g^{f_u}_p \) and \( g^{f_d}_p \)) for the \( u \)-quark (and \( e \)- and \( t \)-quark) to the \( Z \)-boson corresponds to \( g^{f_u}_p = 1/2 - 2/3 \sin^2 \theta_w \) and \( g^{f_d}_p = -2/3 \sin^2 \theta_w \). Similarly, the \( g^f_p \) for the \( d \)-quark (and \( s \)- and \( b \)-quark) corresponds to \( g^{f_d}_p = 1/2 - 1/3 \sin^2 \theta_w \) and \( g^{f_s}_p = 1/3 \sin^2 \theta_w \), the \( g^f_p \) for the electron corresponds to \( g^{f_e}_p = -1/2 + \sin^2 \theta_w \) and \( g^{f_\mu}_p = \sin^2 \theta_w \) and the \( g^{f_\mu}_p \) for the neutrino (\( \nu_\alpha \) with \( \alpha = e, \mu, \tau \)) corresponds to \( g^{f_\mu}_p = 1/2 \) and \( g^{f_\tau}_p = 0 \). \( \theta_w \) is the Weinberg mixing angle [42, 43], with a typical value of \( \sin^2 \theta_w \approx 0.23 [44] \).

The evolution of a generic neutrino state \( \nu_\alpha \equiv (\nu_e, \nu_\mu, \nu_\tau)^T \) is described by a Schrödinger-like equation [38], that expresses the evolution of the neutrino between the flavour states [38] with the distance \( r \), from neutrinos that are produced in the Sun’s core until their arrival to the Earth’s neutrino detectors. The equation reads

\[
\frac{d\nu_\alpha}{dr} = H \nu_\alpha = (H_v + H_m) \nu_\alpha,
\]

where \( H \) is the total Hamiltonian, \( H_v \) and \( H_m \) are the Hamiltonian components expressions for vacuum and in matter flavour variations, such that \( H_v \equiv M^2 \rho_p/2p_v \) where \( M_\nu \) is the mass matrix of neutrinos (the term proportional to the neutrino momentum \( p_v \) is omitted here), and \( H_m \) is the Hamiltonian (a diagonal matrix of effective potentials) which depends on the properties of the solar plasma, i.e., the density and composition of the matter, such that \( H_m = diag(V_v, V_\mu, V_\tau) \).

The flavour evolution is described in terms of the instantaneous eigenstates of the Hamiltonian in matter \( \nu_{\nu m} = (\nu_{1m}, \nu_{2m}, \nu_{3m})^T \). These eigenstates are related to the flavour states by the mixing matrix in matter, \( U_m: \nu_\alpha = U^{m \alpha}_{\nu m} \).

B. The effective matter potential

As neutrinos propagate in the Sun’s interior, they will oscillate between the three flavour states \( \nu_e, \nu_\mu \) and \( \nu_\tau \) due to vacuum oscillations, however in the highly dense medium which is the Sun’s interior, contrary to their propagation in vacuum, the scattering of neutrinos with other elementary particles, like electrons, will enhance their oscillation between flavour states. Indeed, neutrinos propagating in a dense medium like the Sun (or Earth) have their flavour between states affected by the coherent forward scattering, i.e., coherent interactions of the neutrinos with the medium background [38]. The interaction of neutrinos with the medium proceeds through coherent forward elastic Charged-Current (\( cc \)) and Neutral-Current (\( nc \)) scatterings, which as usual are represented by the effective potentials \( V^{cc}_{\alpha} \) and \( V^{nc}_{\alpha} \) for each of the three type of neutrinos.

Therefore, at low energies, the potentials can be evaluated by taking the average of the effective four-fermion Hamiltonian due to exchange of \( W \) and \( Z \) bosons over the state describing the background medium. Accordingly, for a non-
relativistic un-polarized medium, for the effective potential of \(\nu_e, \nu_\mu, \nu_\tau\) neutrinos, one obtains
\[
V_\alpha = V^{cc}_\alpha + V^{nc}_\alpha, \tag{4}
\]
where \(\alpha = e, \mu, \tau\).

Let us consider that the solar internal medium is mainly composed of electrons, up-quarks and down-quarks as in protons and neutrons with the corresponding \(n_e(r), n_u(r)\) and \(n_d(r)\) local number densities. The contribution to \(\mathcal{H}_m\) due to the \(cc\) scattering of electron neutrinos \(\nu_e\) (produced in the Sun’s core) propagating in a homogeneous and isotropic gas of unpolarized electrons (like the electron plasma found in the Sun’s interior) is given by
\[
V^{cc}_e = \sqrt{2}G_F n_e(r) \tag{5}
\]
where \(G_F\) is the Fermi constant. For \(\nu_\mu\) and \(\nu_\tau\), the potential due to its \(cc\) interactions is zero for most of the solar interior since neither \(\mu\)’s nor \(\tau\)’s are present, therefore,
\[
V^{cc}_\mu = V^{cc}_\tau = 0 \tag{6}
\]
Generically, for any active neutrino, the \(V^{cc}_\alpha\) reads
\[
V^{cc}_\alpha = \delta_{\alpha e} \sqrt{2}G_F n_e(r) \tag{7}
\]
Analogously, one determines \(V^{nc}_\alpha\) for any neutrino due to \(nc\) interactions. Since \(nc\) interactions are flavour independent, these contributions are the same for neutrinos of all three flavours. The neutral-current \((nc)\) potential reads
\[
V^{nc}_\alpha = \sum_f \sqrt{2}G_F g^f_{\alpha} n_f(r) \tag{8}
\]
where \(\alpha = e, \mu, \tau\) and \(f = e, u, d, n_f(r)\) is number density of fermions, electrons, up-quarks \((u)\) and down-quarks \((d)\) as in protons \((uud)\) and neutrons \((udd)\). The factors \(g^f_{\alpha}\) are the axial coupling to fermions \(g^e_{\alpha} = -1/2 + 2\sin^2 \theta_w\), \(g^u_{\alpha} = 1/2 - 4/3\sin^2 \theta_w\) and \(g^d_{\alpha} = -1/2 + 2/3\sin^2 \theta_w\), see for example Giunti and Chung [45]). Therefore the effective potential [38] for any active neutrino due to the neutral-current \(V^{nc}_\alpha\) reads
\[
V^{nc}_\alpha = \sqrt{2}G_F \left[ g^e_{\alpha} n_e(r) + g^u_{\alpha} n_u(r) + g^d_{\alpha} n_d(r) \right]. \tag{9}
\]
where \(n_u(r)\) and \(n_d(r)\) are the analogue of \(n_e(r)\), i.e., the number density of up-quarks and down-quarks in the Sun’s interior.

