Model-Independent $\bar{\nu}_e$ Short-Baseline Oscillations from Reactor Spectral Ratios

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Based on [1]

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Neutrino oscillations

Our current understanding of neutrino oscillations features some anomalies that appear at short baselines (SBL) and that we will address here within the context of the 3 + 1 mixing scenario.

The neutrino mixing can be written in terms of the mixing matrix $U_{\alpha i}$, where α represents an active (e, μ, τ) or sterile (s) neutrino flavor eigenstate and $i \in (1, 2, 3, 4)$ a neutrino mass eigenstate. The scenario is labeled as "3 + 1" because the ν_4, mostly mixed with ν_s ($|U_{s4}|^2 \simeq 1$), is much heavier than ν_1, ν_2, ν_3. We also consider $|U_{e4}|^2$, $|U_{\mu 4}|^2$, $|U_{\tau 4}|^2 \ll 1$.

Using the mixing matrix one can write the effective oscillation probabilities of flavor neutrinos at short baselines [2]:

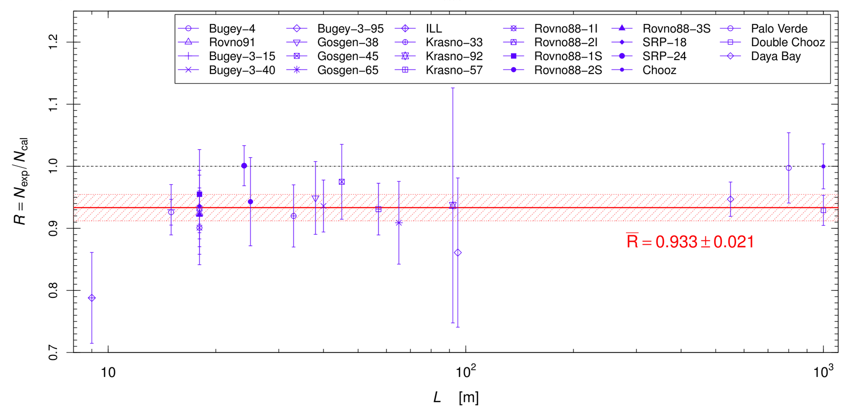
$$P_{\alpha\beta}^{(\mathrm{SBL})} \simeq \left|\delta_{\alpha\beta} - \sin^2 2\vartheta_{\alpha\beta} \sin^2\left(\frac{\Delta m^2_{41} L}{4E}\right)\right|, \tag{1}$$

being $\alpha, \beta \in (e, \mu, \tau, s)$, L the source-detector distance, E the neutrino energy and $\sin^2 2\vartheta_{\alpha\beta} = 4|U_{\alpha 4}|^2 |\delta_{\alpha\beta} - |U_{\beta 4}|^2|$.

Since we will only consider ν_e and $\bar{\nu}_e$ disappearance, we will only be interested in $P_{ee}^{(\mathrm{SBL})}$ and $\sin^2 2\vartheta_{ee} = 4|U_{e4}|^2 \left[1 - |U_{e4}|^2\right]$, with $|U_{e4}|^2 = \sin^2\vartheta_{14}$.

Reactor fluxes and Reactor Antineutrino Anomaly (RAA)

The RAA is a deficit of the rate of $\bar{\nu}_e$ observed in several SBL experiments in comparison with the theoretical expectation as computed in [3, 4]. The RAA has been first analyzed in [5] and a possible explanation can be the existence of (new) neutrino oscillations at $L \lesssim 20$ m, corresponding to $\Delta m^2_{41} \gtrsim 0.5$ eV^2.



Notes:
What if reactor flux is wrong?
Are the calculations reliable?
What about the 5 MeV bump (see e.g. [6])?

Gallium anomaly

Note: what if the GALLEX & SAGE efficiencies have not been determined properly?

The Gallium radioactive source experiments GALLEX and SAGE observed a SBL disappearance of ν_e, which was first noticed in [7].

