

# Sterile Neutrino Decays Face Constraints on the Flux of $\bar{\nu}_e$ from the Sun

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(Dated: November 19, 2019)



## I. INTRODUCTION

The large solar neutrino flux at the Earth provide a unique tool to perform precision measurements of neutrino properties. Beyond the pivotal role solar neutrinos played in the discovery that neutrinos have masses and mix [], they also provide important constraints on Solar models [] and on generic physics beyond the Standard Model (SM) []. Already before the resolution to the solar neutrino puzzle, it was recognised that solar neutrinos are very sensitive to fast decays of the  $\nu_1$  and  $\nu_2$  mass eigenstates []. Although such scenarios are constrained very effectively due to the astronomical distances travelled by solar neutrinos and our knowledge of the Sun's interior from other astronomical probes [], yet another feature explored in the literature is important for new physics searches. The flux of antineutrinos from the Sun at the MeV energies is negligible, which remains an excellent approximation down to tens of keV in energy [1]. Combined with the larger detection cross section for  $\bar{\nu}_e$  compared to that of  $\nu_e$ , this makes solar neutrino experiments sensitive to very small fluxes of antineutrinos [2, 3]. The current sensitivity reaches values as small as hundred-thousandths of the  $^8B$  neutrino flux [4–7].

One of the simplest ways to generate a solar antineutrino flux is through Lepton number violation (LNV). Beyond neutrino-antineutrino oscillations, which are suppressed by the small neutrino mass over the energy, LNV can also be manifested through neutrino decay. For instance, if a pseudo-goldstone boson  $J$  associated with the breaking of Lepton number, the majoron, exists [], solar antineutrinos may be abundantly produced from the decay  $\nu_2 \rightarrow \bar{\nu}_1 J$ . This possibility is, in fact, quite general and can be realised in any model with LNV with neutrinos that decay sufficiently fast, be they  $\nu_3$ ,  $\nu_2$ , or a new mostly-sterile Majorana state  $\nu_4$  (see Ref. [8] for an early discussion in the context of a 17 keV sterile). Other potential sources of  $\nu \rightarrow \bar{\nu}$  conversions include spin-flavour precession [9, 10], where the coupling of a large neutrino magnetic moment to the Solar magnetic field induces  $\nu_e \rightarrow \bar{\nu}_\mu$  conversions, which subsequently lead to a flux of  $\bar{\nu}_e$  due to standard flavour conversions.

In this work, we focus instead on a new possibility motivated by recent proposals to explain the short-baseline experimental anomalies with so-called visible sterile neutrino decays []. These models introduce a sterile neutrino field to the SM,  $\nu_s$ , which has large couplings to electron-neutrinos via a new bosonic mediator  $B$ . This can be done in a gauge invariant way by coupling the new mediator purely to  $\nu_s$  and admitting large mixing between the heaviest neutrino state,  $\nu_4$ , and the electron flavour. Independently of the underlying model, if the new mediator is allowed to decay to a pair of active neutrinos, then one unavoidably introduces a source of antineutrinos for every  $\nu_4$  decay of type  $\nu_4 \rightarrow \nu B \rightarrow \nu \nu \bar{\nu}$ . If neutrinos are Majorana, then an even larger flux of antineutrinos is induced by decays of the type  $\nu_4 \rightarrow \bar{\nu} B \rightarrow \nu \bar{\nu} \bar{\nu}$ .

