I. SUMMARY OF CURRENT GLOBAL PICTURE CONCERNING THE SHORT-BASELINE ANOMALIES

The current three-massive-neutrinos paradigm fits almost all neutrino data very well; it adds nonzero neutrino masses and lepton mixing to the standard model Lagrangian in such a way that no new degrees of freedom or interactions relevant for neutrino laboratory observables are introduced. Data from different experiments and information from cosmological observables seem to hint, however, that there is new neutrino physics beyond the standard paradigm. We refer to these hints collectively as the short-baseline (SBL) anomalies, where short-baseline refers to neutrino energies and baselines such that oscillation effects governed by the established neutrino mass-squared differences, $\Delta m^2_{12} \sim 8 \times 10^{-5}$ eV^2 and $|\Delta m^2_{13}| \sim 2 \times 10^{-3}$ eV^2 are too small to play any role. The conundrum we are facing is that none of the hints, either individually or in combination, is of sufficient statistical significance to be considered convincing evidence for the existence of new physics. The SBL anomalies are, however, intriguing and also persistent enough to warrant further, definitive, investigation. The SBL anomalies can be roughly sub-divided into three categories which we generically describe as

1. Evidence for electron-neutrino disappearance

A recent re-evaluation of the $\bar{\nu}_e$ flux from nuclear reactors implies that SBL reactor antineutrino experiments observe a 6% deficit, at the 2-3σ level, of electron antineutrinos*. This deficit can be interpreted as a hint for $\bar{\nu}_e$ disappearance at SBL. The experiments in question are sensitive to neutrinos with energies in the 3–10 MeV range, and define baselines between 10 m and 1 km. Combined, they span L/E values between a few and a few hundred m/MeV. The evidence is consistent with an effect that is independent from the neutrino energy E or the baseline L (or the ratio L/E).

At the same time, calibration data from the gallium solar neutrino experiments, which make use of intense radioactive ^{51}Cr and ^{37}Ar electron capture sources, hint at the disappearance of ν_e at SBL. This effect is at the two-sigma level. These experiments study neutrinos with energies below 1 MeV and probe baselines around 1 m (hence L/E values around 1 m/MeV). The evidence is consistent with an effect that is independent from the neutrino energy E or the baseline L. These data are consistent with the SBL reactor anomalies.

2. Evidence for muon-neutrinos behaving as electron-neutrinos

Data from the LSND experiment can be interpreted as, roughly, over three-sigma evidence for $\bar{\nu}_\mu \to \bar{\nu}_e$ transitions at SBL. LSND defines a baseline L around 30 m and neutrino energies of tens of MeV, spanning L/E values between 0.2 m/MeV and 3 m/MeV. In more detail, the LSND collaboration observes an excess of $\bar{\nu}_e$ events above background expectations. This excess can be accommodated if one postulates that around 0.2% of the neutrinos produced as $\bar{\nu}_\mu$ behave like $\bar{\nu}_e$ in the detector. The LSND excess, expressed as a flavor conversion probability, is depicted as a function of L/E in Figure 1. As already mentioned, the null-hypothesis is ruled out at over the three sigma level. The data also hint at a phenomenon that depends on L/E favoring that possibility over a "flat" one at around the two-sigma level. The phenomenon observed by LSND is not confirmed by the Karmen experiment. Since the sensitivity of Karmen is similar to that of LSND, it is easiest to account for both data sets by postulating an L dependent phenomenon (at Karmen, L ~ 18 m).

The MiniBooNE experiment was conducted to test the LSND anomaly under the assumption that (a) the physics responsible for it is a function of L/E, and (b) neutrinos and antineutrinos both feel a similar effect, i.e., CP is approximately conserved in the physics responsible for the LSND anomaly. The L/E assumption is valid as long as the anomaly is related to a property of the space-time evolution of the neutrino state (like flavor oscillations or a finite neutrino lifetime).[†] MiniBooNE is set up for L ~ 1 km and neutrino energies around hundreds of MeV, spanning the same L/E region as LSND.

The MiniBooNE data for neutrinos and antineutrinos, expressed as a flavor conversion probability, is depicted as a function of L/E in Figure 1. The MiniBooNE antineutrino data, excluding the two highest L/E bins, are consistent with both the LSND data and the MiniBooNE neutrino data. They are also marginally consistent with the null hypothesis. The MiniBooNE neutrino data, in turn, is also statistically consistent with the null hypothesis if one excludes the two highest L/E bins. The MiniBooNE neutrino data do not agree with those from LSND, at around the two sigma level.

