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## Search for sterile neutrinos with SOX: Monte Carlo studies of the experiment sensitivity and systematic effects

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# Search for sterile neutrinos with SOX: Monte Carlo studies of the experiment sensitivity and systematic effects

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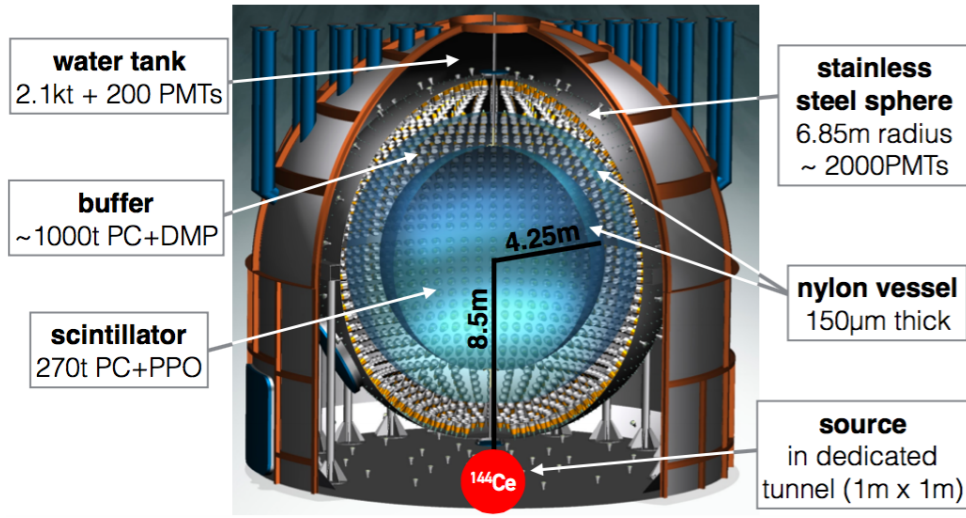
**Abstract.** Some neutrino experiments reveal anomalous results which can make room for new physics beyond the three-flavor neutrino oscillation model. These hints suggest the existence of sterile neutrinos with mass  $m \sim \text{eV}$ . SOX will be a short-baseline disappearance experiment aiming to test this hypothesis, performed with the liquid scintillator detector Borexino at Gran Sasso National Laboratory in Italy [1]. Due to the good energy and position resolution, a light sterile neutrino can create an oscillatory pattern in the signal. The SOX sensitivity, the related analysis and systematics will be briefly discussed.

## 1. Introduction

The SOX project aims to test the hypothesis of existence of sterile neutrinos with  $\Delta m_{14}^2 \sim \text{eV}^2$  through a short baseline disappearance experiment performed with the liquid scintillator detector



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**Figure 1.** Scheme of the Borexino detector, along with the  $^{144}\text{Ce} - ^{144}\text{Pr} \bar{\nu}_e$  source placed underneath the detector.

Borexino at LNGS [1]. It will detect MeV-energy  $\bar{\nu}_e$  through the inverse beta decay (IBD) reaction, produced by a  $^{144}\text{Ce} - ^{144}\text{Pr}$  extremely intense  $\beta^+$  source, with an activity of (4-5) PBq. This source will be placed in a pit beneath the detector itself, at a distance of 8.5 m from the detector center (see Fig. 1). Measuring the event interaction position (and thus the travelled source-interaction point distance, named  $L$ ) and the event energy ( $E$ ), an oscillated signature can be observed in case of a sterile neutrino. SOX will begin its data taking in 2018, with an expected duration of 1.5 years. The combination of the ranges for the distance of the source to the detector ( $L \sim 10$  m) and the energies ( $1.8 \text{ MeV} \leq E \leq 3.0 \text{ MeV}$ ) allows SOX to probe a vast active-sterile  $\Delta m_{14}^2$  range, spanning from  $0.1 \text{ eV}^2$  to  $10 \text{ eV}^2$ .

