Light Sterile Neutrinos

S Uma Sankar

Department of Physics
Indian Institute of Technology Bombay
Mumbai, India

What is Sterile Neutrino?

- The Standard Model (SM) is based on the gauge group $SU(3)_c \times SU(2)_L \times U(1)_Y$. All the particle interactions are guided by this gauge group.
- Any particle which has interactions has non-tirival quantum number under at least one of the gauge groups.
- A sterile neutrino is a particle with no gauge interactions. It is a singlet under $SU(3)_c$ and under $SU(2)_L$ and its hypercharge $Y = 0$.
- Since it has no gauge quantum numbers, it does not couple to any gauge bosons? Does it mean it has **no** interactions?
- In all our models of sterile neutrinos, we assume that they couple to SM neutrinos, ν_e, ν_μ and ν_τ (which are called *active* neutrinos), through Yukawa couplings.

Why do we need sterile neutrinos?

- To generate neutrino masses, we need to couple the (active) left-handed neutrinos to right-handed neutrinos.
- The right-handed neutrinos are, by definition, sterile. Since they are right-handed, they are singlets under $SU(2)_L$. Hypercharge is given by $Y/2 = T_3 - Q$ so it is zero for right-handed neutrinos.
- We can simply write Dirac mass terms coupling the three left-handed neutrinos to three right-handed neutrinos (boring).
- In See-Saw models, we write a Majorana mass for the right-handed neutrinos. These Majorana masses, together with the Dirac masses, lead to three light mass eigenstates (which are essentially left-handed) and three heavy mass eigenstates (which are essentially right-handed).
- The heavy mass eigenstates are sterile neutrinos and they are popular dark matter candidates. Depending on the model, they can have masses from 10^3 eV to 10^{23} eV.

Light Sterile Neutrinos

- The sterile neutrinos I talked about till now occur in almost all models of neutrino mass. They can have various observable consequences, such as lepton flavour violation.
- But they do not affect neutrino oscillations. Neutrino oscillations depend on the difference of masses (strictly speaking difference of squares of masses) and the mass difference between active neutrinos and the sterile neutrinos above is too high.
- In this talk, we will concentrate on light sterile neutrinos.
- These are **light** neutrinos, with masses of a few eV. We are compelled to consider them because various neutrino experiments, over the past few years, have observed effects which can not be explained in terms of standard three flavour oscillation framework.

Standard Three Flavour Oscillation Framework

- The three active neutrinos mix with one another to form three mass eigenstates with masses m_1, m_2 and m_3.
- From these three eigenvalues, we can construct three mass-squared differences $\Delta m_{ij}^2 = m_i^2 - m_j^2$, of which only two are independent.
- The smaller mass-square difference is fixed using solar neutrino and long-baseline reactor neutrino data to be about 8×10^{-5} eV^2.
- The larger mass-squared difference is fixed using atmospheric neutrino and long-baseline accelerator to be about 2.5×10^{-3} eV^2.
- The mixing matrix connecting the flavour eigenstates and mass eigenstates is parametrized in terms of three angles and a phase.
- The angles are measured to be $\theta_{12} \approx 33^\circ$, $\theta_{23} \approx 45^\circ$ and $\theta_{13} \approx 8^\circ$. The CP-violating phase is not yet measured but recent observations seem to be indicate that it may be $\approx -90^\circ$ (maximal CP-violation)

Introduction to Neutrino Oscillations

- Two flavours of neutrinos ν_a and ν_b mix to form two mass eigenstates, with masses m_1 and m_2, where the mixing angle is θ.
- The neutrino survival probability is given by

$$P(\nu_a \to \nu_a) = 1 - \sin^2 2\theta \sin^2 \left(1.27 \frac{\Delta m^2 L}{E}\right). \quad (1)$$

- Here $\Delta m^2 = m_2^2 - m_1^2$, L is the distance between the neutrino source and the detector and E is the energy of the neutrino.
- The flavour ν_a has to be active for this quantity to be measurable. The flavour ν_b can be either active or sterile.
- We can also define the oscillation (or conversion) probability

$$P(\nu_a \to \nu_b) = \sin^2 2\theta \sin^2 \left(1.27 \frac{\Delta m^2 L}{E}\right). \quad (2)$$

  This quantity is measurable only if both ν_a and ν_b are active.
- Energy dependence of P is **dictated** by Δm^2 and L.