The two highest L/E bins at MiniBooNE – i.e. the two lowest energy bins – including data taken with neutrinos and antineutrinos, point to a significant excess of ν_e candidates over background expectations (see Figure FIGURE). This excess occurs in the region where background events are most abundant and may be due to yet-to-be-identified standard model physics effects including, for example, an unexpectedly high rate of photons from certain exclusive neutral current processes, and will be partially explored by the MicroBooNE experiment. Note that these two bins are outside the L/E range probed by the LSND experiment.

3. Evidence for more types of neutrinos

Cosmological data provide curious hints that the relativistic energy density, parametrized as effective number of relativistic degrees of freedom is larger than dictated by the standard model (or the standard neutrino paradigm). A standard model neutrino counts as approximately one relativistic degree of freedom and hence, in the standard paradigm, one would expect 3 relativistic degrees of freedom. Big Bang Nucleosynthesis (BBN) data, i.e., measurements of the relic abundance of light elements, for example, are consistent with an effective neutrino number that lies between 3 and 4. Combinations of lower-redshift cosmological observables, including precision measurements of spatial correlations in the cosmic microwave background radiation temperature, also point to an effective neutrino number that is more consistent with 4 than 3. These data can be explained by postulating that there are four light neutrinos, all of them in thermal equilibrium before BBN. It is important to point out that these data do not imply that the new degrees of freedom are “neutrinos” (i.e., very light, very weakly coupled fermions), they only imply that the ultra-relativistic component of the energy density of the early universe is higher than expected. Next-generation cosmological data will qualitatively change this picture and point to a clearer message as far as new relativistic degrees of freedom in the early universe are concerned. It also should be noted that observations of large scale structure seem to point to a very light additional particle species, if indeed a new particle is the cause for the large value of the relativistic energy density.

There is no model-independent way of relating the different ingredients that make up the SBL anomalies: there remains the logical possibility that these are completely unrelated phenomena. The hypothesis that subsets of these are different manifestations of the same underlying new physics is much more interesting and, in our opinion, provides the strongest motivation for definitively investigating the source of the SBL anomalies. The assumption that the new physics phenomenon is sensitive to L/E, for example, allows one to directly compare MiniBooNE and LSND. Taking all anomalies at face value, such a combination leads one to believe that the new physics is strongly CP- violating. Furthermore, since the reactor SBL anomalies and LSND probe similar L/E ranges, there remains the possibility that the same phenomenon explains electron antineutrino disappearance and muon-neutrino to electron neutrino conversion. This is the case in several concrete scenarios, as we discuss in more detail below. Finally, if the new phenomenon requires the introduction of new degrees of freedom, one may also hope to address the cosmological evidence (3) discussed above.

It is well known that all the data in (1) and (2) can be interpreted as evidence for one or more new massive neutrino states, with masses below a few eV. LEP data allow only three light neutrino weak-eigenstates so the new orthogonal state(s) do not participate in charged-current or neutral-current weak interactions, and are hence dubbed sterile. The scenario where one allows for n new neutrino mass eigenstates is referred to as a 3 + n scenario. Both 3+1 and 3+2 scenarios provide rather mediocre[‡] fits to all neutrino data. 3+3 and "higher" scenarios, it has been argued, do not fare significantly better. The relatively poor fits are consequences of other neutrino data that provide no evidence for new neutrinos at 1 eV. These include the standard neutrino oscillation data (solar and atmospheric, MINOS, K2K, and KamLAND) and short-baseline searches for ν_e and ν_μ (and their antiparticles) disappearance. 3+2 scenarios (and "higher") are particularly interesting because they can resolve the MiniBooNE neutrinos versus LSND antineutrinos tension quite naturally, simply by making use of new CP-violating phases which are observable in short-baseline experiments. The argument has also been made that the 3+2 scenario provides a qualitatively better fit to all data than the 3+1 scenario.

Regardless of the quality of the 3+n fits, light sterile neutrinos serve as the most compelling and most useful complete model capable of addressing the SBL anomalies. They allow, for example, one to correlate neutrino appearance and disappearance and provide a complete suite of well-defined measurements one should pursue in order to definitively test the model. Theoretically, on the other hand, it is possible to construct simple, well-motivated models that lead to light sterile neutrinos. If any of these happen to be true, the investigation of the SBL anomalies will not only reveal new states of matter and new phenomena, but may also contribute to our understanding of the origin of neutrino masses or other outstanding issues in particle physics.