## 2. Sensitivity analysis

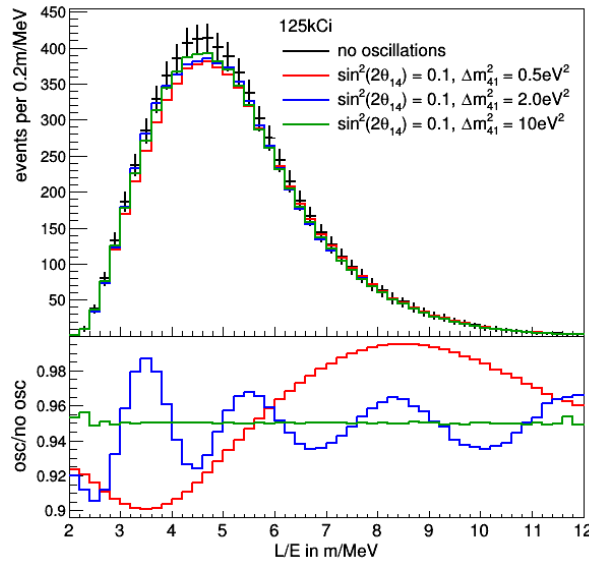
SOX will perform two complementary analysis. The *rate analysis* is a standard disappearance technique, performed in many short-baseline experiments, which consists in the total rate counting to be compared with the expected one ( $\sim 10^4$  events). This analysis critically depends on the accuracy of the expected rate estimation, which in turn is related to the source activity, on its uncertainty, on the detection efficiency and on the active scintillator volume. On the other hand, SOX will be able to perform a *shape analysis*, often named *oscillometry*. It will scan the events pattern as a function of  $L$  and  $E$  in the search of shape deformations due to  $\bar{\nu}_e \rightarrow \bar{\nu}_s$  oscillations. This can be done thanks to the Borexino's high precision in position and energy reconstruction [2] ( $\sigma_E/E \sim 10\%$ ,  $\sigma_L \sim 10 \text{ cm}$  @  $1 \text{ MeV}$ ). The oscillation pattern is expected to follow a well-known two-flavor approximation survival probability:

$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) \approx 1 - \sin^2(2\theta_{14}) \sin^2 \left( \frac{\pi}{2.48} \frac{L}{E} \Delta m_{14}^2 \right)$$

The SOX expected events profiles can be seen in Fig. 2. It reports the detected events as a function of  $L/E$ : in case of oscillations, with three different values of the oscillation parameters, and in absence of oscillations (top). The related ratio of oscillation versus no-oscillation rate for each one of the three cases (bottom).

A 95% confidence level SOX exclusion plot in the  $\sin^2(2\theta_{14}) - \Delta m_{14}^2$  plane, obtained by a profile likelihood ratio test, is shown in Fig. 3. The red and blue bands limit the exclusion regions through the rate only and shape only analysis. The black band derives from the complete rate + shape analysis, which combines the two pieces of information. For each analysis, the band width is due to the fact that the source activity is not currently known: the left border is related to the lowest expected activity (100 kCi), the right border to the highest one (150 kCi). We can separate three main  $\Delta m_{14}^2$  regions:

- Low  $\Delta m_{14}^2$ :  $\Delta m_{14}^2 \lesssim 0.2 \text{ eV}^2$ . The oscillation length  $L_{\text{osc}} \sim E/\Delta m_{14}^2$  in this region is wider than the Borexino size. The oscillations can't act significantly and thus the sensitivity is very poor.
- Intermediate  $\Delta m_{14}^2$ :  $0.2 \text{ eV}^2 \lesssim \Delta m_{14}^2 \lesssim 5 \text{ eV}^2$ .  $L_{\text{osc}}$  is in the order of Borexino detector size: the entire oscillation profile is sampled, thus the sensitivity is maximized. The shape analysis has a crucial role in order to almost cover the experimental anomalies region at 95% confidence level, shown as black closed curves.
- High  $\Delta m_{14}^2$ :  $\Delta m_{14}^2 \gtrsim 5 \text{ eV}^2$ .  $L_{\text{osc}}$  is smaller than the detector resolution, which tends to *flatten* the oscillations to an average value. The sensitivity is driven by the rate analysis.