The most stringent upper limits on an undistorted flux of solar  $\bar{\nu}_e$  from  $^8B$  are given by KamLAND [5]

$$P_{\nu_e \rightarrow \bar{\nu}_e}^{\text{KamLAND}}(E_\nu \geq 8.3 \text{ MeV}) < 5.3 \times 10^{-5}, \quad (1)$$

and Borexino [6]

$$P_{\nu_e \rightarrow \bar{\nu}_e}^{\text{Borexino}}(E_\nu \geq 1.8 \text{ MeV}) < 7.2 \times 10^{-5}. \quad (2)$$

SuperKamiokande (SK) also provides limits at the highest energies, with the most stringent bounds coming from a preliminary analysis of all SK-IV data [7]

$$P_{\nu_e \rightarrow \bar{\nu}_e}^{\text{SK-IV}}(E_\nu \geq 9.3 \text{ MeV}) \lesssim 1.0 \times 10^{-4}. \quad (3)$$

In addition to these, SNO has also set limits at the level of  $P_{\nu_e \rightarrow \bar{\nu}_e}^{\text{SNO}}(E_\nu \in [4, 14.8] \text{ MeV}) < 8.3 \times 10^{-3}$  [4]. All the limits are at 90 C.L. and assume a total  $^8B$  flux of  $5.94 \times 10^6 \text{ cm}^{-2} \text{ s}^{-1}$ . At the lowest energies, a bound can also be obtained by noting that the number of elastic  $\nu$ - $e$  scattering events in solar neutrino experiments decreases if too many  $\nu_4$  states are produced, both due to lower  $\bar{\nu}_e$ - $e$  cross sections and suppressed  $\nu_e$  flux. These effects, however, are insensitive to variations of the total  $\nu_e$  flux below the percent level.

The decay of active neutrinos to invisible final states has received great interest in the past [11, 12]. [8]  $\nu_4 \rightarrow \bar{\nu}_e \phi$  in the context of a 17 keV sterile and Majoron models. Here, for the first time, we consider antineutrinos produced in an intermediate decay, namely,  $\nu_4 \rightarrow \nu_\alpha \phi \rightarrow \nu_e \nu_e \bar{\nu}_e$ .

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## II. VISIBLE NEUTRINO DECAYS

Our analysis is restricted to the Dirac neutrino case, although our bounds would be even stronger if neutrinos were Majorana. This is because the lepton number violating decays  $\nu_4 \rightarrow \bar{\nu}_e B$  would be allowed, providing an even larger source of solar  $\bar{\nu}_e$ .

Due to mixing, sterile neutrinos with masses below the MeV would be produced in the Sun via the same processes responsible for  $\nu_e$  production at a rate  $|U_{e4}|^2$  times smaller. Once produced, the  $\nu_4$  mass eigenstates immediately decay to a massless neutrino and a boson, which may be a scalar or a vector boson. The boson then promptly decays to a neutrino-antineutrino pair, giving rise to our signal. Overall, the process of interest is

$$\nu_4(E_\nu) \rightarrow \nu_e(E_1) + B(E_B) \rightarrow \nu_e(E_2) + \bar{\nu}_e(E_3). \quad (4)$$

We now summarize the decay rates for a heavy Dirac neutrino decaying to a mass active neutrino flavour, and a boson  $B$ , quoting the results for the scalar  $B = \phi$  and vector  $B = Z'$  cases. The heavy neutrino is assumed to be polarised with a definite helicity  $h$ . For most cases of interest,  $E_\nu \gg m_4$ , so if  $\nu_4$  is produced in Weak interactions, the right-handed  $\nu_4$  population is negligible. Nevertheless, due to the assumption of parity conservation for the  $B$  interactions with neutrinos, one can compute the helicity flipping (HF) and helicity conserving (HC) decay channels by noting that

$$\begin{aligned} d\Gamma(\nu_4^{h=-1} \rightarrow \nu_L B) &= d\Gamma(\nu_4^{h=1} \rightarrow \nu_R B), \\ d\Gamma(\nu_4^{h=1} \rightarrow \nu_L B) &= d\Gamma(\nu_4^{h=-1} \rightarrow \nu_R B). \end{aligned} \quad (5)$$

In this way, all HF decay rates are given by  $d\Gamma(\nu_4^{h=1} \rightarrow \nu_L B)$  and all HC channels by  $d\Gamma(\nu_4^{h=-1} \rightarrow \nu_L B)$ . Assuming heavy neutrinos to be ultra-relativistic, we find the decay rates below, in agreement with Refs [ ].