Using equations (7) and (8) in equation (4), the effective potential for any active neutrino crossing the solar plasma reads
\[
V_\alpha = \sqrt{2}G_F \left[ \delta_{\alpha e} n_e + g^e_{\alpha} n_e + g^u_{\alpha} n_u + g^d_{\alpha} n_d \right]. \tag{10}
\]

When neutrinos propagate through matter, the forward scattering of neutrinos off the background matter will induce an index of refraction for neutrinos. This is the exact analogous to the index of refraction of light travelling through matter. However, the neutrino index of refraction will depend on the neutrino flavour, as the background matter contains different amounts of scatters for the different neutrino flavours.

The effective potentials \(V_\alpha\) are due to the coherent interactions of active flavour neutrinos with the medium through coherent forward elastic \(cc\) and \(nc\) scatterings.

Inside the Sun, as local matter is composed of neutrons, protons, and electrons, the effective potential \(V_\alpha\) for the different neutrino species (including \(\nu_e\) neutrinos) has a quite distinct form which depends on the local number densities \(n_e(r), n_u(r)\) and \(n_d(r)\), quantities which depend on the chemical composition (its metalicity \(Z\)) of the Sun’s interior. Nevertheless, at first approximation, since electrical neutrality implies locally an equal number density of protons \((uud)\) and electrons, \(V_\alpha\) takes a more simple form (equation 10), as the \(nc\) potential contribution of protons and electrons cancel each other. Therefore, only neutrons \((udd)\) contribute to \(V^{nc}_\alpha\). Hence the last two terms of equation (9) can be expressed as \(g^e_{\alpha} n_e(r)\) to only take into account the quark contribution for neutrons. In this expression \(n_n(r)\) is the local density of neutrons and the \(g^e_{\alpha}\) is the neutron coupling constant, it follows that \(g^e_{\alpha} = g^u_{\alpha} - 2g^d_{\alpha} = -1/2\), and equation (9) reads \(V^{nc}_\alpha = -\sqrt{2}/2G_F n_n(r)\). Now \(V_\alpha\) (equation 10) inside the Sun yields
\[
V_\alpha = \sqrt{2}G_F \left[ \delta_{\alpha e} n_e(r) - \frac{1}{2} n_n(r) \right]. \tag{11}
\]
where \(\alpha = e, \mu, \tau\).

As we will discuss later, only effective potential differences affect the propagation of neutrinos in matter [46], accordingly, one defines the potential difference between two neutrino flavours \(\alpha\) and \(\beta\) as
\[
V_{\alpha\beta} = V_\alpha - V_\beta, \tag{12}
\]
where \(\alpha, \beta = e, \mu, \tau\).

The Sun’s interior is a normal medium composed of nuclei (protons and neutrons) and electrons. Since the effective potential for muon and tau neutrinos, \(V_\alpha\) (with \(\alpha = \mu, \tau\) or a combination thereof) is due to the neutral current scattering only (see equation 11), this leads to \(V_{\mu\tau} = V_\mu - V_\tau = 0\). However, as the effective potential for electron neutrinos depends on the neutral and charged current scatterings, in this case
\[
V_{e\alpha} = \sqrt{2}G_F n_e(r), \tag{13}
\]
where \(\alpha = \mu, \tau\) or a combination thereof. Although for the Sun and Earth only charged current interactions with electrons are the only effective potential that contributes to the propagation of electron neutrinos, there are other types of non-typical matter, like the one found in the core of supernovae and in the early Universe for which the effective potential difference \(V_{\alpha\beta}\) has a much stronger dependence on the properties of the background plasma [43, 46].

C. Neutrino oscillation data parameters

As shown in the previous section, the neutrino flavour oscillations model is described with the help of 6 mixing parameters all of which are determined from experimental data [47].
that reason their contribution for 
P
 since the evolution of neutrinos in matter is adiabatic and for
trinos, leads to the following survival probability for electron neu-
the standard parametrization of the neutrino mixing matrix
manner to the vacuum-oscillation expression. Accordingly,
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oscillations have very close values [54]. The survival probability of solar neutrinos calculated in a model
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oscillations reverts to an effective theory of two neutrino flavour
survival probability of solar neutrinos calculated in a model
oscillations [53].

An overall fit to the data obtained from the different neu-
trino experiments: solar neutrino detectors, accelerators, at-
mospheric neutrino detectors and nuclear reactor experiments
suggests that the parameters of neutrino oscillations are the
following ones [48, 49]: \( \Delta m^2_{21} \approx 2.457 \pm 0.045 \times 10^{-3} \text{eV}^2 \) or
\( \Delta m^2_{31} \approx -2.449 \pm 0.048 \times 10^{-3} \text{eV}^2 \), \( \Delta m^2_{21} \approx 7.505 \pm
0.019 \times 10^{-5} \text{eV}^2 \), \( \sin^2 \theta_{12} = 0.304 \pm 0.013 \), \( \sin^2 \theta_{13} = 0.2188 \pm 0.001 \), \( \sin^2 \theta_{23} = 0.562 \pm 0.032 \) and \( \delta_{CP} = 2\pi/25 \) n
with \( n = 1, \ldots, 25 \).

