Geoneutrino oscillations approach to discriminate distributions of Heat Producing Elements in the Earth's mantle

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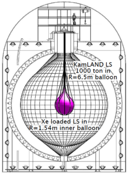
March 14, 2018

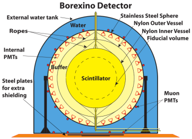
Outline I

Introduction I

- Mantle structure is widely debated.
  - Uniform HPE: Mantle is chemically homogeneous.
  - Two-layer HPE: Chemically Enriched Layer (EL) near the nucleus. + Depleted Layer (DL).
- (Anti)Neutrinos, almost, do not interact with the Earth.
- Antineutrino detectors are being built.



(a) KamLAND.



(b) Borexino

Figure: Taken from [3].

Introduction II

- There is an exact, relatively simple, way to include an exact solution to the evolution of a neutrino through matter.
- Another way to indirectly probe the deep Earth is then possible.
- This probing can **bring information on the distribution of HPE** distribution as well as heat flux.

Main Goal

Evaluate the application of the exact solution to matter neutrino oscillations in the study of deep Earth through flux integration and simulation of detection.

Specific Goals

- Write a computer program that calculates geoneutrino transition/survival probabilities, given a density profile and an energy.
- Write a simulation program that integrates the geoneutrino flux in the detector.
- Simulate the detector in terms of efficiency of detection.
- Draw conclusions on mantle HPE distribution based on the results of the simulation and the comparison with the existing data.

Timetable I

Tasks \ Weeks	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
1	X															
2	X	X														
3		X	X													
4				X	X	X	X									
5							X									
6								X	X							
7										X						
8											X	X				
9												X	X			
10	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X

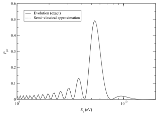
- Task 1: Write a C++ code (based on [4])that, given a neutrino energy (E_ν) value and a density profile $\rho(r)$, calculates the survival or transition probabilities.
- Task 2: Test the code with the examples given in [4], once it works correctly, make necessary modifications to the code so it uses antineutrinos instead.

Timetable II

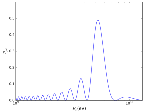
- Task 3: Write a code that involves creating a class/object/structure that allows the relatively easy management of data that includes position of origin, direction, energy and density profile for each geoneutrino generated.
- Task 4: Write a program that generates random numbers within different given distributions: the HPE distribution geometry being tested and the energy spectrum for certain isotope. These numbers must be assigned to the different objects/attributes of the structure of Task 3.
- Task 5: Progress evaluation: 30%.
- Task 6: Test program in the cluster, make necesssary adjustments.
- Task 7: Optimize and parallelize computing.
- Task 8: Run simulations in cluster and retrieve final data.
- Task 9: Analysis of the results.
- Task 10: Write document.

Task 1 & 2: Before I

UANdINO v01. Was able to reproduce one graph.
For neutrinos:



(a) Transition Probability (TP) from [4]



(b) TP from UANdINO

For antineutrinos:

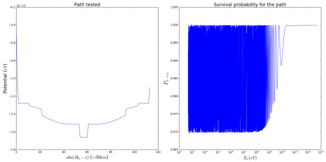


Figure: Antineutrino survival probability for the path shown, which is across the Earth.

Task 1: Now I

UANdINO_v02. Written in C++ is able to reproduce all figures in reference [4].

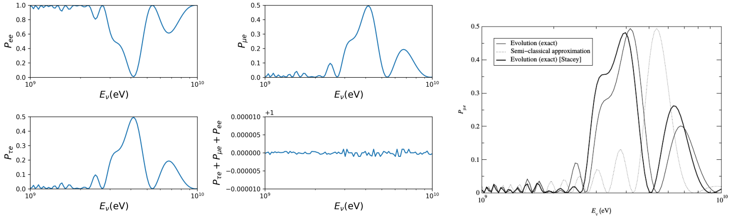


Figure: UANdINO's results for figure 1 of the paper. Compared to the results shown in Reference [4].

Task 1: Now II

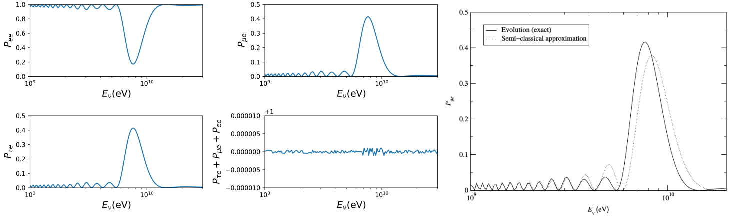


Figure: UANdINO's results for figure 2 of the paper. Compared to the results shown in Reference [4].

Task 1: Now III

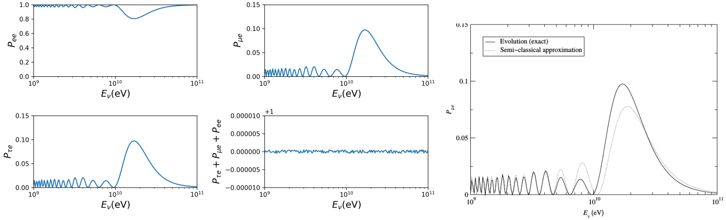


Figure: UANdINO's results for figure 3 of the paper. Compared to the results shown in Reference [4].