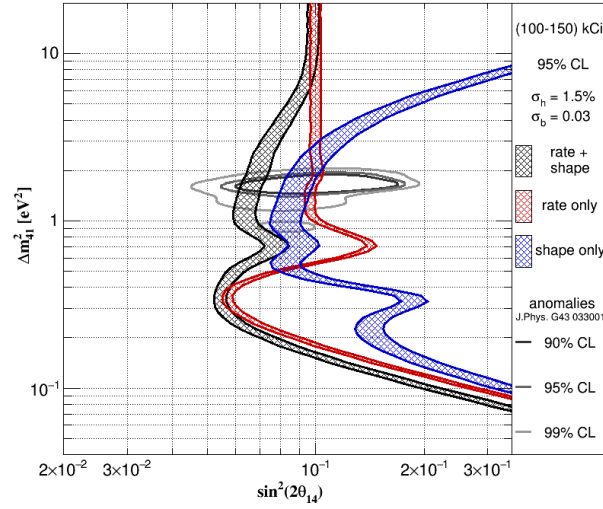


**Figure 2.** Total expected events as a function of  $L/E$ : in case of oscillations, with three different values of the oscillation parameters, and in absence of oscillations (top). The related ratio of oscillation versus no-oscillation rate for each one of the three cases (bottom).

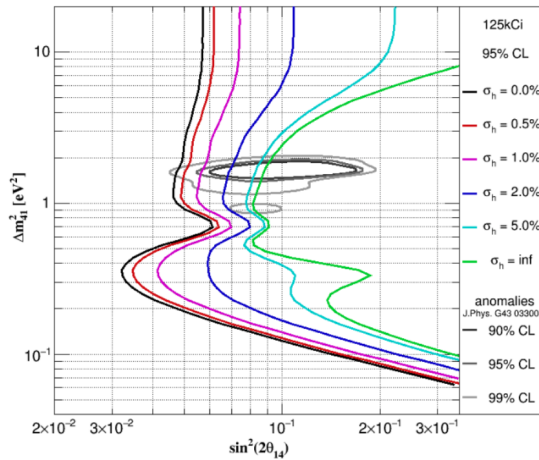
### 3. Systematics

Many systematics can affect the rate either/or the shape analysis. The main source-related uncertainties are:

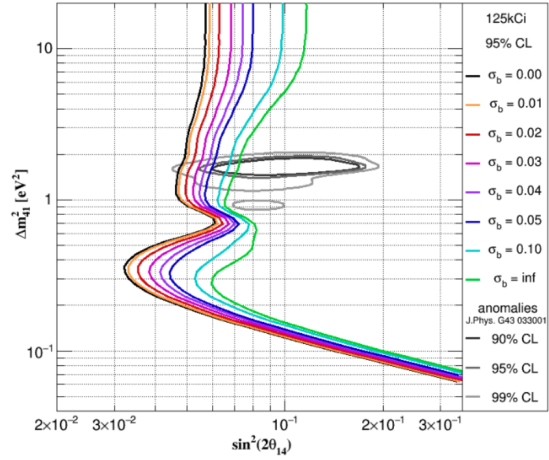
- **Uncertainty of the source activity ( $\sigma_H$ ).** This is currently expected to be lower than 1% thanks to an independently developed calorimeter that measures the emitted heat of the source. A large  $\sigma_H$  value implies an increased uncertainty on the expected event rate



**Figure 3.** Expected SOX exclusion plot (95% C.L.) in the  $\sin^2(2\theta_{14}) - \Delta m^2_{14}$  plane. The rate analysis contour is showed in red, the shape analysis in blue, the rate+shape one in black. The uncertainty on the source activity is set to be 1.5%. The bands border are related to the lowest expected activity (100 kCi, left borders), and to the highest one (150 kCi, right borders).