In the limiting case where the value of the mass differ-
ences, \( \Delta m^2_{21} \) or \( \Delta m^2_{31} \), is large, or one of the angles of mixing
(\( \theta_{12}, \theta_{23}, \theta_{13} \)), the theory of three neutrino flavour osc-
illations reverts to an effective theory of two neutrino flavour
oscillations [53]. Balantekin and Yuksel have shown that the
survival probability of solar neutrinos calculated in a model
with two neutrino flavour oscillations or three neutrino flavour
oscillations have very close values [54].

D. The survival of electron neutrinos

Mostly motivated by solar neutrino data, the focus of this
work is the study of the propagation of electron neutrinos,
in particular to determine the survival probability of electron
neutrinos \( P_e (\equiv P(\nu_e \rightarrow \nu_e) \) arriving on Earth which have
their flavour changed due to vacuum and solar matter oscilla-
tions. Luckily, in the Sun \( P_e \) takes a particularly simple form,
since the evolution of neutrinos in matter is adiabatic and for
that reason their contribution for \( P_e \) can be cast in a similar
manner to the vacuum-oscillation expression. Accordingly,
the standard parametrization of the neutrino mixing matrix
leads to the following survival probability for electron neu-
trinos, \( P_e \) reads

\[
P_e = c^2_{13} c^2_{12} P^{ad}_{2} + s^2_{13} s^2_{12}
\]

where \( c_{ij} = \cos \theta_{ij}, s_{ij} = \sin \theta_{ij} \), and \( P^{ad}_{2d} \) reads

\[
P^{ad}_{2d} = \frac{1}{2} (1 + \cos (2\theta_{12}) \cos (2\theta_{13}))
\]

The matter angles, \( \theta_{12}^m \) and \( \theta_{13}^m \) which depends equally of the
fundamental parameters of neutrino flavour oscillation and
the properties of solar plasma are determined as follows:

- The mixing angle \( \theta_{12}^m \) is determined by

\[
\cos (2\theta_{12}^m) = -\frac{V^{*}_{12}}{\sqrt{V_{12}^2 + (A^{-1}_{12} \sin (2\theta_{12}))^2}}
\]

where the effective potential \( V_{12}(E, r) \) reads

\[
V_{12}(E, r) = c^2_{12} - A_{12}^{-1} \cos (2\theta_{12})
\]

where \( A_{12} = A_s/\Delta m^2_{12} \) and \( A_s = 2E V_{\alpha \beta} [53] \). The parameter \( A_s(E, r) \) consists of the effect of on the
electron neutrino propagation as defined by \( V_{\alpha \beta} \),
given by equation (13). In the specific case of elec-
tron neutrinos, \( A_s(E, r) = 2E \sqrt{2} G_F n_e (r) \) (with
\( V_{\alpha \beta} = \sqrt{2} G_F n_e (r) \)).

- The mixing angle \( \theta_{13}^m \), accordingly to Goswami and
Smirnov [55], is determined by

\[
\sin^2 (\theta_{13}^m) = \sin^2 (\theta_{13}) [1 + 2 A_{13}^2]
\]

with \( A_{13} = 2E V^o_{\alpha \beta}/\Delta m^2_{31} \), where \( V^o_{\alpha \beta} \) is the effective potential at the electron neutrino production radius \( r_o \),
i.e., \( V^o_{\alpha \beta} = \sqrt{2} G_F n_e (r_o) \). The value of \( r_o \) is different for the
different neutrino sources of the pp chains and CNO cycle.

E. New Neutrino Physics

In the presence of physics beyond the standard model [e.g.,
56], the neutral current interactions that are flavour diagonal
and universal in the standard model can have a more general
form. Hence, new interactions arise between neutrinos and
matter, which conveniently one defines as non-standard inter-
actions (nsi), these new neutrino interactions with fermions
are described by a new effective lagrangian [e.g., 41, 57, 58].
Accordingly, the classical lagrangian (equation 2) is general-
ized to take into account these new types of interactions pre-
viously forbidden. The new lagrangian reads

\[
\mathcal{L}_{nsi} = -2\sqrt{2} G_F \epsilon^{P}_{\alpha \beta} (\bar{\nu}_\alpha \gamma_\mu L \nu_\beta) (\bar{f} \gamma^\mu P f)
\]

where \( \epsilon^{P}_{\alpha \beta} \) is the equivalent of \( g_{\mu}^P \) for the standard interactions
(equation 2), which corresponds to the parametrization of the
strength of the non-standard interactions between neutrinos of
flavours \( \alpha \) and \( \beta \) and the \( P \)-handed component of the fermion
\( f \) [e.g., 56]. Without loss of generality we consider only neu-
trino interactions with up- and down-quarks [e.g., 59]. In
the latter Lagrangian, \( \epsilon^{P}_{\alpha \beta} \) corresponds to two classes of non-
standard terms: flavour preserving non-standard terms pro-
tional to \( \epsilon^{P}_{\alpha \beta} \) (known as non-universal interactions), and
flavour changing terms proportional to \( \epsilon^{P}_{\alpha \beta} \) with \( \alpha \neq \beta \).

Since the atoms and ions of the solar medium in which neu-
trinos propagate are non-relativistic, the vector part of the nsi
operator gives the dominant contribution for the interactions of
the neutrinos with the plasma of the Sun’s interior, in which
case the effective \( nsi \) coupling can be described by the following combination [57]: \( \epsilon_{\alpha\beta}^f = \epsilon_{\alpha\beta}^{f_P} + \epsilon_{\alpha\beta}^{f_D} \). These new kinds of neutrino interactions lead to a new effective potential difference to describe the propagation of neutrinos in matter [59]. Accordingly, the effective potential difference \( V_{\alpha\beta} \) is written as a generalization of the \( V_{\alpha\beta} \) obtained in the standard case: equations 11 and 13. Hence, \( V_{\alpha\beta} \) reads

\[
V_{\alpha\beta} = V_\epsilon \delta_{\alpha\epsilon} \delta_{\beta\epsilon} + \sqrt{2} G_F \sum_f \epsilon_{\alpha\beta}^f n_f (r) \tag{20}
\]

where \( \epsilon_{\alpha\beta}^f \) is the strength of \( nsi \) interaction of neutrinos with the medium. A more detailed discussion about the relations between \( \epsilon_{\alpha\beta}^f \) and \( \epsilon_{\alpha\beta}^{f_P} \) can be found in Gonzalez-Garcia and Maltoni [57]. Usually, \( \epsilon_{\alpha\beta}^f \) is considered as a free parameter to be adjusted to fit the solar observational data.

