Neutrino Oscillation

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Introduction

Neutrinos are the the lightest leptons in the nature. Unlike electrons, they are neutral and can interact with other particles via gravity and the weak interaction. Neutrinos can be important to astrophysicist as they can help them to collect a different set of data than just photons. Scientists can use them to understand more about the Sun and try to come up with models such as the solar standard model. Neutrino oscillations are a unique phenomenon that has not been observed for other particles.

Where does the oscillation come from?

Neutrinos can travel the longest distances in the universe without interaction so for detecting them scientists have to develop the most sensitive detectors and use them meticulously. Although atmospheric and reactor neutrinos can also be detected, the Sun still remains the most dominant source of the neutrinos received on Earth. The preliminary numbers of detected solar neutrinos were significantly less than what was expected and this resulted in as what is known as the solar neutrino problem. To explain this discrepancy, the models had to be modified and new experiments were conducted. we do not have only one type of neutrino, but we have three different flavors of them which are always in a mixed state and have to be considered as a superposition of different energy eigenstates. Over long distances the mixture changes and for example, if we start with an electron neutrino, we might detect a muon neutrino depending on the distance between two detectors. The mass difference between two flavors is extremely small and it means that their oscillation can be seen over long distances, as a result, neutrinos are the only particles that allow us to observe such a behavior.

How neutrino oscillation can be explained?

We can explain this phenomenon within a simple 2-state quantum system in a superposition of energy eigenstates

$$\begin{pmatrix}\psi_x\\ \psi_y\end{pmatrix} = \begin{pmatrix}\cos\theta & \sin\theta\\ -\sin\theta & \cos\theta\end{pmatrix}\begin{pmatrix}E_a\\ E_b\end{pmatrix}$$

The probability to find the system in the same superposition at a later time is for instance

$$P_{xx} = \cos\theta^4 + \sin\theta^4 + 2\sin\theta^2\cos\theta^2\cos\left(\frac{\Delta E t}{\hbar}\right)$$

This result directly applies to neutrinos, where the flavor eigenstates are a superposition of energy eigenstates. As discussed there are 3 neutrino flavors, but to good approximation one simplify the problem by considering the simple two states situation. Neutrinos move nearly at the speed of light so that at a later time they travel a distance L and using the relativistic energy-momentum relation the probability to find an electron again depends on the the mass difference Δm^2:

$$P_{ee} = sin^2 2\theta sin^2\left(\frac{\frac{L}{E}}{\frac{4\pi}{\Delta m^2}}\right)$$

The arising quantity is called the oscillation length: $L_{osc} = \frac{4\pi E}{\Delta m^2}$