**Figure 4.** SOX exclusion contours as a function of the uncertainty on the source activity ( $\sigma_H$ ).



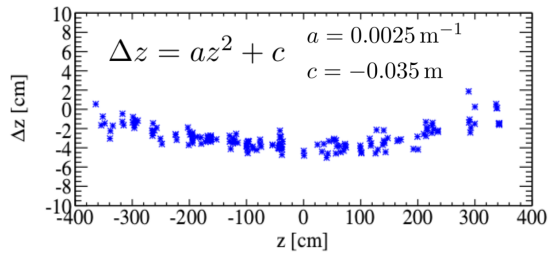
**Figure 5.** SOX exclusion contours as a function of the uncertainty on a  $^{144}\text{Ce} - ^{144}\text{Pr}$  shape factor parameter ( $\sigma_b$ ).

and thus a weakening of the rate analysis. Fig. 4 shows the SOX exclusion contours as a function of  $\sigma_H$ .

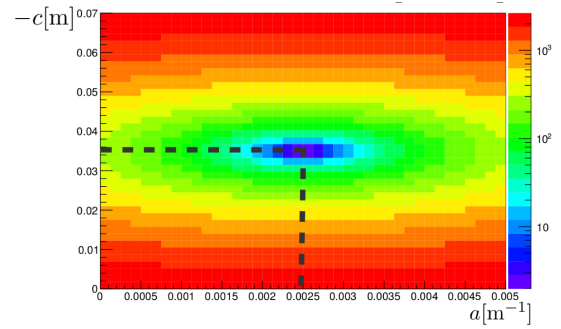
- **Uncertainty of  $^{144}\text{Ce} - ^{144}\text{Pr}$  decay spectral shape.** The shape factor is modeled empirically, since it can't be fully described by the nuclear theory. The empirical trend is  $S(E_e) = 1 + aE_e + b/E_e + cE_e^2$ , where  $E_e$  is the total positron energy and  $a, b, c$  are three shape parameters. The most impacting parameter is  $b$ , whose absolute error is aimed to be  $\sigma_b \approx 0.03$ . The most affected analysis is the rate one: the mean emitted energy per

decay  $\overline{E}$  changes, and thus the source activity, since it is calculated through the source power/ $\overline{E}$  ratio. The shape analysis can be weakened too, due to the uncertainty on the  $\overline{\nu}_e$  energy spectrum deformations. Spectral shape measurements are ongoing to constrain the  $b$  uncertainty. Fig. 5 shows the SOX exclusion contours as a function of  $\sigma_b$ .

### 3.1. Detector related systematics - preliminary results



**Figure 6.** Borexino  $z$  coordinate reconstruction bias: difference between the reconstructed  $z$  coordinate and the nominal one, with respect to the nominal coordinate.



**Figure 7.** Likelihood profile in the  $(a, c)$ -parameter plane. The minimum is consistent with the initial values obtained by the calibration data. Therefore the  $z$ -shift bias doesn't seem to affect the sensitivity on sterile neutrino oscillations.

Calibration campaigns carried out in 2009 highlighted a small position reconstruction bias for the  $z$ -coordinate [3] which can be described by a parabolic function  $\Delta z = az^2 + c$ , where  $a$  and  $c$  are two parameters. In Fig. 6 the  $z$  coordinate reconstruction distortion  $\Delta z$ , that is the difference of reconstructed and nominal coordinate, is plotted as a function of the nominal one. Introducing in the likelihood analysis the uncertainty of the two parameters describing this bias, preliminary results showed that a sterile neutrino signature cannot be mimicked. An exemplary profile of the likelihood function for the null hypothesis over the  $(a - c)$  bias parameter plane is depicted in Fig. 7. The minimum is consistent with the initial values obtained by the calibration data, therefore the  $z$ -shift bias doesn't seem to affect the sensitivity on sterile neutrino oscillations. A new Borexino calibration campaign, that is going to be carried out in the next months, will allow to check if this position reconstruction bias is currently present.

### References

- [1] Bellini G *et al* 2013 *JHEP* **08** 038
- [2] Alimonti G *et al* 2009 *NIM* **A600** 568-593
- [3] Back H *et al* 2012 *JINST* **7** P10018