Evidence (3) does provide an interesting challenge to the hypothesis that there are new massive neutrino states. While the existence of one new neutrino degree of freedom is preferred by the cosmological data, other such observables, including studies of the large scale structure of the universe, require all new degrees of freedom to be lighter than a fraction of an eV. Hence, if there is evidence for new neutrinos from cosmology, these appear not to be the same as the ones that can accommodate the SBL anomalies. This ambiguity will either be resolved by next-generation data or may end up pointing towards an improved understanding of particle physics or the early universe and its constituents.

Using the light-sterile-neutrino model as a guide, it is possible to identify definitive tests of the short-baseline anomalies. These include: better than per mille searches for $\nu_\mu \leftrightarrow \nu_e$ transitions at short baselines, and percent- level searches for ν_μ and ν_e disappearance at SBL.

Slightly more model dependent arguments point to searches for τ appearance, at the per-mille level as complementary, nontrivial sources of information. In more detail, the main goal is to (a) look for $\nu_\mu \rightarrow \nu_e$ at L/E values around 1 m/MeV with precision that is qualitatively superior to that obtained by both LSND and MiniBooNE (see Figure FIGURE), and (b) measure $\nu_e \rightarrow \nu_e$ and $\nu_\mu \rightarrow \nu_\mu$ survival probabilities at L/E values around 1 m/MeV at around the percent level. A good rule of thumb is as follows: appearance probabilities of order ε^2 imply disappearance rates around ε. Also, all of the SBL anomalies so far are reasonably consistent with an L/E-independent effect and therefore, the observation of the L/E-dependence which is characteristic for oscillations is of the essence to establish oscillation as the underlying physics model. Another phenomenological feature very specific to sterile neutrino oscillations is, that these oscillation signatures should exist with the same strength also in neutral current detection experiments.

* Note, that not only the fluxes have changed but also the recently revised value of the neutron lifetime contributes to this effect.

† For $m_\nu/E \ll 1$, L/E is proportional to the proper time of the neutrino, i.e., it is a measure of the time elapsed between production and detection in the neutrino's rest frame.

‡On the other hand, one can argue that both fare better than the standard paradigm and that none are ruled out.

II. Upcoming Measurements

A variety of running and approved experiments are expected to add new information that may help us to interpret the present tensions with the three-neutrino paradigm, and contribute to the search for light sterile neutrinos at the $\Delta m^2 \sim 1\text{eV}^2$ scale. Table 1 lists the anticipated experimental information as a function of time, broken up into near-term (2012-2013), mid-term (2013-2014), and longer-term (2014-2017) intervals. Contacts from each experiment have informed the focus group about the relevant results that are expected and the associated sensitivities.

Different upcoming measurements will cover different regions of L/E, as shown in Fig. 1. Together, these measurements will explore oscillations driven by splittings Δm^2 from 0.002 eV^2 to infinity.

One cannot predict the impact that the upcoming measurements will have on the programmatic short-baseline decisions of the community. Results expected within the next year or two, which could influence decisions in the 2014 time frame, may have a large impact. It is possible that these measurements will be inconclusive regarding the tensions with the three-neutrino paradigm. However, that would be the outcome in which a longer-term, ***definitive*** program to resolve these tensions would be most strongly needed.

2012-2013	***2013-2014***	***2014-2017***
Appearance:		
MiniBooNE anti-ν_e (x2 more data)	ICARUS ν_e	MicroBooNE ν_e
MiniBooNE ν_e, anti-ν_e combination	T2K near detector ν_e	NOvA near detector ν_e, anti-ν_e
Disappearance:		
MiniBooNE/SciBooNE joint anti-ν_μ	IceCube ν_μ and anti-ν_μ	MicroBooNE ν_μ MINOS+ ν_μ
Other:		
reactor flux calculations	radioactive source exps. Planck results	

Table I: List of expected measurements from on-going and near-term approved experiments.