Task 1: Now IV

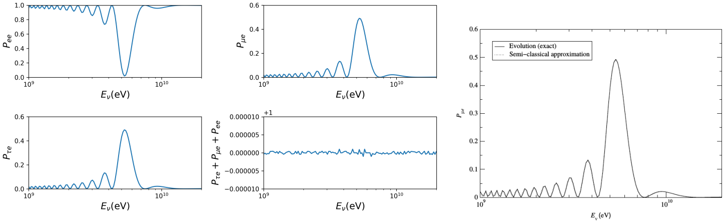


Figure: UANdINO's results for figure 4 of the paper. Compared to the results shown in Reference [4].

Task 1: Now V

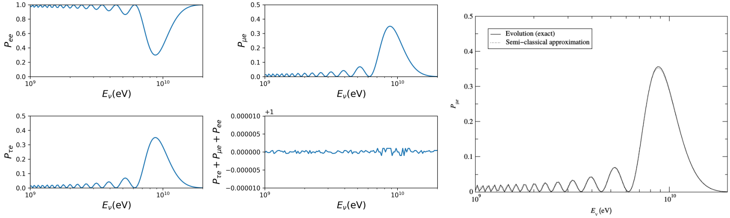


Figure: UANdINO's results for figure 5 of the paper. Compared to the results shown in Reference [4].

Task 1: Now VI

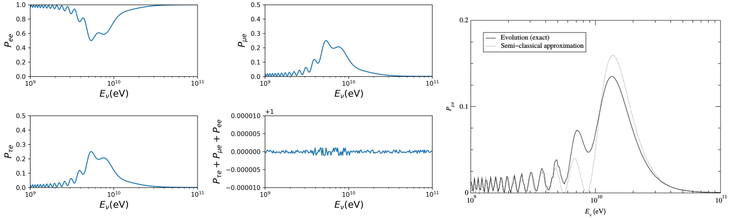


Figure: UANdINO's results for figure 6 of the paper. Compared to the results shown in Reference [4].

Task 1: Now VII

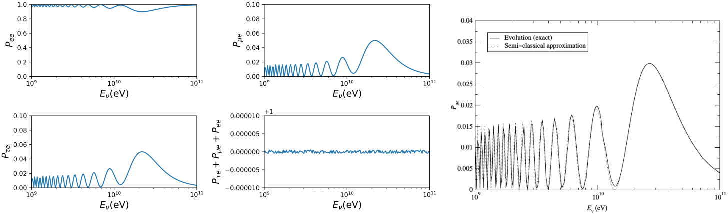


Figure: UANdINO's results for figure 7 of the paper. Compared to the results shown in Reference [4].

New

- Use of actual oscillation parameters provided by reference [5].
- Numerical "stability" of the code when $\Delta m^2_{21} \neq 0$.
- Implementation of corrections to probability unitarity.
- Sensibility to step length, the lower, the better.
- MATLAB implementation: UANdINO_mat
- Simulations for solar neutrinos. Data from reference [2].

Real Parameters + UANdINO_v02

Using current oscillation parameters and probability unitarity correction, this code gives

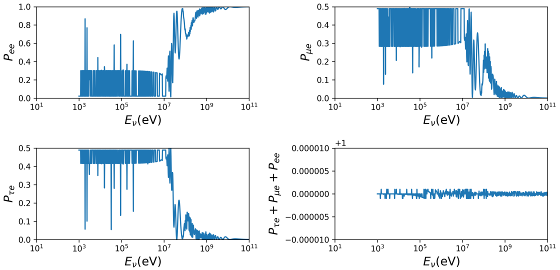


Figure: Antineutrinos through Earth-like density profile. UANdINO_v02

Note that $P_{e\mu} \neq P_{e\tau}$. Overflow issues in low energies.

Real Parameters+MATLAB I

MATLAB is fast with matrices and avoids memory leaks while C++ doesn't. $\rightarrow$ Is able to perform more steps (in more time). Currently: 1M spatial steps $\times$ 100 energies $\approx$ 1.5h. Result is

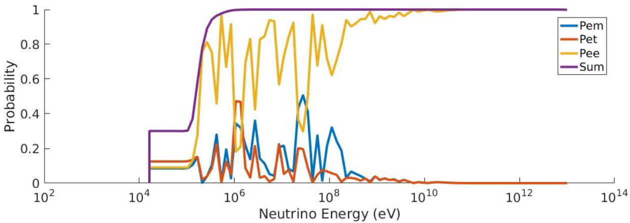


Figure: Antineutrinos through Earth-like density profile. UANdINO_mat

Real Parameters+MATLAB II

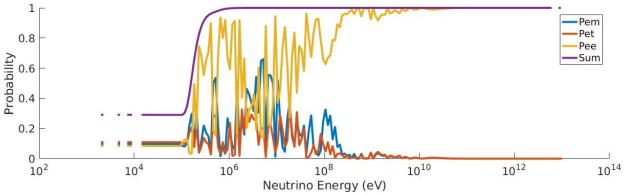


Figure: Antineutrinos through Earth-like density profile. UANdINO_mat

Solar Neutrinos I

In reference [2], three flavor solar neutrino oscillations gives the following curve