This anomaly can be explained by neutrino oscillations generated by a squared-mass difference $\Delta m^2_{41} \gtrsim 1$ eV^2.

How to be model independent?

Is there a way to avoid all the model dependencies and have a clean signature of the SBL neutrino oscillations?

YES!

We can measure the fluxes at different distances and use their ratios. In this way, the systematic effects related to the theoretical calculations and the flux normalization are automatically removed from the final results.

A distance-dependent effect would be the signature of SBL oscillations.

NEOS

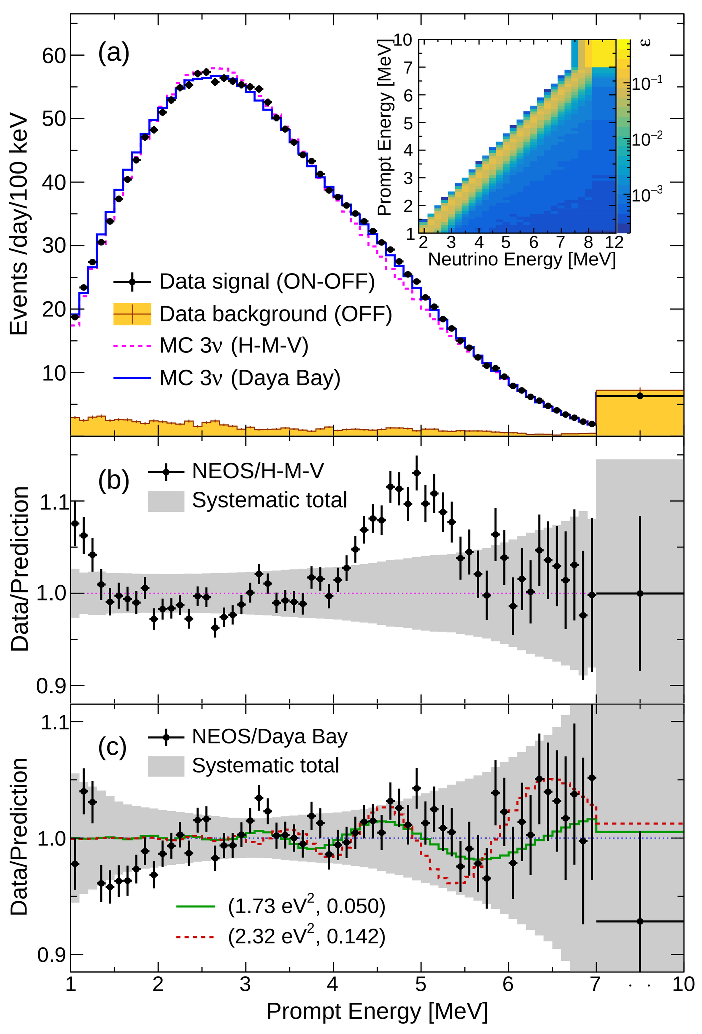


Fig. 1: NEOS results, from [8].

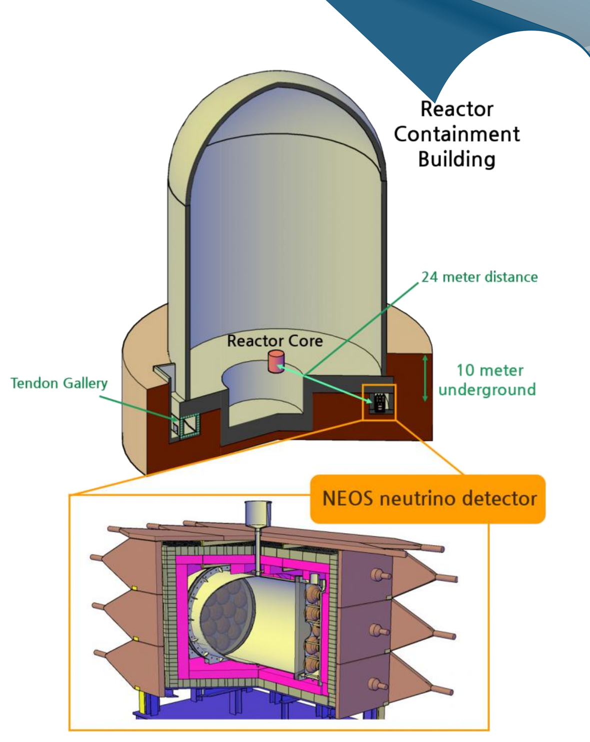


Fig. 2: Scheme of the NEOS experiment.