$\nu_4^h \rightarrow \nu_L \phi$ :

$$|\mathcal{M}_h|^2 = \frac{m_4^2}{2} \left[ (1+h)(1-r^2) + 2h \frac{E_1}{E_\nu} \right] \quad (6)$$

$\nu_4^h \rightarrow \nu_L Z'$ :

$$|\mathcal{M}_h|^2 = \frac{m_4^2(1-r^2)}{2r^2} \left[ (1-h) + (1+h)2r^2 - 2h \frac{E_1}{E_\nu} \frac{1-2r^2}{1-r^2} \right]. \quad (7)$$

## III. THE SIGNAL

To leading order in the small mixing angles, the number of IBD events in a given experiment can be computed

as

$$\frac{dN_{\text{events}}}{dE_\nu dE_1 dE_3} = \mathcal{N} \frac{d\Phi^{\nu_4}}{dE_\nu} \frac{dP^{\text{dec}}}{dE_1 dE_3} \sigma^{\text{IBD}}(E_3) \overline{P_{ee}}(E_3), \quad (8)$$

where  $\mathcal{N}$  stands for total exposure of the experiment and

$$\begin{aligned} \frac{d\Phi^{\nu_4}}{dE_\nu} &= |U_{e4}|^2 \frac{d\Phi^{\nu_e}}{dE_\nu}, \\ \frac{dP^{\text{dec}}}{dE_1 dE_3} &= \frac{1}{\Gamma_{\nu_h} \Gamma_{Z'}} \frac{d\Gamma_{\nu_h \rightarrow \nu_e Z'}}{dE_1} \frac{d\Gamma_{Z' \rightarrow \nu_e \bar{\nu}_e}}{dE_2}. \end{aligned} \quad (9)$$

Note that Eq. (8) is the analogue of Eq. (18) from Ref. [13], and is simpler since we work with very long baselines and under the assumption that the number of initial  $\nu_\mu$  states is negligible.

Inverse beta decay (IBD) of free protons has a large cross section for MeV electron antineutrinos and is the primary detection channel for reactor neutrinos. If compared to the neutrino-electron elastic scattering cross section (see Fig. 1), it is orders of magnitude larger and offers a much cleaner signal. After produced, the positron annihilates and the final state neutron is quickly captured by Hydrogen. This results in a double-bang signature with the positron kinetic energy  $T_e = E_\nu - 1.8$  MeV, and a later emission of a  $\approx 2.2$  MeV gamma which greatly reduces backgrounds. The cross section for this process is well understood at high [14] and low [15] energies, and relatively simple formulae that are valid at all energies have been provided by Ref. [16]. Here we implement the latter calculation, which is provided as machine-friendly data files by Ref. [17].

The largest flux of solar neutrinos at the energies we are interested comes from  $^8B$ . This has been extensively studied in the literature, and here we implement the fluxes provided in Ref. [18]. For the total flux from  $^8B$  and its uncertainty, we use the high-metallicity fluxes from Ref. [19].

## IV. RESULTS

## V. FURTHER CONSEQUENCES

- a. *SN1987A neutrino events* lack of events + time delay
- b. *Cosmology*

## VI. CONCLUSIONS

As pointed out by Li *et al*, JUNO will be able to improve on such limits [20].

SuperKamiokande with Gd – lower thresholds and larger efficiency. In fact, the presence of Gd would allow SuperK to lower the  $\bar{\nu}_e$  detection threshold to neutrino energies as low as the IBD threshold provided  $E_e > 0.8$  MeV [21].