In this work, we study only the \( nsi \) interactions of electron neutrinos (\( \nu_e \)) with the solar plasma. Accordingly, as is common practice, we chose to take into account only the \( nsi \) coupling of electron neutrinos with the up-quarks and down-quarks of the solar plasma. Among others, Friedland et al. [60] have shown that the coupling of electron neutrinos with up-quarks is parametrized by a set of two independent parameters (\( \epsilon_N^e, \epsilon_D^e \)), and similarly the coupling of electron neutrinos with down-quarks is parametrized by another set of two independent parameters (\( \epsilon_N^d, \epsilon_D^d \)). Each of these parameters corresponds to a linear combination of the original parameters \( \epsilon_{\alpha\beta}^f \) which defines the strength of the non-standard neutrino interactions with fermions as defined in equation 19. In the appendix A we show the relation of \( \epsilon_D^\beta \) and \( \epsilon_N^\alpha \) with the parameters \( \epsilon_{\alpha\beta}^f \), for which \( f \) is either \( d \) or \( u \) since in our study we are only concerned about the interaction with down- and up-quarks of the solar plasma. A detailed account of the relevance of these quantities can be found in Gonzalez-Garcia and Maltoni [e.g., 57], Maltoni and Smirnov [e.g., 59], Friedland et al. [e.g., 60].

As in the case of standard neutrino interactions, for these \( nsi \) interactions the oscillations of neutrino flavour are still adiabatic, so the probability of electron neutrino survival is given by equation (14). However, in this case the quantity \( \cos (2\theta_{\mu}) \) has been redefined to take into account the new effective matter potential [59], accordingly

\[
\cos (2\theta_{\mu}) \approx V_{\mu\mu}^* \sqrt{\sum f \epsilon_{\alpha\beta}^f V_{\alpha\beta}^2 + 2 r_f \epsilon_N^\mu + A_{12}^* \sin (2\theta_{\mu} \cos (2\theta_{\mu})))^2} \tag{21}
\]

where \( V_{\mu\mu}^* \) reads

\[
V_{\mu\mu}^* (E, r) = c_{13}^2 - A_{12}^* \sin (2\theta_{12}) - 2 r_f \epsilon_{\alpha\beta}^f \tag{22}
\]

where \( r_f (r) = n_f (r)/n_e (r) \). Figure 3 shows the variation of the ratios \( r_u (r) \) and \( r_d (r) \) inside the star. The \( r_d (r) \) is smaller than \( r_u (r) \) because the star’s composition is dominated by free protons (ionized hydrogen). As such, for each down-quark there are two up-quarks.

![FIG. 3. Variation with the solar radius of the ratios \( r_u (r) = n_u (r)/n_e (r) \) (red curve) and \( r_d (r) = n_d (r)/n_e (r) \) (blue curve), and relative variation of up and down quarks \( n_u (r)/n_d (r) \) (black curve).](image)

**F. The electron neutrino probability survival**

The neutrino emission reactions of the pp chains and the CNO cycle are produced at high temperatures in distinct layers in the Sun’s core. Similarly, the neutrino flavour oscillations occur in the same regions. The average survival probability of electron neutrinos in each nuclear reaction region is given by

\[
\langle P_e (E) \rangle_j = N_j^{-1} \int_0^{R_j} P_e (E, r) \phi_j (r) 4 \pi r^2 dr \tag{23}
\]

where \( N_j \) is a normalization constant given by \( N_j = \int_0^{R_j} \phi_j (r) 4 \pi r^2 dr \) and \( \phi_j (r) \) is the electron neutrino emission function for the \( j \) nuclear reaction. \( j \) corresponds to the following electron neutrino nuclear reactions: \( PP, PeP, ^8B, ^7Be, ^13N, ^15O \) and \( ^17F \). \( \phi_j (r) \) defines the location where neutrinos are produced in each nuclear reaction \( j \) for which the production is maximum in the layer of radius \( r_j \) (Cf. figure 1). The neutrino fluxes produced by the different nuclear reactions are sensitive to the local values of the temperature, molecular weight, density and electronic density. In this study, we consider that all neutrinos produced in the solar nuclear reactions are of electron flavour as predicted by standard nuclear physics, therefore, the local density of quarks only affects the \( \langle P_e (E) \rangle_j \) by modifying the flavour of electron neutrinos by a new \( nsi \) interaction like the generalized MSW mechanism.

The survival probability of electron neutrinos \( \langle P_e (E) \rangle_j \) given by equation (23) is computed using equations (14), (21) and (22). Figures 4 and 5 show \( \langle P_e (E) \rangle_j \) for the different solar neutrino sources, either in the standard MSW or a generalized MSW. The different neutrino interaction models are described by a specific set of parameters: (\( \epsilon_N^e, \epsilon_D^e, \epsilon_N^d, \epsilon_D^d \)). Figures 4 and 5 top panels show \( \langle P_e (E) \rangle_j \) for the standard MSW mechanism in which case all the parameters mentioned above are equal to zero. The other panels of Fig-
FIG. 4. The survival probability of electron-neutrinos: the $P_e$ curves correspond to neutrinos produced in the nuclear reactions located at different solar radius. The three panels correspond to the following neutrino models of interaction: $si$—interaction with electrons (top panel), $nsi$—interaction with up-quarks with the coupling constants, $\epsilon^u_N = -0.30$ and $\epsilon^u_D = -0.22$ (middle panel), and $nsi$—interaction with down-quarks with coupling constant, $\epsilon^d_N = -0.16$ and $\epsilon^d_D = -0.12$ (bottom panel). The reference dotted-black curve defines the survival probability of electron-neutrinos in the centre of the Sun for which the $si$— or $nsi$—MSW flavour oscillation mechanism is maximum. The other coloured curves follow the same colour scheme shown in Figure 1.

