Final Report: DOE Grant to organize "International Symposium on Opportunities in Underground Physics", Asilomar, CA, May 24-27, 2013

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The International Symposium in Opportunities in Underground Physics (ISOUP) was held in Asilomar, CA during May 24-27,2013. The Symposium brought together scientists from the US and abroad for an open discussion on science opportunities provided by the possibility of a new generation of large underground detectors associated with long baseline neutrino beams. The Symposium was highly successful. The main focus of the Symposium was the science goals that could be achieved by placing such a detector deep underground.

The symposium was organized by an organizing committee with the following membership: Robert Svoboda (University of California, Davis, Co-chair), Milind Diwan (Brookhaven National Laboratory, Co-chair), Kaladi Babu (Oklahoma State University), Alex Friedland (Los Alamos National Laboratory), Maury Goodman (Argonne National Laboratory), Boris Kayser (Fermi National Accelerator Laboratory), Jogesh Pati (Stanford National Laboratory), Kate Scholberg (Duke University), and Robert Wilson (Colorado State University). In addition, Marc Bergevin served as the Scientific Secretary. The committee held weekly organizational meetings via phone for a period of about three months leading to the Symposium, which helped in having a well organized symposium.

The Symposium was attended by 84 registered participants from the US and from overseas. A description of the Symposium, along with the full list of participants and speakers, including files of the talks is made available on the following webpage:

http://neutrino.physics.ucdavis.edu/indico/conferenceProgram.py?confId=0

There were a total of 38 invited talks. In addition, a Panel Discussion was held on May 27, withe the following panelists: Pier Odone, JoAnne Hewett, Hank Sobel, Antonio Masiero, Marzio Nessi, Yasuhiro Okada, Jogesh Pati, Natalie Roe and Georg Raffelt. The major world labs in HEP were represented in the Panel, including Fermilab, INFN, Italy, CERN and KEK. A consensus view of the scientific goals at large neutrino detectors, as well as the need to place such detectors deep underground emerged from the discussions.

Expenditure:

The DOE funding of \$8,000 for organizing the Symposium was fully spent. The Asilomar Conference Center was paid this amount to cover in part the Audio Visual equipment, and to cover in part the travel and waived registration fee of a few young participants. Additional support for the Symposium came from INPAC (Institute for Nuclear and Particle Astrophysics and Cosmology) of the University of California in the amount of \$20,000. There was a small registration fee charged to the participants, which provided further support. The registration fee was waived for several young participants and a few participants who came from abroad.

Deliverables

Three deliverables were promised to the DOE. They are

1. Talks to made available on the conference web page which will be accessible to the HEP community.
2. A summary document of panel discussion between lab representatives, endorsed by the panel members.
3. A 10-page summary of the workshop science and potential U.S. involvement in these projects available for the Snowmass meeting.

All three commitments are being fulfilled. Files of the talks delivered at the Symposium are being made available at the following web page:

http://neutrino.physics.ucdavis.edu/indico/contributionListDisplay.py?confId=0

A summary document signed by the panel members as well as the participants was prepared soon after the meeting. A copy of the document is enclosed as an Appendix, entitled "Opportunities in Underground Physics: The View from Asilomar."

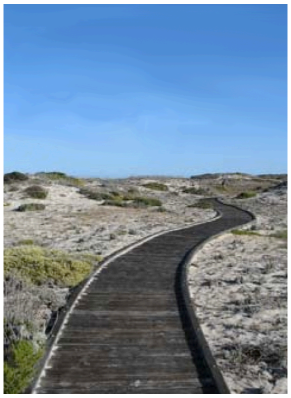
A short 16 page scientific summary of the Symposium was prepared and made available to the Snowmass process. This document is also enclosed as an Appendix, entitled "Physics Sensitivity of New Large Underground Neutrino Detectors".

Appendix

1. "Opportunities in Underground Physics: The View from Asilomar"

2. "Physics Sensitivity of New Large Underground Neutrino Detectors".

Opportunities in Underground Physics: The View from Asilomar



The International Symposium on Opportunities in Underground Physics (ISOUP) was held at Asilomar, California on May 24-27. [1]The goal of the symposium was to bring together experimental and theoretical physicists to discuss the science opportunities offered by the possibility of a new generation of large neutrino detectors associated with long-baseline neutrino experiments. The focus was on the broad science program that would be enabled by the *underground* location of these detectors. What are the truly “Big Questions” we want to answer by going deep into mines and building huge detectors?