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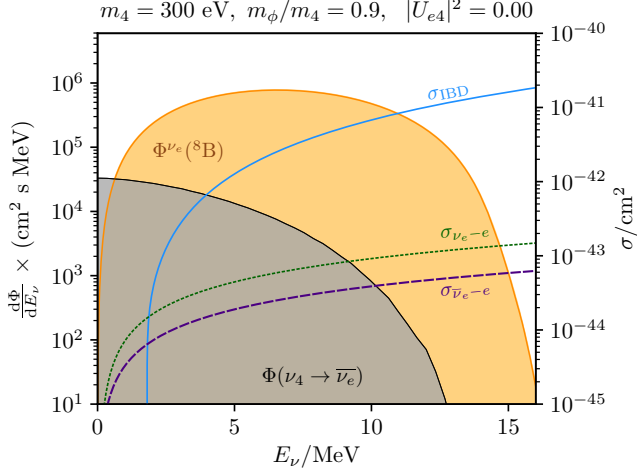


FIG. 1. The solar neutrino energy spectrum from  $^8\text{B}$  (shaded orange) and from the decays of  $\nu_h$  (shaded grey). We also show the inverse beta decay (IBD) and neutrino-electron scattering cross sections on an overlaid axis.

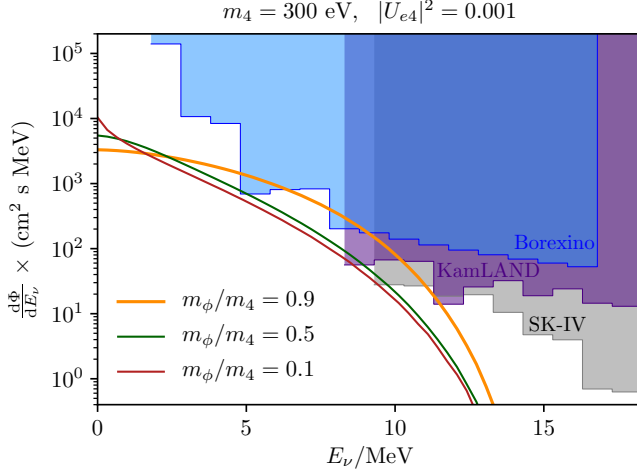


FIG. 2. The experimental limits on solar  $\bar{\nu}_e$  at 90% C.L. as a function of the neutrino energy. The shaded regions are excluded by Borexino (blue), KamLAND (purple) and SuperK-IV (grey). Three different new physics predictions are also shown as solid curves assuming  $|U_{\mu 4}| = |U_{\tau 4}| = 0$ .

## ACKNOWLEDGMENTS

The authors would like to thank Linyan Wan for useful comments on the SuperKamiokande searches.

## Appendix A: Visible Decays

We now summarise the decay rates for a heavy Dirac neutrino decaying to a mass active neutrino flavour, and a boson  $B$ , quoting the results for the scalar ( $B = \phi$ ) and vector ( $B = Z'$ ) cases. The heavy neutrino is as-

sumed to be polarised with a definite helicity  $h$ . For most cases of interest,  $E_\nu \gg m_4$ , so if  $\nu_4$  is produced in Weak interactions, the right-handed  $\nu_4$  population is negligible. Nevertheless, due to the assumption of parity conservation for the  $B$  interactions with neutrinos, one can compute the helicity flipping (HF) and helicity conserving (HC) decay channels by noting that  $d\Gamma(\nu_4^{h=-1} \rightarrow \nu_L B) = d\Gamma(\nu_4^{h=1} \rightarrow \nu_R B)$  and  $d\Gamma(\nu_4^{h=1} \rightarrow \nu_L B) = d\Gamma(\nu_4^{h=-1} \rightarrow \nu_R B)$ . In this way, all HF decay rates are given by  $d\Gamma(\nu_4^{h=1} \rightarrow \nu_L B)$  and all HC channels by  $d\Gamma(\nu_4^{h=-1} \rightarrow \nu_L B)$ . Our results are shown below.