FIG. 5. The survival probability of electron-neutrinos in function of the neutrino energy for the different regions of emission. The different panels show the difference between the survival probability of the different electron neutrino sources and the reference curve (dotted-black curve in Figure 4). The coloured curves follow the same colour scheme shown in Figures 1 and 4.

FIGURES 4 and 5 correspond to a generalized MSW mechanism for which the parameters ($\epsilon^u_N, \epsilon^d_N, \epsilon^u_D, \epsilon^d_D$) can have values
different of zero. Maltoni and Smirnov [59] among others have shown that only a relatively small ensemble of parameter combinations \((\epsilon_N^u, \epsilon_D^u, \epsilon_N^d, \epsilon_D^d)\) can be accommodated with the current set of neutrino flux observations. In this study, for convenience, we choose to focus on neutrino interactions for which electron neutrinos couples either with up-quarks (for which \(\epsilon_N^u = \epsilon_D^d = 0\)) or with down-quarks (for which \(\epsilon_N^d = \epsilon_D^u = 0\)). Specifically, we chose two fiducial sets of values \((\epsilon_N^u, \epsilon_D^u, f = u, d)\) of the ensemble of parameters that fits simultaneously the solar and KamLAND neutrino data sets with good accuracy. Figure 4 shows the survival probability of electron-neutrinos in the case of the \(n\text{si}--\)interaction for the parameters sets: \((\epsilon_N^u = -0.30, \epsilon_D^u = -0.22)\) and \((\epsilon_N^d = -0.16, \epsilon_D^d = -0.12)\). As discussed by Maltoni and Smirnov [59] these values correspond to the two parameters that best fit simultaneously both the solar and KamLAND neutrino data sets. Figures 4 and 5 middle panels show \(\langle P_e(E)\rangle_j\) for a neutrino up-quark interaction model, and Figures 4 and 5 bottom panels show \(\langle P_e(E)\rangle_j\) for a neutrino down-quark interaction model.

All the different neutrino interaction models have several common features. In general the \(\langle P_e(E)\rangle_j\) are very similar for low- and high-energy neutrinos. It is only for neutrinos with intermediate energy that it is possible to distinguish between the different models (Cf. figure 4). For neutrinos in this energy interval it is possible to distinguish two effects: one relates with the location of the different neutrino sources, and a second effect relates with the parameter values \((\epsilon_N^u, \epsilon_D^u, \epsilon_N^d, \epsilon_D^d)\) of the neutrino interaction model. In the former effect, the \(\langle P_e(E)\rangle_j\) differentiation results from the fact that \(\phi_j(r)\) are located at different solar radius, as shown in figure 1. Such effect arises equally in \(s\text{i}--\) and \(n\text{si}--\) neutrino interaction models. The second effect occurs only for \(n\text{si}--\) neutrino interaction models, and it is related with the radial distribution of up- and down-quarks (cf. Figure 2).

This latter effect is shown in figures 4 and 5 for the two fiducial models adopted in this study: a pure neutrino up-quark model \((\epsilon_N^u = \epsilon_D^d = 0)\) and a pure neutrino down-quark model \((\epsilon_N^d = \epsilon_D^u = 0)\). Accordingly, for neutrinos with an intermediate energy, the \(\langle P_e(E)\rangle_j\) corresponding to the neutrino up-quark interaction model has an impact of larger amplitude than the neutrino down-quark interaction model (compare middle and bottom panels in figure 5). For instance, this effect is very significant for the \(\langle P_e(E)\rangle_{1pp}\). Nevertheless, these preliminary results should be interpreted with caution, since each neutrino source only produces neutrinos within a limited range of energy, as such the \(n\text{si}--\)effect of \(\langle P_e(E)\rangle_j\) shown in figure 5 can be significantly reduced in the final neutrino spectrum of some solar neutrino sources. Indeed, we remind that the neutrinos emitted by \(\phi_j(r)\) are limited to a specific energy range for each \(j--\) nuclear reaction. As such only an energy portion of \(\langle P_e(E)\rangle_j\) affects the final emitted neutrino spectrum. This point will be discussed in more detail in the next section.

IV. THE SOLAR ELECTRON NEUTRINO SPECTRA

The solar energy spectrum of electron neutrinos from any specific nuclear reaction is known to be essentially independent of solar parameters, that is, the energy spectrum created by a specific nuclear reaction is the same independently of whether neutrinos are produced in an Earth laboratory or in the core of the Sun. Therefore, the neutrino energy spectrum of the different nuclear reactions, can be assumed to be equivalent to its Earth laboratory counterpart. A typical example of such spectra is the \(^8\text{B}\) neutrino energy spectrum emitted by the \(^8\text{B}\) nuclear reaction of the \(pp\) chains in the Sun’s core. This solar neutrino spectrum has been shown to be equivalent to several experimental determinations of the \(^8\text{B}\) neutrino spectrum [e.g. 61, 62]. Bahcall and Holstein [63], Napolitano et al. [64], among others, have shown that the \(^8\text{B}\) neutrino spectrum emitted in the Sun’s core is equal to the spectrum measured in the laboratory, as the surrounding solar plasma does not affect this type of nuclear reaction. The \(^8\text{B}\) neutrino spectrum measured in the laboratory agrees remarkably well with its theoretical prediction for neutrinos with an energy below 12 MeV, a small difference appearing only for high energy neutrinos. The experimental \(^8\text{B}\) neutrino spectrum deduced from four laboratory experiments shows a difference with the theoretical prediction at most of 1% [62, 65–68]. Accordingly, we will consider that the electron neutrino energy spectrum of a solar nuclear reaction at the specific location where these neutrinos are created is identical to the equivalent neutrino spectrum measured in the laboratory.