The Big Questions

What are the “Big Questions” for particle physics and astrophysics? The Standard Model (SM) provides insight on the interaction of fundamental particles by relating the interactions to a few simple and elegant principles. It can be deemed successful in that all its predictions involving electroweak and QCD phenomena are accurately borne out experimentally, including the recent discovery of the Higgs-like particle at the LHC. Yet it has major shortcomings in that it does not provide any explanation of the quantization of electric charge, of coexistence of quarks and leptons, quantum numbers of these particles within a family, the existence of dark matter, the origins of the three basic forces, the observed mass scales of the neutrinos, and the value of many fundamental parameters that must be set by hand. These shortcomings suggest that there must exist fundamental new physics beyond that of the SM. In this regard, some "Big Questions" are:

Do the parameters of the neutrino mixing matrix follow a pattern determined by a new symmetry?

In other words, are the elements of the mixing matrix determined by an overall organizing symmetry (perhaps broken by subtle interactions not yet discovered), or are they unimportant, essentially “random” numbers? The precision mixing measurement program outlined at ISOUP will address these questions directly. *It is worth reiterating that some important precision measurements (like θ_{12} and θ_{13}) are best done with underground detectors*.

Why is there a “periodic table” of elementary particles?

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[1] Slides from presentations and photos of the Symposium can be viewed at: http://neutrino.physics.ucdavis.edu/indico/conferenceDisplay.py?ovw=True&confId=0

The SM does not provide any insight to the observed number of families, nor predict the possible symmetry of quark and lepton family organization. Is there an overall "grand unification" of the lepton family organization that predicts three chiral families with identical quantum numbers? What is the ordering of neutrino masses in this table? Are quark and lepton mixing related? Neutrino mixing experiments also address this question. *The ordering of neutrino masses and a precise measurement of θ_{23} (resolving the octant degeneracy) can be measured by underground experiments using atmospheric neutrinos.*

Is CP violation peculiar to quarks, or do leptons also violate CP?

We currently do not know the answer to some very fundamental questions, like "do leptons respect CP symmetry?" and the related question "is the CP phase for neutrinos essentially a random number?" The discovery of CPV in the neutrino system would not only be as important as it was for the quark system, but it would also shed light on our understanding of the origin of matter- antimatter asymmetry of the universe. Furthermore, measurement of the corresponding CP phase could help distinguish between theoretical models which predict the same. In this case, the best neutrino CP measurements are made using neutrino beams.

How many different kinds of matter are there?

We do not know whether the neutrinos have Dirac or Majorana masses. Both can be accommodated into the SM and thus further experimental guidance is needed. In addition, the SM does not give us much insight into the nature of dark matter or dark energy, and makes no prediction of the number of neutrino families or whether "sterile" neutrinos exist. It may be that water and scintillator underground detectors built for long-baseline experiments can be modified for future neutrinoless double beta decay experiments with enormous reach, and large liquid argon detectors could in principle be modified to look for dark matter. *Underground facilities are an investment in future experimental capabilities for the physics of 2030 and beyond.*

Are the forces of Nature unified at high energy?

There are several popular SM extensions, including SUSY, grand unification models, the "see-saw" mechanism, and so on. These extensions link the observed low-energy phenomenon such as the baryon asymmetry of the universe, the existence of stable, neutral dark matter, and the running of coupling constants to more general principles. It is particularly attractive to imagine that these coupling constants actually become unified at very high energy scales ($\sim 10^{16}$ GeV) and that superlight left-handed neutrino masses may be a result of the existence of superheavy right-handed partners. *This would have experimental consequences such as proton decay that can only be tested in large underground experiments*.

What surprises might be in store for us with new measurements in neutrino astrophysics?

While it is useful to take guidance from some elegant theoretical ideas embodied in the SM and its various extensions, it may be that some new concepts are currently beyond our ability to easily imagine. Thus, exploiting novel technology and/or new technical capabilities to do experiments that view the universe in new ways has historically been important to our field. For example, experiments in neutrino astrophysics provided the first evidence for neutrino mass and mixing. New possibilities include looking for relic supernova neutrinos, detection of ultra-high energy astrophysical neutrinos, a high statistics/multi-flavor measurement of neutrinos from a galactic supernova, and precision measurements of the solar and atmospheric neutrino flux. All hold the promise of the "unexpected".