$\nu_4^h \rightarrow \nu\phi$ :

$$\begin{aligned} |\mathcal{M}_h|^2 &= \frac{m_4^2}{2}(1-r^2)(1-h\cos\theta) \\ &= \frac{m_4^2}{2} \left( (1+h)(1-r^2) + 2h\frac{E_1}{E_\nu} \right) \\ &= m_4^2 \begin{cases} \frac{E_1}{E_\nu} & \text{for } h = -1 \\ 1 - \frac{E_1}{E_\nu} - r^2 & \text{for } h = 1 \end{cases} \end{aligned} \quad (\text{A1})$$

$\nu_4^h \rightarrow \nu Z'$ :

$$\begin{aligned} |\mathcal{M}_h|^2 &= m_4^2(1-r^2) \left( 1 - h\cos\theta + \frac{1+h\cos\theta}{2r^2} \right) \\ &= \frac{m_4^2(1-r^2)}{2r^2} \left( (1-h) + (1+h)2r^2 - 2h\frac{E_1}{E_\nu} \frac{1-2r^2}{1-r^2} \right) \\ &= \frac{m_h^2}{r^2} \begin{cases} 1 - \frac{E_1}{E_\nu} - r^2 \left( 1 - 2\frac{E_1}{E_\nu} \right) & \text{for } h = -1 \\ \frac{E_1}{E_\nu} + 2r^2 \left( 1 - \frac{E_1}{E_\nu} - r^2 \right) & \text{for } h = 1 \end{cases} \end{aligned} \quad (\text{A2})$$

We assume the heavy neutrinos are ultra-relativistic, so that we are justified in using

$$E_1 = \frac{E_\nu}{2}(1-r^2)(1+\cos\theta). \quad (\text{A3})$$

## Appendix B: Solar Flavour Transitions

Once produced from the  $\nu_4$  decay, the active neutrinos propagate from the Sun's core to the Earth, subject to matter effects. The flavour evolution of these neutrinos is given by the well-known LMA-MSW solution [1]. Here, we are primarily interested in the total  $\bar{\nu}_e$  flux that exits the Sun, so all antineutrinos produced in the decay of the boson  $B$  contribute. In what follows, we will assume that  $|U_{\mu 4}| = |U_{\tau 4}|$  for simplicity.

To a very good approximation, the flavour transitions of neutrinos in the Sun can be taken to be adiabatic [1]. In this limit, the relevant flavour conversion probabilities are for a  $\nu_\alpha$  to convert into a  $\nu_\beta$ ,  $P_{\alpha\beta}$ , are given by

$$\begin{aligned} P_{ee}(E_\nu) &\approx c_{13}^4 \left( \frac{1}{2} + \frac{1}{2} \cos 2\theta_{12} \cos 2\theta_{12}^M \right) + s_{13}^4, \\ P_{\mu e}(E_\nu) + P_{\tau e}(E_\nu) &= 1 - P_{ee}(E_\nu), \end{aligned} \quad (\text{B1})$$