All neutrinos produced in the Sun’s nuclear reactions are of electron neutrino type. It is only during the propagation phase that these neutrinos vary their flavour between electron, \(\tau\) and \(\mu\). Suitably, we define the original energy spectrum of electron neutrinos by \(\Psi_e^o(E)\) and the end energy spectrum of neutrinos after the neutrino flavour oscillations by \(\Psi_e^\circ(E)\). The first spectrum, which is identical to the neutrino spectrum obtained in an Earth’s laboratory, relates to the neutrinos produced in nuclear reactions (see figure 1). The latter spectrum corresponds to neutrinos that have their flavour modified by the vacuum oscillations and the generalized MSW oscillation mechanism.

Conveniently, the neutrino spectra \(\Psi_e^o(E)\) and \(\Psi_e^\circ(E)\) associated to each of the different solar nuclear reactions of the \(pp\)-chain and CNO-cycle are labelled by an unique subscript \(j\) which can take one of these values: \(PP\), \(HeP\), \(^{13}\text{N}\), \(^{15}\text{O}\) and \(^{17}\text{F}\). Hence, the two previous neutrino energy spectra have a simple relation, it reads

\[
\Psi_e^\circ_{e,j}(E) = \langle P_e(E)\rangle_j \Psi_e^s_{e,j}(E),
\]

where \(\langle P_e(E)\rangle_j\) is the survival probability of an electron neutrino of energy \(E\). Figure 6 shows the shape of several neutrino spectra \(\Psi_e^\circ_{e,j}(E)\). The final neutrino energy spectrum \(\Psi_e^\circ_{e,j}(E)\) is significantly different from the original spectrum \(\Psi_e^s_{e,j}(E)\). Indeed, while \(\Psi_e^s_{e,j}(E)\) depends only on the properties of the nuclear reaction, \(\Psi_e^\circ_{e,j}(E)\) becomes distinct from \(\Psi_e^s_{e,j}(E)\) due to the contribution of neutrino flavour oscillations. Specifically, the \(\Psi_e^\circ_{e,j}(E)\) depends on the fundamen-
tal parameters related with the neutrino vacuum oscillations through the (generalized) MSW oscillation mechanism, which depends on the local densities of electrons and quarks, and the nsi—coupling constants [69]. As discussed previously, all these effects are taken into account in \( \langle P_{\nu_e}(E) \rangle_j \) (equation 23). In this study, we do not include the mono-energetic spectral lines of pp chains nuclear reactions \( PeP \) and \( ^7Be \). Although, the previous result (equation 24) also holds for these two neutrino sources (corresponds to the sources marked with the subscript \( ^* \) in figure 1), we opt for not including them in this study, since for these neutrino sources other solar plasma properties contribute to change the shape of the neutrino spectral lines.

Figure 6 shows the spectra of electron neutrinos for some of the leading nuclear reactions of the Sun’s core. The general shape of the spectra \( \Psi_{\nu_e,j}(E) \) (equation 24) is a combination of the neutrino spectrum of the nuclear reaction \( \Psi_{\nu_e,j}(E) \), and \( \langle P_{\nu_e}(E) \rangle_j \) which depends of local density of electrons, down-quarks and up-quarks, as well as of the nsi- parameters of the generalized MSW mechanism. For the specific set of nsi-parameters discussed in this study, clearly the \( HeP \) and \( ^8B \) neutrino emission shows the larger variation of the shape of their spectra.

In both cases the interaction of neutrinos with (up- and down-) quarks leads to neutrino spectra with quite distinct shapes (blue and green areas in Figure 6) from the ones found in the standard MSW neutrino interaction (red area in Figure 6). Equally important is the fact that it is possible to distinguish between the two neutrino models of interaction with quarks, since each model depends differently of the neutrino energy. The \( ^{15}O \) and \( ^{17}F \) nuclear reactions also show neutrino spectra with different shapes, although in this case the impact of the nsi—interactions is much less pronounced than in the previous case, at least for the current set of parameters. For the two other nuclear reactions, \( PeP \) and \( ^{13}N \), the impact of the nsi—interactions is very small. This is somehow expected since the energy of the neutrinos emitted in these nuclear reactions is relatively small. For this neutrino energy range the flavour oscillations are dominated by vacuum oscillations and are almost independent of matter oscillations.
FIG. 7. The $\Psi^\circ_{eB}(E)$ is the electron solar neutrino spectrum for the standard MSW effect (red area) with the error bar computed for the forthcoming LENA experiment. The error (black lines) in the spectrum shape is computed assuming the error in the survival probability is $P_\nu(E) \pm 0.025$, which corresponds to 5 years of the LENA measurements. The coloured curves follow the same colour scheme shown in Figure 6. For clarity we have not included the error bar in the two other curves. Nevertheless, we note that the error bars for the other curves are identical to this one.

V. CONCLUSION

In this study we have computed the expected alteration in the shape of some leading solar neutrino spectra resulting from neutrinos having a new type of interactions with up- and down-quarks, identical to the MSW oscillations of neutrinos with electrons. This new type of matter interaction, also known as generalized MSW oscillations, depends on the specific properties of the neutrino interaction model but also of the local thermodynamic properties of the Sun’s interior.

The study shows that the neutrino spectra of the different solar nuclear reactions have quite distinct sensitivities to the new neutrino physics. The $HeP$ and $^8B$ neutrino spectra have their shapes more affected by the new interaction between neutrinos and quarks. The $^{15}O$ and $^{17}F$ neutrino spectra also have a small alteration to their shapes, but these effects are much less pronounced than in the previous case. The impact of new physics in the $PP$ and $^{13}N$ spectra is also very small.