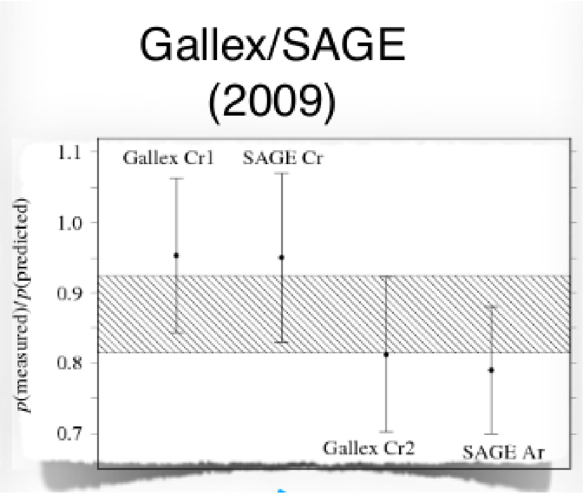
Neutrino Parameter Extraction from Oscillations

- Ideal situation to observe neutrino oscillations is to design experiments with values of L and E such that $\Delta m^2 L/E \simeq 1$, for one of the Δm^2 values.
- Probabilties are measured as a function of E. As $1.27(\Delta m^2 L/E)$ goes through $\pi/2$, the survival probability goes through a minimum and the oscillation probability goes through a a maximum.
- Observation of such extrema are smoking gun signals of oscillations. They also lead to precision determination of Δm^2 and θ, when the theory is fitted to data.
- It is also possible to observe the effect of oscillations if $\Delta m^2 L/E \gg 1$. In such cases, the oscillating term goes through many cycles for small variations in E and $\sin^2(1.27\Delta m^2 L/E)$ averages out to 0.5. If θ is large enough, the effect of this averaged oscillation can be measured but we can't estimate Δm^2.

Need for Light Sterile Neutrinos

- A number of short baseline (a few meters to a few hundreds of meters) neutrino experiments have observed lower than expected rates. In a few cases $\nu_\mu \rightarrow \nu_e$ conversion is also observed.
- If we interpret these deviations in terms of neutrino oscillations, we need $\Delta m^2 = 1 - 10$ eV^2, which is much different from the solar and atmospheric mass-squared difference.
- To generate such a mass-squared difference, we need to invoke a light sterile neutrino.
- Disappearance Experiments $P(\nu_e(\bar{\nu}_e) \rightarrow \nu_e(\bar{\nu}_e))$
  1. Gallium Anomaly (GA)
  2. Reactor Anti-Neutrino Anomaly (RAA)
- Appearance Experiments $P(\nu_e(\bar{\nu}_e) \rightarrow \nu_\mu(\bar{\nu}_\mu))$
  1. LSND at Los Alamos (Liquid Scintillator Neutrino Detector)
  2. MiniBooNE at Fermilab

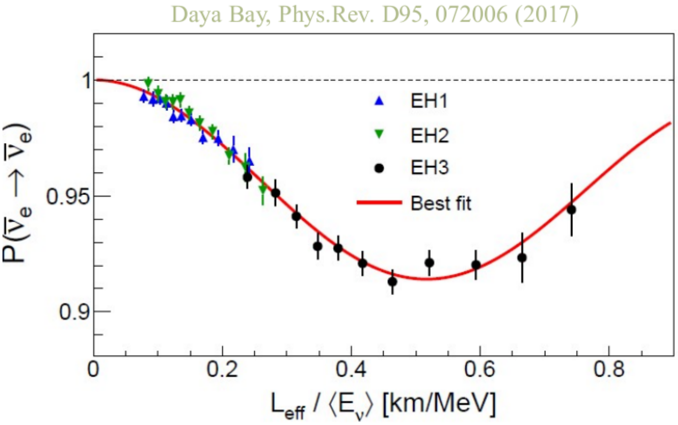
Gallium Anomaly



Gallium Anomaly

- Gallium experiments (GALLEX and SAGE) were constructed to observe the low energy $p - p$ neutrinos emitted by the sun through the reaction $^{71}Ga + \nu_e \rightarrow {}^{71}Ge + e^-$.
- To calibrate the ^{71}Ge collection efficiency, an intense β^+ source is kept close to the detector.
- In two cases, the calibration is consistent with 1 and in two other cases it is noticeably lower. Average value is about 0.86.
- The shortfall is ascribed to about 15% of ν_e emitted by the source oscillating into something else within the short distance between the source and the detector.