NEOS only has one detector at 24 m from the source, so it relies on the DayaBay flux at 550 m (at which oscillations are averaged out) for computing the ratio.

This method works because the reactor compositions and the detector properties are similar.

DANSS

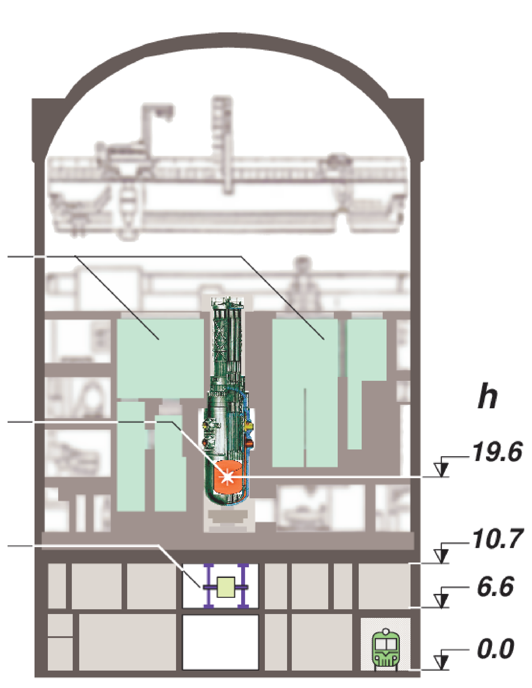


Fig. 3: Scheme of the DANSS experiment.

The detector can be moved in three positions with respect to the reactor core:

Top : 10.7 m;

Middle : 11.7 m;

Bottom : 12.7 m;

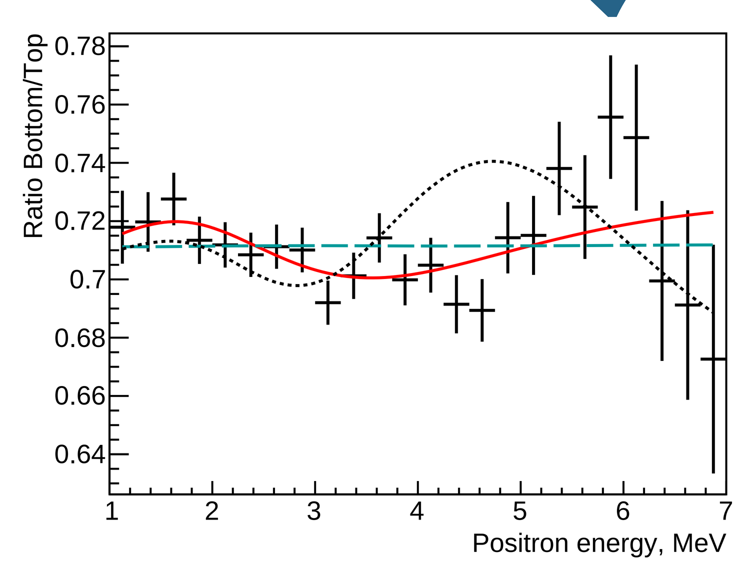


Fig. 4: DANSS results, from [9].

The first release of the DANSS experiment [9] considered the ratio of the spectra measured in the "top" and "bottom" positions using a total of $\sim$ 663k antineutrino events. The best-fit points in the case of 3+1 and 3 neutrinos mixing have a difference $\Delta\chi^2 \simeq 13$, in favor of 3+1 oscillations ($\sim 3\sigma$).

The collaboration provided in [9] an exclusion plot only, while the significance for the existence of the fourth neutrino will be studied with more data.