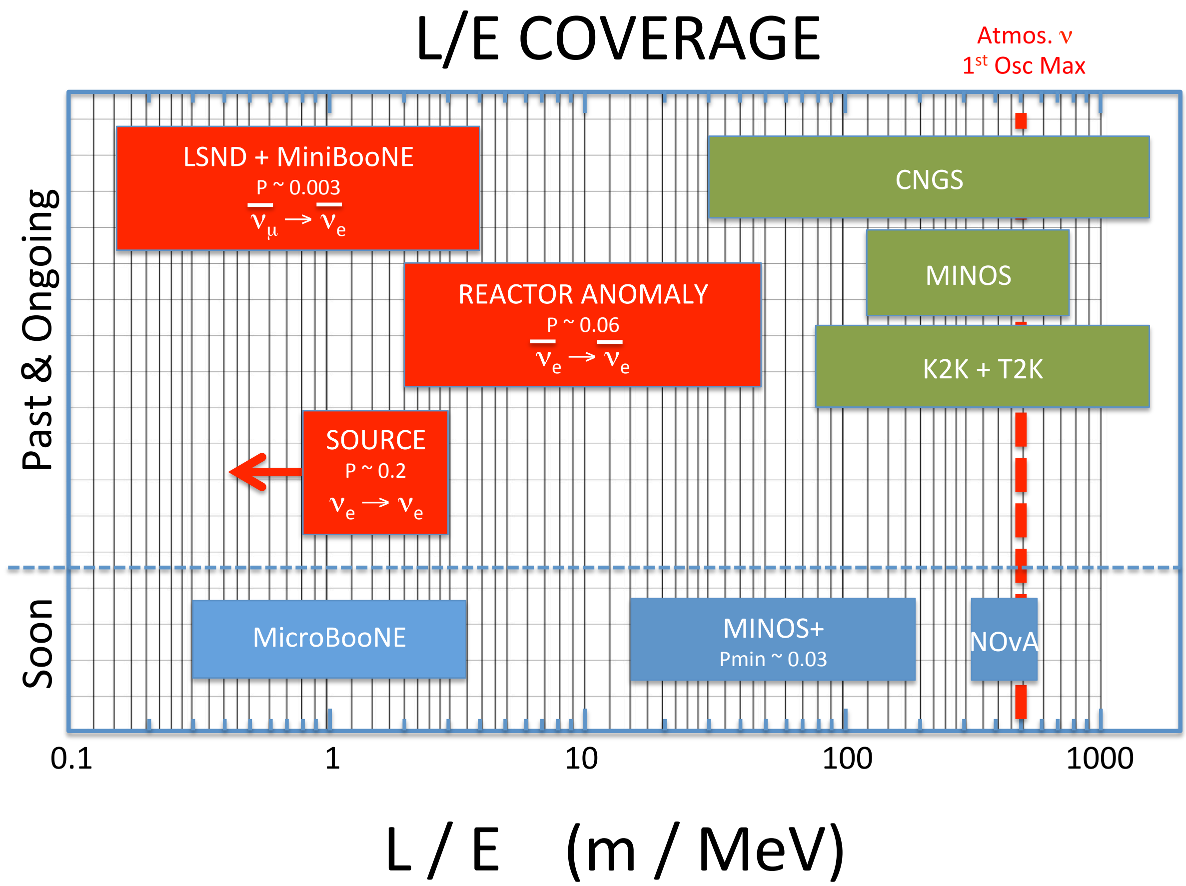

Figure 1. The L/E coverage of upcoming experiments.

III. The Future

This is a work in progress. It will discuss what should be done, and especially what role Fermilab can play, assuming an inconclusive situation in 2014. It will address what is needed to confirm or exclude the existence of sterile neutrinos or new mass eigenstates whose masses lead to splittings $\Delta m^2 > 10^{-2}\mathrm{eV}^2$. To allow for the possibility that there is new physics that is not sterile neutrinos, or not "just" sterile neutrinos, it will also address what is needed to confirm or exclude the leading individual existing experimental anomalies.

If there are sterile neutrinos, then disappearance and appearance probabilities are related, as already mentioned in Part I. In 3 + 1 models, $P(\nu_\mu \rightarrow \text{Not } \nu_\mu)P(\nu_e \rightarrow \text{Not } \nu_e) \approx 2P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$. In 3 + 2 models, neglecting small terms, $P(\nu_\mu \rightarrow \text{Not } \nu_\mu)P(\nu_e \rightarrow \text{Not } \nu_e) \geq 2P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$. Thus, measurements of both disappearance and appearance probabilities can test these physics models.

To explore the LSND anomaly specifically, perhaps we should advocate a better version of LSND, searching for $\bar{\nu}_\mu \to \bar{\nu}_e$ with neutrinos from stopped pions, but with better statistics than LSND, and with LSND's systematic weaknesses addressed. Such an experiment should have a better beam duty factor that LSND to test any cosmic-ray-based explanation of LSND, the experiment should probably be very far off axis to test odd beam-related possibilities as explanations of LSND, and it should be a two-detector or single-but-long detector experiment to test the L dependence of any excess.