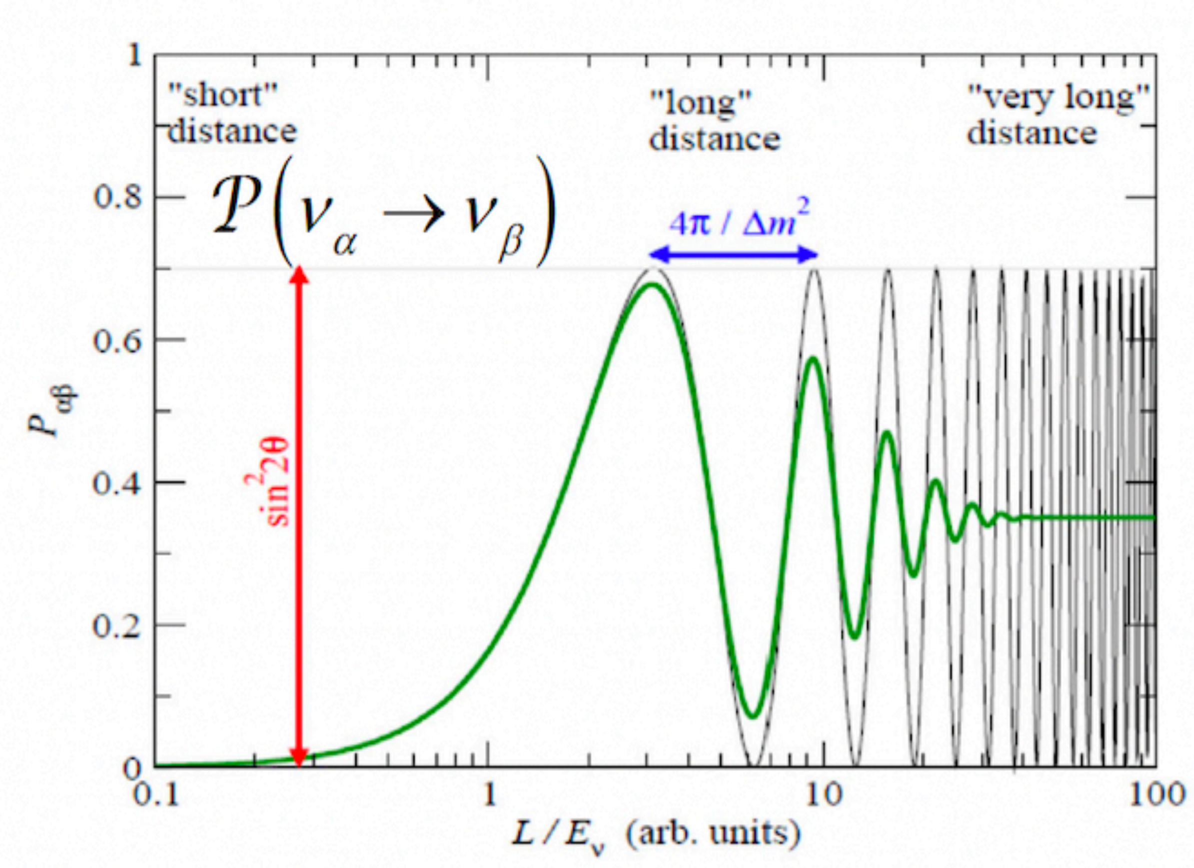


Figure 1: This plot shows the parameters that the oscillation depend on. The amplitude depends on the angle between these two flavors and the oscillation length depends on the mass difference. It is seen that the oscillation length should match up with the difference between two detectors. If this distance is too short, the oscillation would not be built yet and if it is too long, there would be too many oscillations that makes it impossible to distinguish them. One should notice that the only thing that we are able to compute is the square of difference between two different flavors and not the mass of each flavor precisely.

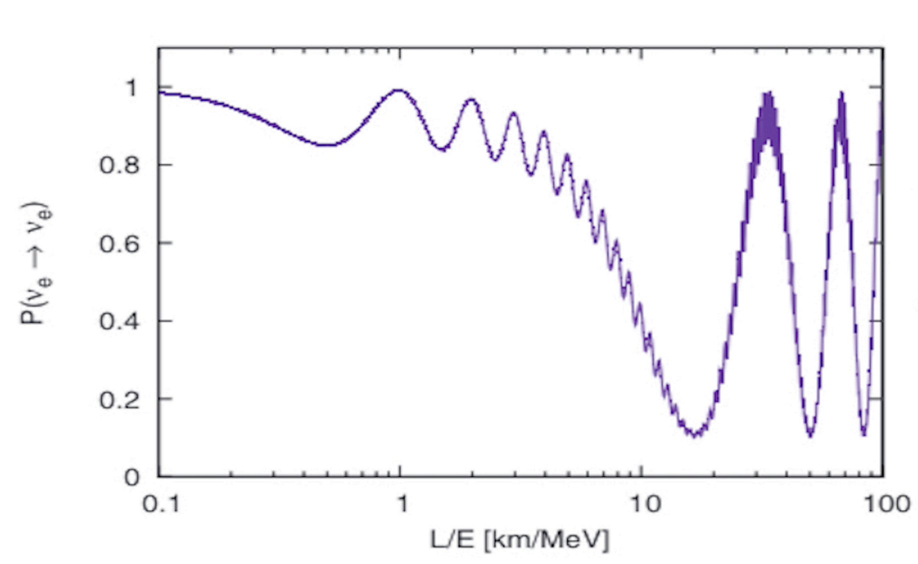


Figure 2: This plot shows the probability of neutrino oscillation.
In experiments it was proved that the probability for electron neutrinos to transform into muon neutrinos are higher than transforming into tau neutrinos and the small wiggles demonstrate this fact.

First evidence of neutrino oscillation and the solution

After several experiments and computations in 1960s, scientists found out about a glitch in Solar Standard Model. Although the measured number of detected neutrinos did not match up with their anticipations, they were still certain about other aspects of this model. As facilities such as Kamiokande were designed to do more research on the matter and come up with some reasonable answers, they learned to change their processes and methods. $\nu_e + Cl \to e^- + Ar$ was the reaction used by Davis at Homestake, whereas $\nu_x + e^- \to \nu_x + e^-$ is an elastic reaction between neutrino and electron that has been used in Kamiokande and Super Kamiokande. In addition, in 2001 the SNO experiment started to contribute but with a different approach. They have built a vessel containing heavy water (D_2O) which eventually use Cherenkov radiation as a mechanism to detect neutrinos. The charged current $\nu_e + d \to e^- + p + p$ and the neutral current $\nu_x + d \to \nu_x + p + n$ interactions were observed at the SNO experiment. As the result of these experiments they discovered that neutrinos not only have masses, but they also oscillate. Finally it was proven that the SSM prediction was correct but since at that time they were not familiar with the phenomenon, they just computed almost 1/3 of the real number which belonged to ν_e but now we know that if we add up all three flavors, the SSM works properly.