Daya Bay Spectrum



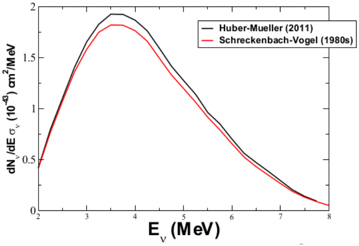
Reactor Anti-neutrino Anomaly

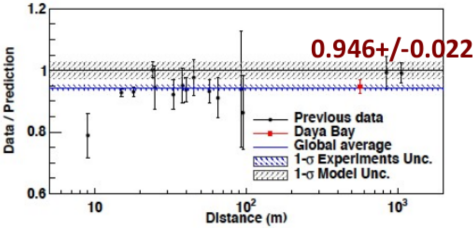
- CHOOZ experiment showed the importance of anti-neutrino measurements at a distance of 1 km in the determination of θ_{13}. Mohan Narayan, G. Rajasekaran and SUS, PRD 58 (1998) 031301 . P. Huber, M. Lindner *et al*, NPB 665 (2003) 487.
- The precise measurement available currently is the result of having a near detector (at a distance of 100 meters or so) and a far detector (at a distance of a km or so).
- It is assumed that the near detector measures the unoscillated event rate. Is it really so?
- How do we know what the near detector interaction rate should be?
- First we measure the β decay spectrum of the reactor. With this spectrum and the isotope composition of the reactor core as inputs, we use the Fermi theory of β decay to calculate the $\bar{\nu}_e$ spectrum.
- Need to take into account a number of corrections into account.

Reactor Anti-neutrino Anomaly

- The calculations of anti-neutrino event rates for near detectors were revised in 2011, just as Double CHOOZ, Daya Bay and RENO started taking data.
  G. Mention *et al* PRD 83 (2011) 073006.
  P. Huber [PRC 84 (2011) 024617, PRC 85 (2012) 029901]
- These calculations showed that the old calculations of unoscillated event rate underestimated the total flux by about 5%.
- If the near detector measurements agree with old calculations, it means they are actually observing a shortfall of 5%!
- Analyzing this shortfall in the framework on oscillations, we get $|\Delta m^2| > 1.5$ eV^2 and $\sin^2 2\theta \approx 0.14 \pm 0.08$ (95% C.L.).

Reactor Anti-neutrino Anomaly





Is RAA really there?

- Further refined calculations reduced the discrepancy with near detector measurements.
- But to settle the question, a number of experiments were designed and constructed.
  1. NEOS (accurate measurement of spectral shape, completed)
  2. DANSS (measure the rate as a function of distance, taking data)
  3. STEREO (measure rate at different distances, taking data)
  4. PROSPECT (also measure rate at different distances, taking data)
  5. SoLid (2-d oscillometry in E and L, taking data)
- The analysis of current data from the first four experiments does not show any evidence for neutrino oscillations with Δm^2 of the order of eV^2 and mixing angle $\sin^2 2\theta \sim 0.1$.
- Stay tuned to see what future data reveals!

The SAGA of LSND

- Liquid Scintillator Neutrino Detector was an experiment at Los Alamos lab, set up to primarily measure neutrino-nucleus cross sections at medium energies $30 - 200$ MeV. The source to detector distance is 30 m.
- In 1995, they claimed to have seen evidence for $\bar{\nu}_\mu \to \bar{\nu}_e$ oscillations. They quote the following measured values for $\langle P(\bar{\nu}_\mu \to \bar{\nu}_e) \rangle$
  - nucl-ex/9504002: $(3.4 \pm 1.9) \times 10^{-3}$
  - nucl-ex/9605003: $(3.1 \pm 1.1) \times 10^{-3}$
  - hep-ex/0104049: $(2.6 \pm 0.7 \pm 0.5) \times 10^{-3}$

  They also measured $\nu_\mu \to \nu_e$ oscillation probability and get a consistent measurement $(2.6 \pm 1.0 \pm 0.5) \times 10^{-3}$.
- Point in favour: All the numbers are consistent with each other, with error going down with more data, as expected.
- Points against:
  - The oscillation probability is consistent with zero at 3σ.
  - An almost identical experiment, KARMEN, did not see a signal.
  - Solutions to solar and atmospheric neutrino oscillations exhuasted all possible oscillations between active flavours.