Other experiments

Other experiments that also provide model-independent measurements are (see [1] for the details):

- Bugey-3 (ratio of spectra at 40 m and 15 m from the source);
- ratio of KARMEN and LSND data at 18 m and 30 m from the source.

We included all these experiments, but they play a **marginal role** in the analyses!

More soon?

Several experiments which aim at measuring SBL neutrino oscillations in a model-independent way are under development or already taking data.

Some of them are:

- STEREO
- SoLid
- PROSPECT

We will possibly have new data soon!

DANSS+NEOS fit

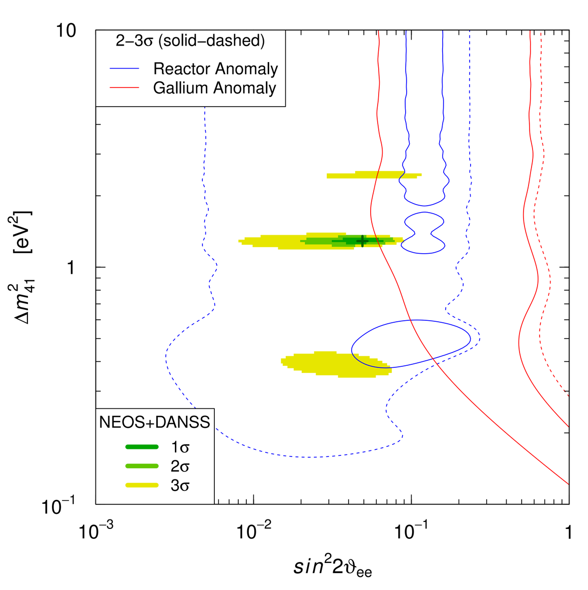


Fig. 5: DANSS + NEOS results, compared with the RAA and Gallium anomaly, from [1].

In figure 6 we plot the best-fit region from the model-independent analysis of ν_e and $\bar{\nu}_e$ data in comparison with the expected sensitivity of future experiments. As we can see, many of the already running or incoming experiments will have direct access to the region of the currently preferred mixing parameters. This, together with new data from DANSS or NEOS, means that *we will soon know if the sterile neutrino really exists or if we are observing something else.*

We show in figures 5 the result of the DANSS+NEOS fit (colored regions), compared with the 2σ (solid) and 3σ (dashed) constraints from the RAA (blue) and Gallium (red) anomalies. As we can see, there is a tension between the model-independent result and the RAA and Gallium constraints. The statistical significance for the preference for a light sterile neutrino from the different datasets is similar, but the *DANSS+NEOS result is much more reliable since it is model-independent.* Note that this tension may indicate that something is wrong in the RAA or Gallium cases (see the blocks on the right).

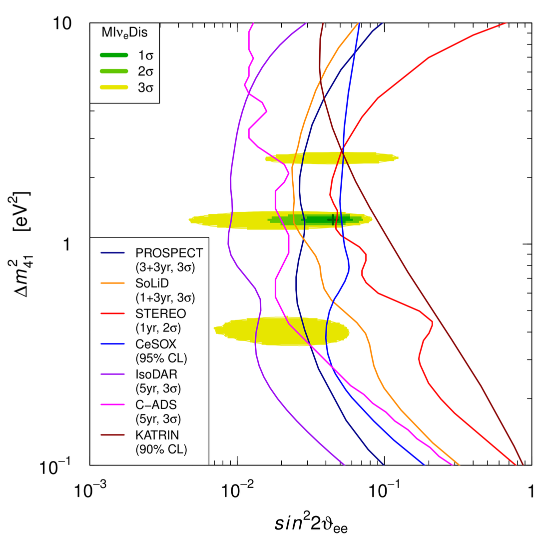


Fig. 6: The current best-fit compared with perspectives from future experiments. From [1].