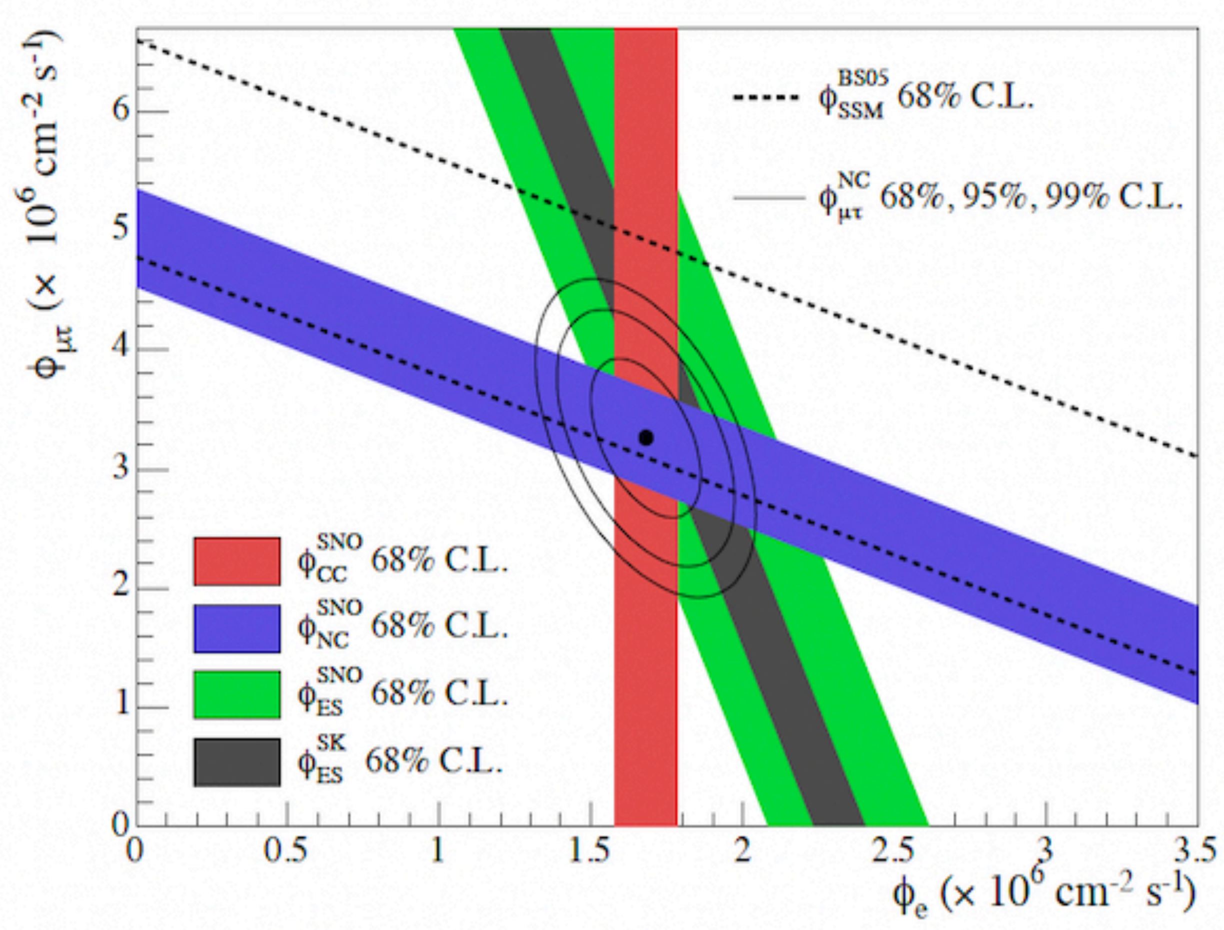
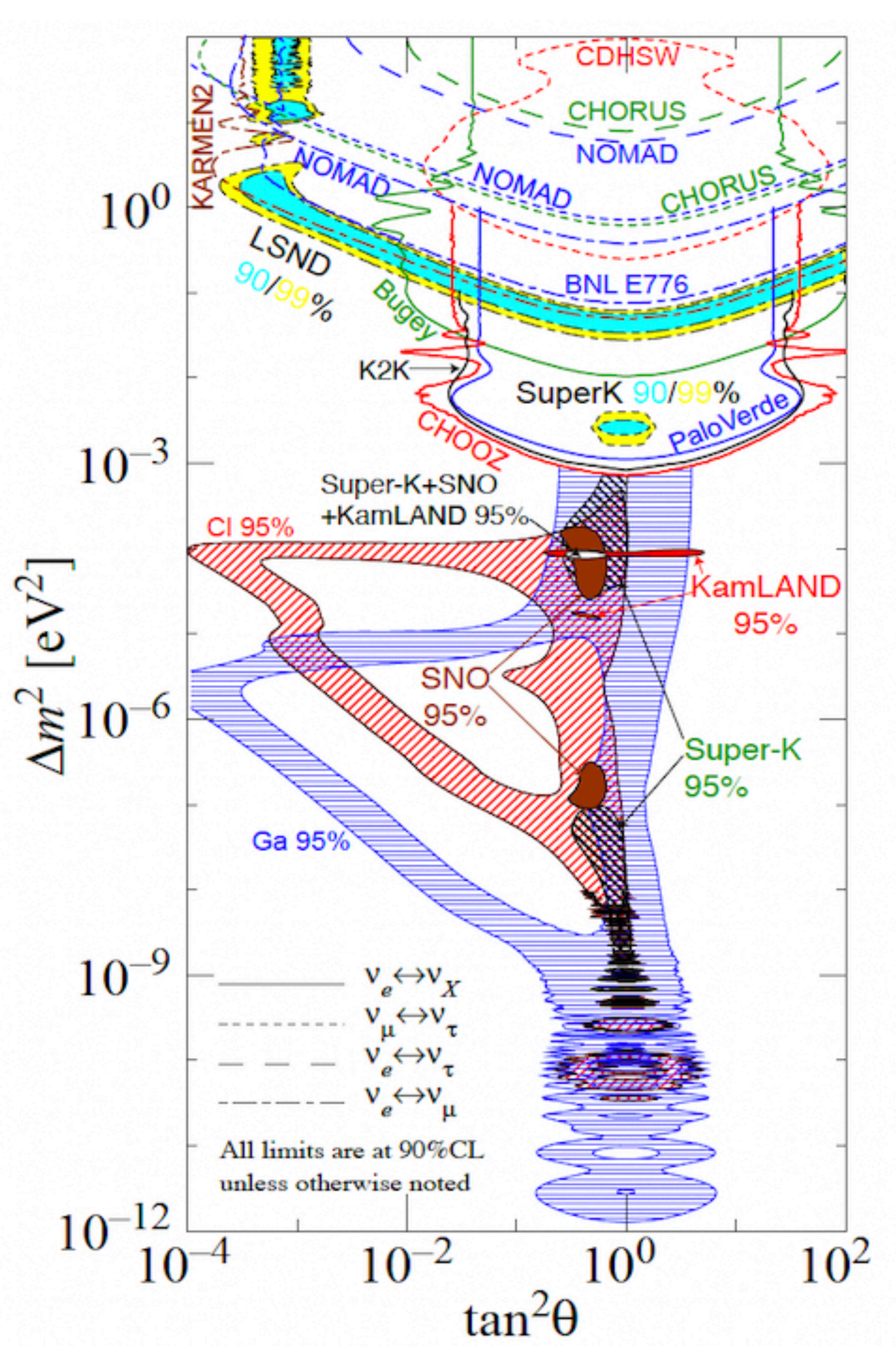


Figure 3: The figure depicts the flux of electron neutrinos in relation to muon neutrino and tau neutrino. It is construed if one wants to measure the number of received neutrinos, they should use the flux and then through computing the probability the result is achievable. The region in the middle is where it is highly likely for them to be found.

Figure 4: At this figure, the data from different experiments are shown. The data from solar neutrinos and accelerator neutrinos are at the bottom and at the top respectively.
As it is seen here, the collected data from Super Kamiokande, SNO and Kamiokande help us compute the mass difference with much more precision and can improve our understanding of neutrino oscillation. Also, the results from Super Kamiokande with different uncertainties are presented as the yellow and turquois blobs.
The reactor experiments focused mostly on the sterile neutrinos which are supposedly heavier than other kinds, but the results were not promising and they have not been discovered yet.



Conclusion

As we saw, by using quantum mechanics it was proved that neutrinos have masses which are extremely small. Nonetheless, they have a significant effect on neutrino astronomy. Still there should be much more experiments conducted by scientists since they can only compute the mass difference square and not the mass itself. Nevertheless, no doubt in the future neutrinos will play an even important rule and we will learn how to use them to gather information from celestial objects.

References

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