LSND Results

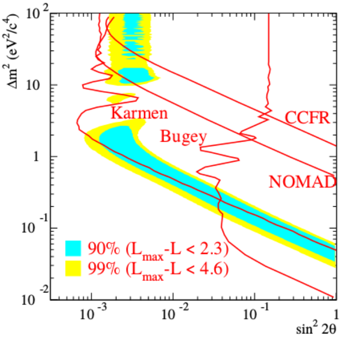
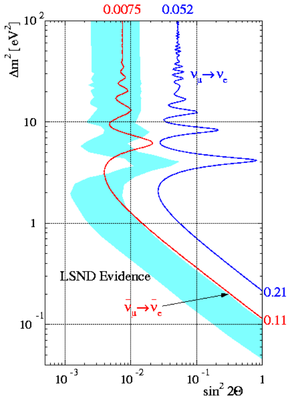


FIG. 27: A $(\sin^2 2\theta, \Delta m^2)$ oscillation parameter fit for the entire data sample, $20 < E_e < 200$ MeV. The fit includes primary $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillations and secondary $\nu_\mu \rightarrow \nu_e$ oscillations, as well as all known neutrino backgrounds. The inner and outer regions correspond to 90% and 99% CL allowed regions, while the curves are 90% CL limits from the Bugey reactor experiment, the CCFR experiment at Fermilab, the NOMAD experiment at CERN, and the KARMEN experiment at ISIS.

KARMEN Results



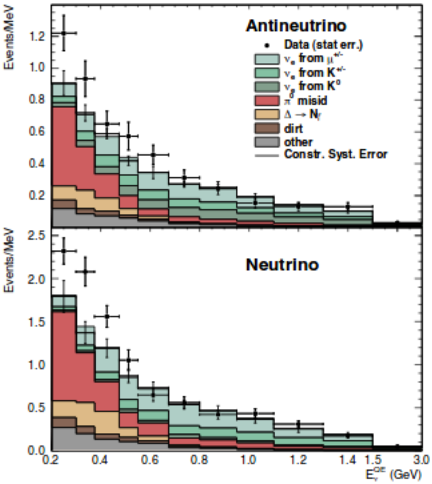
Whither Neutrino Oscillations if LSND is true?

- If LSND result is interpreted in terms of neutrino oscillations, then the Δm^2_{LSND} required to explain it is quite large, anywhere between $0.4 - 10$ eV^2.
- That why it is in conflict with solar and atmospheric neutrino oscillations.
- If you want to account for LSND result also, then you must introduce a fourth neutrino of light mass (mass of order eV). Since LEP has already shown that there are only light active neutrinos, this fourth neutrino must be **sterile**. Point first made by Srubabati Goswami in 1996.
- That is, you assume that there are three active and one sterile neutrino. They all mix (somehow) and form four mass eigenstates, one which has a mass of about an eV.
- This state has an overlap of about 0.05 with both ν_e and ν_μ so that you end up getting an average oscillation probability of about 2.5×10^{-3}.