The new generation of neutrinos experiments such as Low Energy Neutrino Astronomy [LENA, 6], Jiangmen Underground Neutrino Observatory [JUNO, 7] Jinping Neutrino Experiment [Jinping, 10], Deep Underground Neutrino Experiment [DUNE, 8], and NOvA Neutrino Experiment [NOvA, 9], will allow to test some of new neutrino physics theories. The most promising evidence to discover $nsi-$ in solar neutrino data is the precise measurement of the $^8B$ spectrum. Conveniently, we have estimated how the experimental error of the next generation of detectors like LENA [70] could affect our conclusion. In Figure 7 is show an error bar estimation on the $^8B$ spectrum computed assuming the error in the survival probability is $P_\nu(E) \pm 0.025$, which is the precision possible to be obtained for the electron neutrino survival probability after 5 years of LENA measurements [70]. Even in a relatively short period of 5 years of neutrino observations, it is already possible to find if neutrinos are experiencing flavour oscillations due to their interaction with quarks. Indeed, the identification by a future solar neutrino detector of a strong distortion in the shape of the solar neutrino spectrum, like the $^8B$ neutrino spectrum compared to the one predicted by the standard solar model, will constitute a strong indication for the existence of interactions between neutrinos and quarks in the Sun’s core. The location and magnitude of the distortion of the solar spectrum should give us some indication about the type of interaction (i.e., up- and down-quarks or both).

In conclusion, we have shown that in the near future neutrino spectroscopic measurements will be used to infer the new interaction between neutrinos and quarks. This will be an important and totally independent way of testing new neutrino physics interaction models.

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Appendix A: dimensionless parameters encoding the deviation from standard interactions

The interactions of neutrinos with matter in the theoretical framework of the non-standard model [e.g., 57] can be described by the Lagrangian term given by equation 19. In the following, it is assumed that electron neutrinos couples only with the up-quarks and down-quarks of the solar plasma (see section III E for details). For convenience, we adopt the parametrization of Gonzalez-Garcia and Maltoni [57], Maltoni and Smirnov [59], Friedland et al. [60] in which the coupling of electron neutrinos with either up-quarks or down-quarks of the solar plasma is parametrized by a set of two independent parameters $(\epsilon^f_N, \epsilon^f_D)$ or $(\epsilon^f_e, \epsilon^f_\mu)$. Accordingly, the coefficients $\epsilon^f_D$ and $\epsilon^f_N$ relate to the original parameters $\epsilon_{\alpha\beta}$ as

$$\epsilon^f_D = c_{12}s_{13}R e \left[ e^{i\delta_{CP}} \left( s_{23}\epsilon^f_{e\mu} + c_{23}\epsilon^f_{e\tau} \right) \right]$$

$$-(1 + s_{13}^2) c_{23}s_{23} Re \left( \epsilon^f_{e\tau} \right)$$

$$-c_{13}^2 \left( \epsilon^f_{ee} - \epsilon^f_{e\mu} \right) + \frac{s_{23}^2 - s_{13}^2s_{23}^2}{2} \left( \epsilon^f_{e\tau} - \epsilon^f_{e\mu} \right)$$

(A1)

and

$$\epsilon^f_N = c_{13} \left( c_{23}\epsilon^f_{e\mu} - s_{23}\epsilon^f_{e\tau} \right) + s_{13}e^{-i\delta_{CP}} \left[ s_{23}^2\epsilon^f_{e\mu} - c_{23}^2\epsilon^f_{e\tau} + c_{23}s_{23} \left( \epsilon^f_{e\tau} - \epsilon^f_{e\mu} \right) \right]$$

(A2)
As in this work we are only interested in the interaction of neutrinos with the solar plasma, we will consider at a time the following values of $f$: $e$, $u$ and $d$. A detailed discussion about the relevance of this parametrization can be found in Gonzalez-Garcia and Maltoni [e.g., 57], Friedland et al. [e.g., 60].

[1] C. K. Jung, T. Kajita, T. Mann, and C. McGrew. Oscillations of Atmospheric Neutrinos. Annual Review of Nuclear and Particle Science, 51:451–488, 2001. doi:10.1146/annurev.nucsci.51.101701.132421

[2] T. Kajita and Y. Totsuka. Observation of atmospheric neutrinos. Reviews of Modern Physics, 73:85–118, January 2001. doi:10.1103/RevModPhys.73.85

[3] Q. R. et al. Ahmad. Measurement of the Rate of Interactions $\nu_e + d \rightarrow p + p + e^-$ Produced by $^8$B Solar Neutrinos at the Sudbury Neutrino Observatory. Physical Review Letters, 87(7):071301, August 2001. doi:10.1103/PhysRevLett.87.071301

[4] R. Davis, D. S. Harmer, and K. C. Hoffman. Search for Neutrinos from the Sun. Physical Review Letters, 84:2012–2019, May 1998. doi:10.1103/PhysRevLett.84.2012

[5] W. C. Haxton, R. G. Hamish Robertson, and A. M. Serenelli. Solar Neutrinos: Status and Prospects. Annual Review of Astronomy and Astrophysics, 51:21–61, August 2013. doi:10.1146/annurev-astro-081811-125539

[6] M. et al. Wurm. The next-generation liquid-scintillator neutrino observatory LENA. Astroparticle Physics, 35:685–732, June 2012. doi:10.1016/j.astropartphys.2012.02.011

[7] P. et al. An. Neutrino physics with JUNO. Journal of Physics G Nuclear Physics, 43(3):030401, March 2016. doi:10.1088/0954-3899/43/3/030401

[8] A. de Gouvêa and K. J. Kelly. Non-standard neutrino interactions at DUNE. Nuclear Physics B, 908:318–335, July 2016. doi:10.1016/j.nuclphysb.2016.03.013

[9] A. Friedland and I. M. Shoemaker. Searching for Novel Neutrino Interactions at NOvA and Beyond in Light of Large theta_13. ArXiv e-prints:1207.6642, July 2012.

[10] J. F. et al. Beacom. Letter of Intent: Jinping Neutrino Experiment. ArXiv e-prints:1602.01733, February 2016.

[11] A. et al. Bandyopadhyay. Physics at a future Neutrino Factory and super-beam facility. Reports on Progress in Physics, 72(10):106201, October 2009. doi:10.1088/0034-4885/72/10/106201

[12] A. et al. de Gouvea. Neutrinos. ArXiv e-prints:1310.4340, October 2013.