Efficiency of GALLEX and SAGE

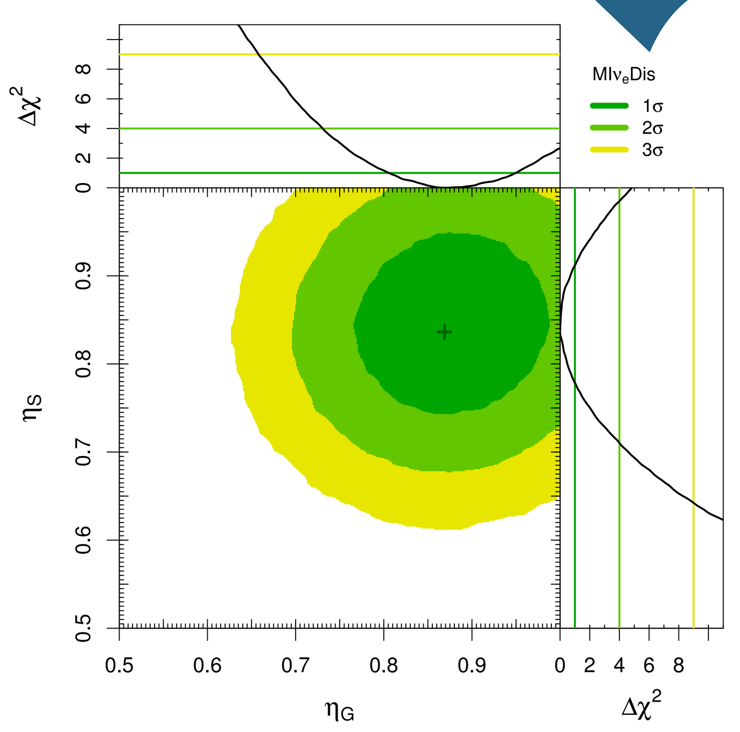


Fig. 7: Constraints on the free efficiencies η_G and η_S of the GALLEX and SAGE experiments. From [1].

In order to test the possible influence of an incorrect GALLEX and SAGE efficiency on the light sterile neutrino constraints, we fit the Gallium data using the free normalizations η_G and η_S.

We found (see fig. 7) that SBL data slightly prefer an efficiency smaller than one for both the experiments. The preferred regions for Δm^2_{41} and $\sin^2\vartheta_{ee}$, however, are not affected by the introduction of the Gallium data in the analysis, nor by the uncertainties η_G and η_S.

In other words, **the best-fit parameters Δm^2_{41} and $\sin^2\vartheta_{ee}$ are determined by DANSS and NEOS alone.**

Free fluxes: obtaining the normalization

In the last part of our analysis we considered the possibility for the theoretical antineutrino fluxes of the principal fission actinides to have a different normalization with respect to the predicted one. In order to do this, we multiply each spectrum (^{235}U, ^{238}U, ^{239}Pu) by a free factor (r_{235}, r_{238}, r_{239}), which is one if the theoretical calculations are correct. We also verified that the spectrum of ^{241}Pu cannot be constrained with current data.