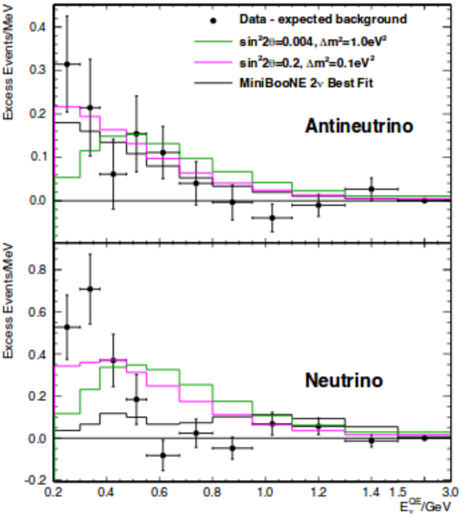
MiniBooNE

- MiniBooNE is an accelerator experiment at Fermilab, which has been running at Fermilab from 2002 onwards. It shoots a beam $\nu_\mu/\bar{\nu}_\mu$, with peak flux at an energy 500 MeV at a detector 500 m away.
- Note that it has the same value of L/E of about 1 m/MeV as LSND. So if LSND signal is really due to oscillations, then MiniBooNE should also see such a signal.
- The idea of constructing MiniBooNE is that it will have much more intensity than LSND so that if the oscillation signal is really there, then it will be clearly visible.
- They have been seeing excess events at lower energies, especially in the bins 200-300 MeV and 300-400 MeV. But those are also the bins in which their background events are the largest.
- So there has been a long running debate about whether what they see are really excess or just statistical fluctuation.
- In a paper released in 2013 (arXiv:1303.2588), they felt that the excess was more than 3σ and claimed to see a signal for $\nu_\mu \to \nu_e$ and $\bar{\nu}_\mu \to \bar{\nu}_e$ oscillations.

Early Results of MiniBooNE (2013)



Early Results of MiniBooNE (2013)



Latest MiniBooNE results (arXiv:1805.12028)

- At the end of May 2018, MiniBooNE released another paper with the results of their full neutrino and anti-neutrino data. In this paper, they claim oscillation signal with much more confidence of about 4.8σ.
- They have more statistics but the old problem of "Is it really the excess or it it a fluctuation of the background?" still should be raised. They answer it by saying that they developed various methods, related to their own data, by which they can constrain their background event rates quite precisely.
- They claim that they have taken all possible standard model processes into account in constraining the background. If somebody insists that what they see is larger than expected background, then that person has to come up with a standard model process which can explain this larger background.
- They say that the combined significance of LSND and MiniBooNE is better than 6σ.

Results of MiniBooNE (2018)

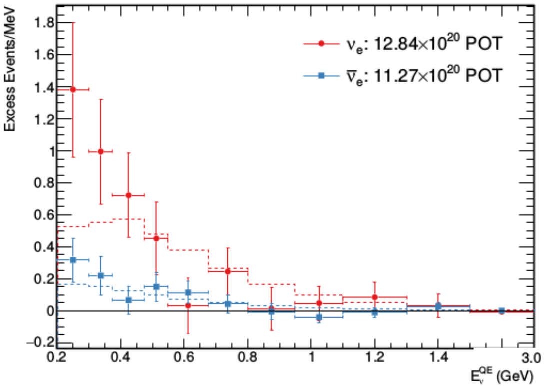


FIG. 2: The MiniBooNE total event excesses as a function of E_ν^{QE} in both neutrino mode and antineutrino mode, corresponding to 12.84×10^{20} POT and 11.27×10^{20} POT, respectively. (Error bars include both statistical and correlated systematic uncertainties.) The dashed curves show the best fits to the neutrino-mode and antineutrino-mode data assuming standard two-neutrino oscillations.

Results of MiniBooNE (2018)

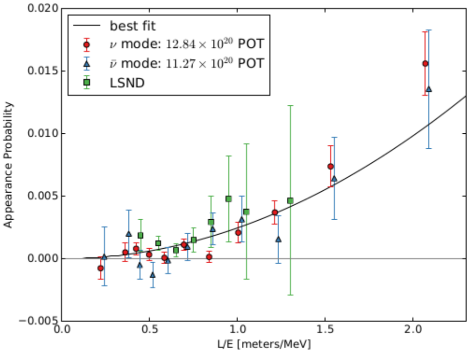


FIG. 3: A comparison between the L/E_ν^{QE} distributions for the MiniBooNE data excesses in neutrino mode (12.84×10^{20} POT) and antineutrino mode (11.27×10^{20} POT) to the L/E distribution from LSND [1]. The error bars show statistical uncertainties only. The solid curve shows the best fit to the LSND and MiniBooNE data assuming standard two-neutrino oscillations. The excess of MiniBooNE electron-neutrino candidate events is consistent with the LSND excess.