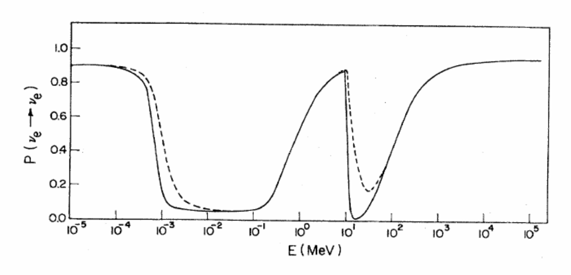


Figure: Solar neutrino oscillations.

While my MATLAB code gives:

Solar Neutrinos II

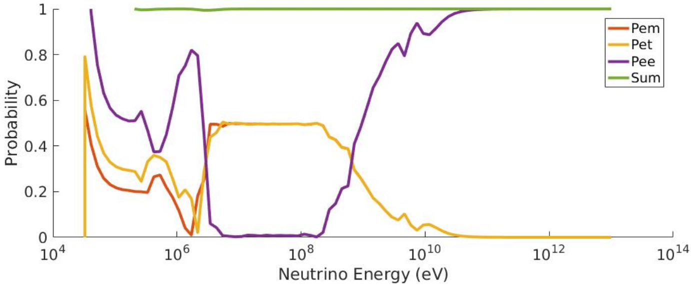
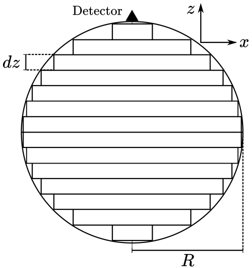
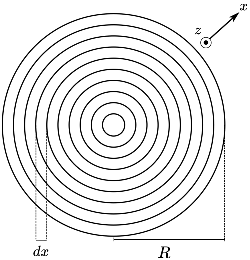


Figure: Neutrino generated in the center of the Sun and traveling until the solar radius.

Task 3: Modeling The Earth I



(a) Cross section of the model-Earth parallel to z-axis.



(b) Cross section of the model-Earth parallel to x-axis (map view).

Figure: The model consists of a 500×1000 matrix in which every element represents a **ring**. For each $z \in [-R, R]$, there are $N(z)$ rings.

Task 3: Modeling The Earth II

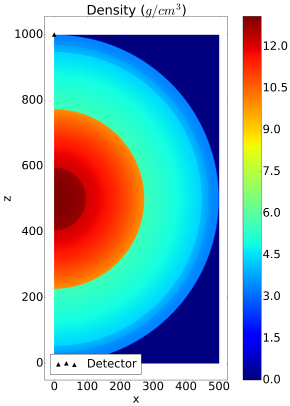


Figure: PREM [1] Model implemented.

Modeling is done in C++.
Each ring has various attributes:

- Coordinates: x, z, r.
- Volume ΔV and Attenuation factor $|\mathbf{r} - \mathbf{r'}|^{-2}$
- Mass density (according to reference [1]), Isotopic abundance.
- Flux contribution.
- A path from each one to the detector.

Task 4:

Since flux is integrated according to

$$\Phi_X(\mathbf{r}) = \frac{n_X \lambda_X}{4\pi} \int_\Omega \int_\oplus \frac{a_X(\mathbf{r'})\rho(\mathbf{r'})P_{ee}(\mathbf{r} - \mathbf{r'}, E_\nu)}{|\mathbf{r} - \mathbf{r'}|^2} d^3 r dE_\nu \qquad (1)$$

The generation of random numbers (geoneutrinos) is deprecated.

Now what?

- **Task 6: Test in cluster.** Waiting for account re-opening. Once I have it, start simulating according to Task 7.
- **Task 7: Optimization and parallelization.** Given the characteristics of the code, it would be unwise to parallelize it. Nevertheless, something can be done. Python manager runs the same MATLAB code with different parameters.
- **Task 8 & 9: Deploy program and Analysis.**

References I

Adam M. Dziewonski and Don L. Anderson. "Preliminary reference Earth model". In: *Physics of the Earth and Planetary Interiors* 25.4 (1981), pp. 297–356. ISSN: 00319201. DOI: 10.1016/0031-9201(81)90046-7.

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Tommy Ohlsson and Hakan Snellman. "Neutrino oscillations with three flavors in matter of varying density". In: *The European Physical Journal C* 20.3 (2001), pp. 507–515. ISSN: 1434-6044. DOI: 10.1007/s100520100687. arXiv: 0103252 [hep-ph]. URL: https://arxiv.org/abs/hep-ph/0103252.

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