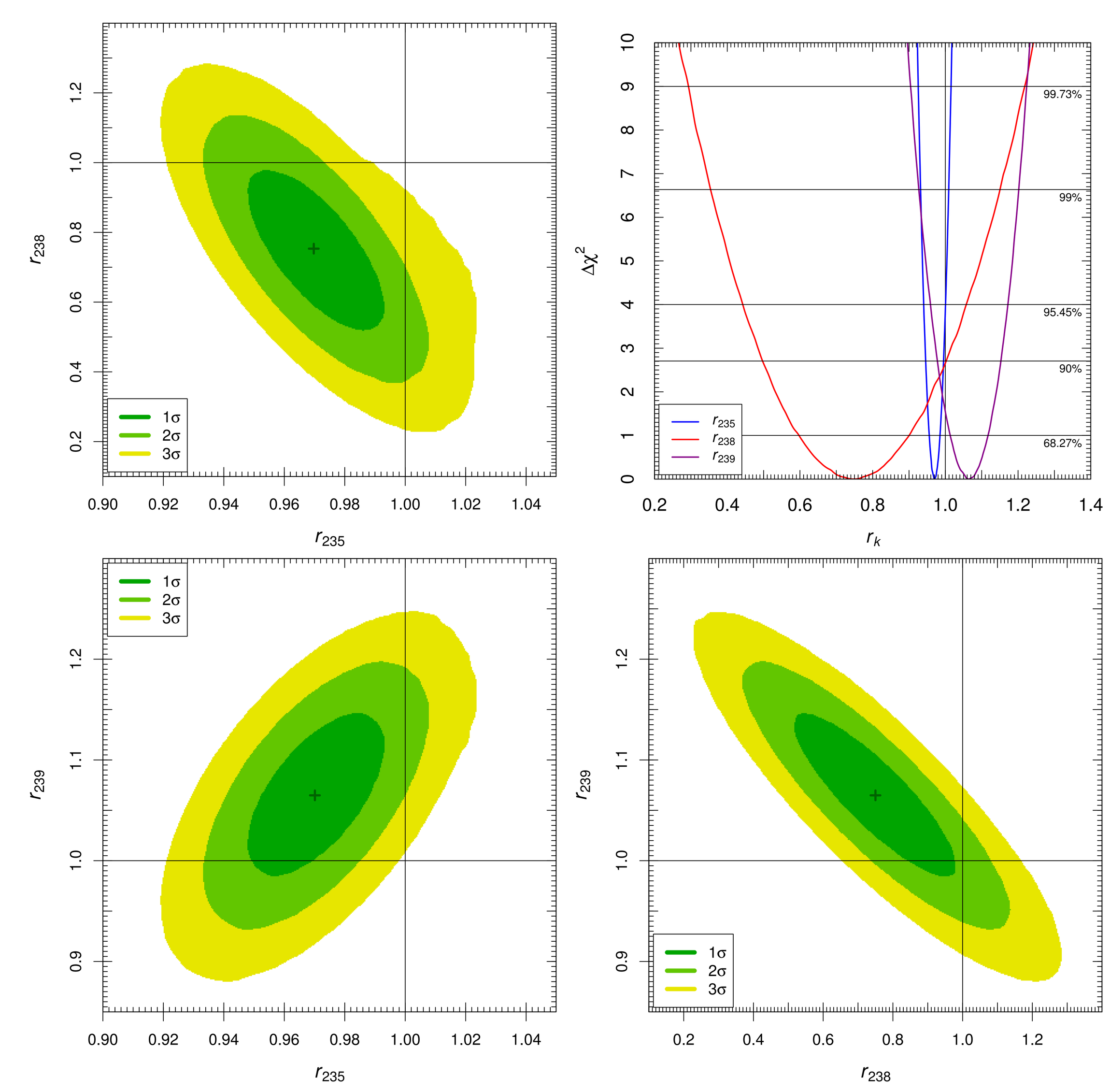


Fig. 8: Constraints on the free amplitudes of the reactor antineutrino fluxes. From [1].

As for the Gallium case, we find that the best-fit for the oscillation parameters Δm^2_{41} and $\sin^2\vartheta_{ee}$ is almost independent of the r_i coefficients, as they are constrained by DANSS and NEOS alone. The fit, however, shows a $\sim 2\sigma$ **deviation of r_{235} and r_{238} from the expected value**.

When analysing the SBL data with a free normalization for the reactor antineutrino fluxes, we take into account the uncertainties on the fuel fractions inside the reactors and we find that they have a small influence on the results.

To our best knowledge, this is the **first time** that the **uncertainties on the fuel fractions** are taken into account when analysing the RAA data. See [1] for the use of the Lagrange multipliers and more details on the treatment of the fuel fraction uncertainties.

Essential bibliography

[1] S. Gariazzo, C. Giunti, M. Laveder and Y. F. Li, *Model-Independent $\bar{\nu}_e$ Short-Baseline Oscillations from Reactor Spectral Ratios*, *PLB* **782** (2018) 13–21, [arxiv:1801.06467].

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Acknowledgments

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