Results of MiniBooNE (2018)

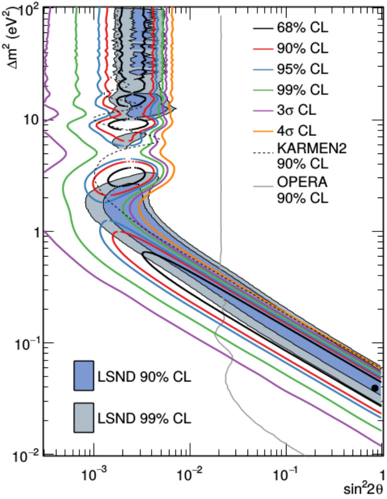


FIG. 4: MiniBooNE allowed regions in neutrino mode (12.84×10^{20} POT) for events with $200 < E_\nu^{QE} < 1250$ MeV within a two-neutrino oscillation model. The shaded areas show the 90% and 99% C.L. LSND $\bar{\nu}_\mu \to \bar{\nu}_e$ allowed regions. The black circle shows the MiniBooNE best fit point. Also shown are

Results of MiniBooNE (2018)

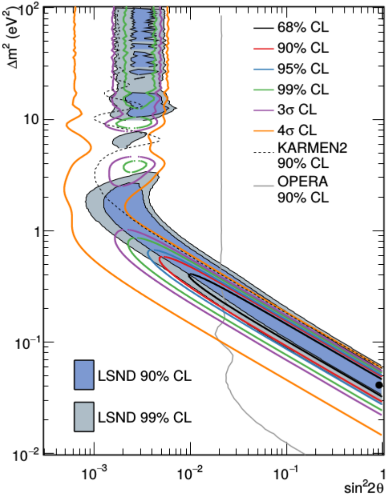


FIG. 5: MiniBooNE allowed regions for a combined neutrino mode (12.84×10^{20} POT) and antineutrino mode (11.27×10^{20} POT) data sets for events with $200 < E_\nu^{QE} < 1250$ MeV within a two-neutrino oscillation model. The shaded areas show the 90% and 99% C.L. LSND $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ allowed

(3+1) light neutrino oscillations

- It is striking that both reactor neutrino data and accelerator neutrino data seem to favour a fourth neutrino with $\Delta m^2 \sim 1$ ev^2.
- Very likely that is a just a consequence of the fact that for all these experiments that is the value of Δm^2 for which $\Delta m^2 L/E \sim 1$.
- We ask the question, if there is a third independent $\Delta m^2 \sim 1$ eV^2, what are the consequences we can expect in (a) current experiments and (b) in future experiments?
- Post Super-Kamiokande, global data fits were performed for solar, atmospheric and LSND data.
- These fits, in general, did not give a good fit to the data. The spoilsport is the observed zenith angle dependent atmospheric neutrino data of Super-K.
  S.M. Bilenky et al., PRD 60 (1999) 073007 [hep-ph/9903454].
  M. Maltoni, T. Schwetz, J. W. F. Valle, PLB 518 (2001) 252 [hep-ph/0107150].
- The survival probability $P(\nu_\mu \to \nu_\mu)$ for downward going neutrinos would have been smaller than 1, if there are sterile neutrinos with

(3+1) light neutrino oscillations

- In four flavour mixing scenario, all the short baseline oscillations are driven by the same $\Delta m^2 \sim 1$ eV^2.
- But different oscillation channels depend on different mixing matrix paramters. $P(\nu_e \to \nu_e)$ depends only $|U_{e4}|$, $P(\nu_\mu \to \nu_\mu)$ depends only on $|U_{\mu 4}|^2$, but $P(\nu_\mu \to \nu_e) \propto |U_{e4}|^2 |U_{\mu 4}|^2$.
- Given that the reactor anti-neutrino anomaly is becoming less compelling, we may assume $|U_{e4}|^2$ is small. Then to explain $P(\nu_\mu \to \nu_e)$, we need to make $|U_{\mu 4}|^2$ moderately large. But that, in turn, will make $P(\nu_\mu \to \nu_\mu)$ too small.
- In the (3+1) global fits done, the Δchi^2 for (3+1) fit is considerably worse than the fit for 3 flavour fit.
  Dentler, Hernandez-Cabezudo, Kopp, Machado, MM, Martinez-Soler, Schwetz, arXiv:1803.10661.