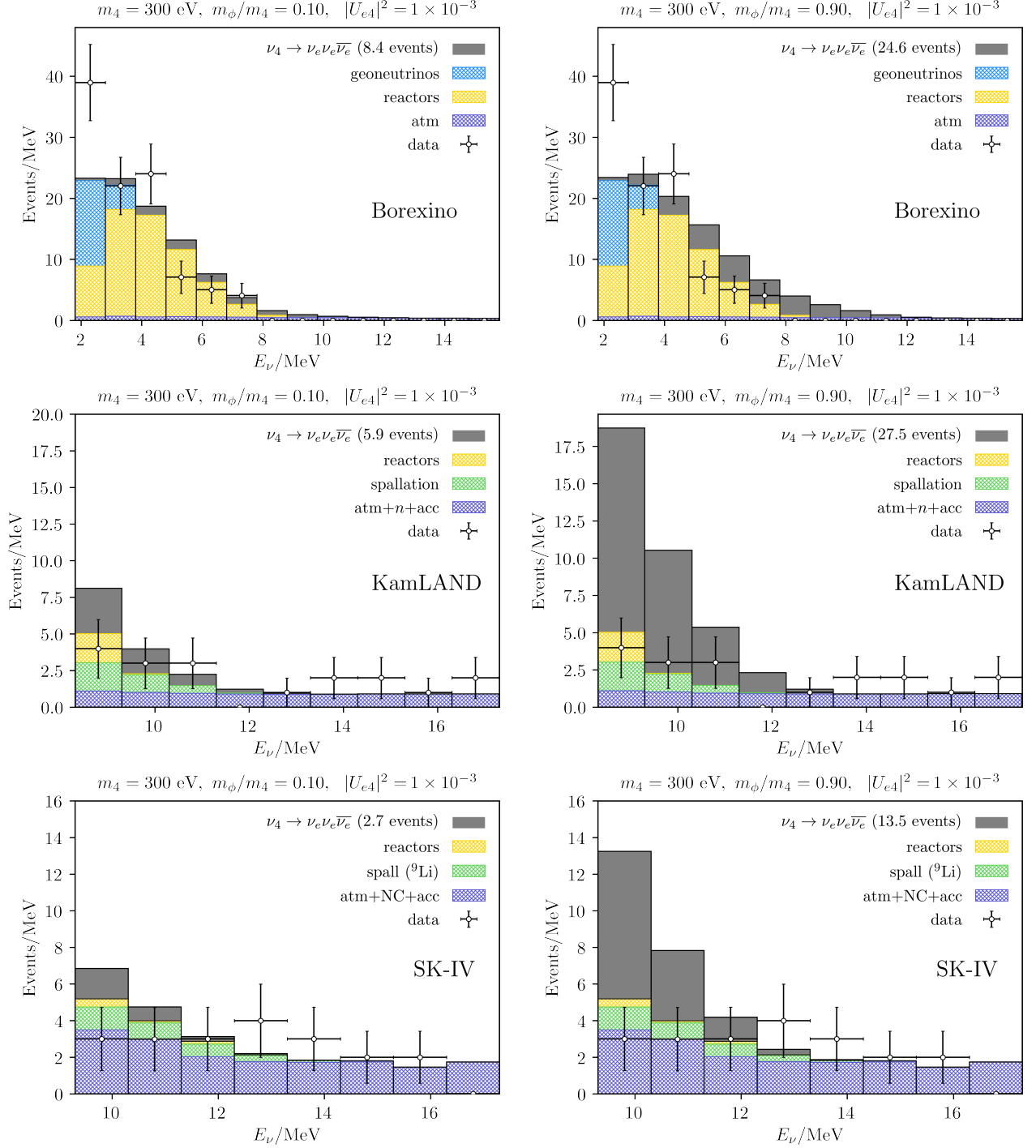


FIG. 3. The inverse beta decay spectrum at KamLAND (top row) and Borexino (bottom row) as stacked histograms. The filled histograms show the background estimations by the collaboration, and the hashed histogram the prediction of visible neutrino decays. For KamLAND, we also show the 90% C.L. upper limit on the event spectra provided by the collaboration. All plots assume  $|U_{\mu 4}| = |U_{\tau 4}| = 0$ .

with their antineutrino  $\bar{P}_{\alpha\beta}$  analogue. Here,  $\theta_{12}^M$  is the solar mixing angle in matter at the core, defined as

$$\tan 2\theta_{12}^M = \frac{\sin 2\theta_{12}\Delta m_{12}^2}{\Delta m_{12}^2 \cos 2\theta_{12} - A_{CC}}, \quad (\text{B2})$$

with  $A = \pm 2\sqrt{2}E_\nu G_F N_e(0)$  for neutrinos (antineutrinos). It is easy to see that while  $\nu_e$  states undergo the usual MSW transition, having enhanced flavour transitions due to adiabatic conversions above the resonance,  $P_{ee}(5 \text{ MeV}) \approx 0.32$ , the  $\bar{\nu}_e$  states do not. Instead,  $\bar{\nu}_e$