[13] A. B. Balantekin and H. Yüksel. Physics potential of solar neutrino experiments. Nuclear Physics B Proceedings Supplements, 138:347–349, January 2005. doi:10.1016/j.nuclphysbps.2004.11.080

[14] A. B. Balantekin, J. F. Beacom, and J. M. Fetter. Matter-enhanced neutrino oscillations in the quasi-adiabatic limit. Physics Letters B, 427:317–322, May 1998. doi:10.1016/S0370-2693(98)00231-7

[15] I. Lopes. Search for Global f-Modes and p-Modes in the $^8$B Neutrino Flux. The Astrophysical Journal Letters, 777:L7, November 2013. doi:10.1088/2041-8205/777/1/L7

[16] A. Serenelli, C. Peña-Garay, and W. C. Haxton. Using the standard solar model to constrain solar composition and nuclear reaction S factors. Phys. Rev. D, 87(4):043001, February 2013. doi:10.1103/PhysRevD.87.043001

[17] I. P. Lopes and J. Silk. Solar Neutrinos: Probing the Quasisothermal Solar Core Produced by Supersymmetric Dark Matter Particles. Physical Review Letters, 88(15):151303, April 2002. doi:10.1103/PhysRevLett.88.151303

[18] R. et al. Wendell. Atmospheric neutrino oscillation analysis with subleading effects in Super-Kamiokande I, II, and III. Physical Review D, 81(9):092004, May 2010. doi:10.1103/PhysRevD.81.092004

[19] P. et al. Adamson. Electron Neutrino and Antineutrino Appearance in the Full MINOS Data Sample. Physical Review Letters, 110(17):171801, April 2013. doi:10.1103/PhysRevLett.110.171801

[20] K. Abe, J. Adam, H. Aihara, T. Akiri, C. Andreopoulos, S. Aoki, A. Ariga, T. Ariga, S. Assylbekov, D. Autiero, and et al. Observation of Electron Neutrino Appearance in a Muon Neutrino Beam. Physical Review Letters, 112(6):061802, February 2014. doi:10.1103/PhysRevLett.112.061802

[21] O. G. Miranda and H. Nunokawa. Non standard neutrino interactions: current status and future prospects. New Journal of Physics, 17(9):095002, September 2015. doi:10.1088/1367-2630/17/9/095002

[22] T. Ohlsson. Status of non-standard neutrino interactions. Reports on Progress in Physics, 76(4):044201, April 2013. doi:10.1088/0034-4885/76/4/044201

[23] I. Girardi, D. Meloni, and S. T. Petcov. The Daya Bay and T2K results on sin^2 13 and non-standard neutrino interactions. Nuclear Physics B, 886:31–42, September 2014. doi:10.1016/j.nuclphysb.2014.06.014

[24] S. Turkc-Chezze and I. Lopes. Toward a unified classical model of the sun - On the sensitivity of neutrinos and helioseismology to the microscopic physics. The Astrophysical Journal, 408:347–367, May 1993. doi:10.1086/172592

[25] P. Morel. CESAM: A code for stellar evolution calculations. A & A Supplement series, 124, 597, September 1997. doi:10.1051/aas:1997209

[26] M. Asplund, N. Grevesse, and A. J. Sauval. The Solar Chemical Composition. In T. G. Barnes, III and F. N. Bash, editors, Chemical Composition of the Sun: A New Step Towards a Complete Picture?, volume 336 of Astronomical Society of the Pacific Conference Series, San Francisco, page 25, September 2005.

[27] M. Asplund, N. Grevesse, A. J. Sauval, and P. Scott. The Chemical Composition of the Sun. Annual Review of Astronomy & Astrophysics, 47:481–522, September 2009. doi:10.1146/annurev.astro.46.060407.145222

[28] S. Turkc-Chezze and S. Couvidat. Solar neutrinos, helioseismology and the solar internal dynamics. Reports on Progress in Physics, 74(8):086901, August 2011. doi:10.1088/0034-4885/74/8/086901

[29] S. Turkc-Chezze, S. Couvidat, L. Piau, J. Ferguson, P. Lambert, J. Ballot, R. A. Garcìa, and P. Nghiem. Surprising Sun: A New Step Towards a Complete Picture? Phys. Rev. Letters, 93(21):211102, November 2004. doi:10.1103/PhysRevLett.93.211102

[30] J. N. Bahcall, S. Basu, M. Pinsoneault, and A. M. Serenelli. Helioseismological Implications of Recent Solar Abundance Determinations. The Astrophysical Journal, 618:1049–1056, January 2005. doi:10.1086/426070

[31] J. N. Bahcall, A. M. Serenelli, and S. Basu. New SolarOpacities, Abundances, Helioseismology, and Neutrino Fluxes.
[68] O. S. Kirsebom, S. Hyldegaard, M. Alcorta, M. J. G. Borge, J. Büscher, T. Eronen, S. Fox, B. R. Fulton, H. O. U. Fynbo, H. Hultgren, A. Jokinen, B. Jonson, A. Kankainen, P. Karvonen, T. Kessler, A. Laird, M. Madurga, I. Moore, G. Nyman, H. Penttilä, S. Rahaman, M. Reponen, K. Riisager, T. Roger, J. Ronkainen, A. Saastamoinen, O. Tengblad, and J. Äystö. Precise and accurate determination of the B8 decay spectrum. Physical Review C, 83(6):065802, June 2011. doi:10.1103/PhysRevC.83.065802

[69] I. Lopes. Probing the Sun’s inner core using solar neutrinos: A new diagnostic method. Physical Review D, 88(4):045006, August 2013. doi:10.1103/PhysRevD.88.045006

[70] R. Möllenberg, F. von Feilitzsch, D. Hellgartner, L. Oberauer, M. Tippmann, J. Winter, M. Wurm, and V. Zimmer. Detecting the upturn of the solar $^8$B neutrino spectrum with LENA. Physics Letters B, 737:251–255, October 2014. doi:10.1016/j.physletb.2014.08.053