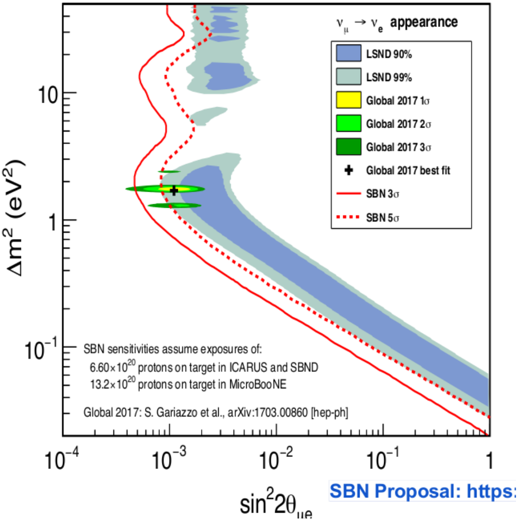
Are There Short Baseline $\nu_\mu \to \nu_e$ Oscillations?

- A major goal of DUNE is to measure δ_{CP}, the CP violating phase of the MNS matrix, accurately. This is possible provided under the assumption that the three flavour oscillation paradigm is the correct one.
- It is imperative to firmly establish or rule out the existence of a fourth light neutrino as is implied by LSND/MiniBooNE.
- Interpretation of DUNE results in the (3+1) flavour oscillation framework will be very different from those in three flavour framework. Agarwala *et al* JHEP 1602 (2016) 111.
  Dutta, Gandhi *et al* JHEP 1611 (2016) 122.

MicroBooNE and SBN

- MicroBooNE (phase 1) and Short Baseline Neutrino programe (phase 2) at Fermilab are Liquid Argon detectors which aim to (a) resolve the anomalies and (b) measure neutrino cross sections with Argon to provide input to DUNE.
- The biggest problem in MiniBooNE is the background coming from π^0 being misidentified as an electron, thus faking ν_e appearance.
- Liquid Argon detectors have a much better resolution and should be able to identify π^0 cleanly. The separation between electrons and π^0s will be more effective and the question of ν_e appearance can be settled.
- MicroBooNE is taking data. SBN and ICARUS will start taking data in 2020.
- A two year run (6×10^{20} POT) of SBN and ICARUS will settle if short baseline $\nu_\mu \to \nu_e$ oscillations exist or not.

Sensitivity of MicroBooNE and SBN



Conclusions-Reactors

- Reactor Anti-neutrino Anomaly (RAA) and Gallium Anomaly (GA) revived the interest in light sterile neutrinos.
- A number of experiments are launched to verify if neutrino oscillations are the reason for RAA.
- Some of them concentrate measuring the event spectrum accurately with the expecation of observing the distortion caused by oscillations (technique used by KamLAND to determine $\Delta m^2_{\rm solar}$ accurately).
- Others try observe the modifications caused by variation in the source-detector distance. Such experiments can be done only at sources with small cores (of about 30 cm).
- These experiments take the ratios of differential event rates at different distances. The nuclear modelling uncertainties cancel out in the ratios, leaving the ratio a pure function of the distance.
- Early results of these experiments show that they do not favour oscillations as the explanation of RAA.

Conclusions-Accelerators

- Recent results of MiniBooNE revived the interest in the LSND claim of $\nu_\mu \to \nu_e$ transitions at short baselines.
- MiniBooNE claim a nearly 5 σ evidence for such transitions. They also claim a 6 σ evidence when their data is combined with that of LSND.
- Two problems with MiniBooNE data:
  1. The energy range where they see most excess electron events is also the range where their π^0 mis-identification background is the largest.
  2. Most of their signal events are the in range 200-500 MeV. They present data only for $E > 200$ MeV, which means that their energy reconstruction is effective only above the threshold 200 MeV.
  3. Question: If most of the signal is close to the threshold region, what is its significance?
- Fermilab Short Baseline Neutrino Program addresses this problem.

Final Conclusions

- **Big Question:** Are there sterile neutrinos or not?
- The reactor data seems to favour a nuclear physics solution to RAA.
- There are other issues in reactor neutrino data (such as a bump at 5 MeV) which can't be explained by oscillatons.
- **A very personal opinion:** RAA is probably not due to sterile neutrino oscillations.
- MiniBooNE confirmation of LSND ν_e appearance has made the situation very interesting, to say the least.
- On the other hand, there are some valid questions about observed ν_e excess seen by MiniBooNE.
- Fermilab SBN program will settle the question of the existence/non-existence of light sterile neutrino, which is very important for its long baseline program.
- **One last thought:** An analysis of T2K near detector data may also throw some light on this question.