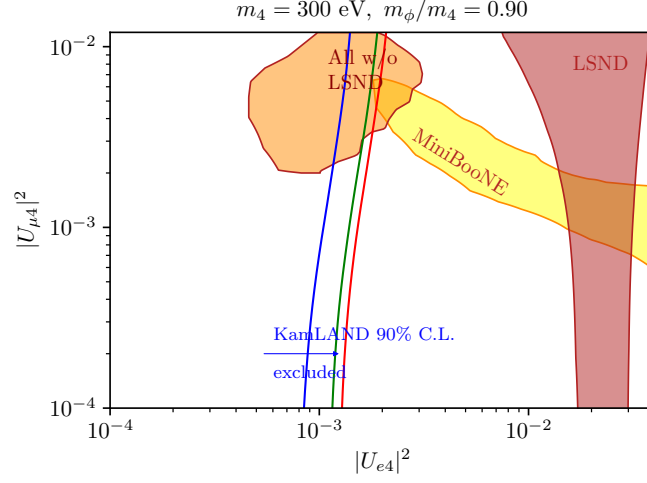


FIG. 4. fixed some bugs..

change flavour less often above the resonance and have enhanced survival probabilities,  $\overline{P}_{ee}(5 \text{ MeV}) \approx 0.64$ . The full flavour transition probability is shown in Fig. 5.

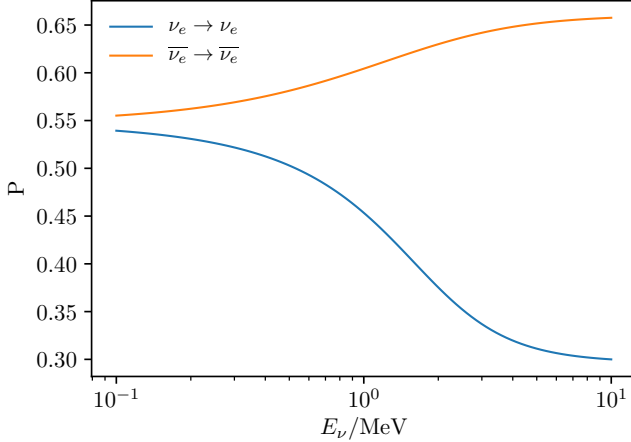


FIG. 5. Caption

Finally, we may also compute  $\overline{P}_{\mu e}$  by noting that within the two flavour approximation the T symmetry

always holds ( $P_{\alpha\beta} = P_{\beta\alpha}$ ). This is a consequence of the unitarity of the Hamiltonian, and holds even for non-symmetric matter profiles, such as the Sun [22, 23]. Hence, the CPT asymmetry is equivalent to the CP asymmetry  $P_{\alpha\beta} - \overline{P}_{\alpha\beta}$ , such that  $\overline{P}_{\mu e} = \overline{P}_{e\mu}$ .

#### Appendix C: Statistical Method

When deriving upper limits on the mixing angles, we minimize the following log-likelihood function

$$\mathcal{L} = 2 \sum_i \left[ \mu_i(\vec{\theta}, \vec{\beta}) - D_i + D_i \ln \frac{D_i}{\mu_i(\vec{\theta}, \vec{\beta})} \right] + \sum_j \frac{\beta_j^2}{\sigma_j^2}, \quad (\text{C1})$$

where  $\vec{\theta}$  stands for the vector of physics parameters (*e.g.*,  $|U_\alpha|^2$ ),  $\vec{\beta}$  the vector of nuisance parameters with individual entries  $\beta_j$  and associated Gaussian errors  $\sigma_j$ . As an approximation, we assume  $\mathcal{L}$  to follow a  $\chi^2$  distribution when estimating our confidence intervals.

The most important systematics for our study are the uncertainties on the total  $^8\text{B}$  solar neutrino flux and total backgrounds numbers. We assume an overall

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