In summary, given the opportunity for a new generation of large long-baseline neutrino detectors the "View from Asilomar" is that:

I. An underground location for these new experiments is essential if a program is to have widespread scientific appeal and capabilities.
II. These long-baseline neutrino facilities will be in use for several decades. It should be assumed that the physics of the mid 21st century will likely require lower backgrounds and enhanced capabilities compared to those now existing. Building far detectors underground from the beginning will extend the useful scientific lifetime of these investments.
III. While redundancy is to be avoided, a variety of detector types with complementary capabilities is the program with highest discovery potential. There is no single detector capable of addressing all the physics. Indeed, results depending on detection of rare events and/or difficult precision measurements will need to be validated.
IV. Large-scale underground experiments should be truly international in scope – similar to other large facilities such as telescopes, space probes, and accelerators. This will make the best use of resources in the context of the scientific community as a whole.

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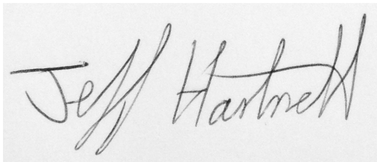

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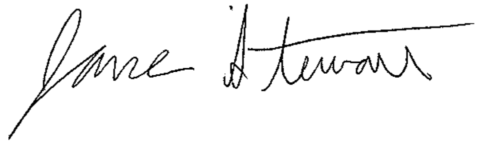

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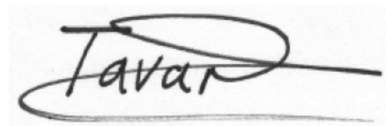

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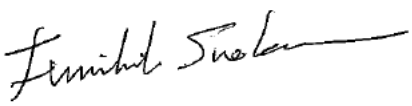

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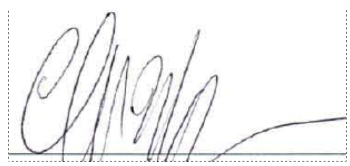

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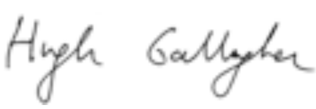

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Physics Sensitivity of New Large Underground Neutrino Detectors

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September 18, 2013

Abstract

A new generation of large underground neutrino detectors is being planned. These detectors will have unprecedented precision in the measurement of neutrino oscillation parameters, and in addition will be able to determine the neutrino mass hierarchy and search for CP violation. In addition, the underground location of these detectors make them sensitive to proton decay, high energy astrophysical neutrinos, and stellar core collapse bursts. Determination of the mixing angle octant and a complimentary determination of the mass hierarchy are also possible using using atmospheric neutrinos. The expected sensitivity of such experiments is presented.

1 Introduction

A new generation of large underground detectors are being planned over the next decade. While many of these are associated which high intensity neutrino beams, the underground location will also facilitate a broad program in neutrino physics, rare processes, and astrophysics. These detectors will have greatly enhanced capabilities compared to the current generation of experiments, and the expected scientific sensitivity was the the subject of the International Symposium on Opportunities in Underground Physics (ISOUP), help at Asilomar, CA May 24-27. This paper summarizes the scientific discussions and conclusions from that meeting.

The suite of proposed next-generation large detectors presented at ISOUP included the following (in alphabetical order of target material):

1. Liquid argon TPCs in the mass range of 30 to 70 ktons (LBNE, LBNO)
2. Liquid scintillator detectors in the mass range of 10 to 50 ktons (JUNO, Hano-Hano, LENA, RENO-50)
3. Magnetized Iron Calorimeter (ICAL) with a mass of 50 ktons (INO)

*editor

4. Water Cherenkov detector with a mass of 560 ktons (Hyper-Kamiokande) and a megaton scale detector located under ice at the south pole (PINGU)

In addition, there were presentations and discussions on existing experiments in order to put the increased sensitivity of proposed experiments in context. In most cases, we refer readers to the posted talk slides rather than a series of published papers. This is completely reasonable (and very convenient) for the reader who plans to attend the Snowmass workshop. This is not a "white paper" but rather a guide for Snowmass discussion and a stimulus for thinking! In addition, the panel discussion on future facilities is posted on the ISOUP web site[1]. We invite you to listen in to get a sense of what the community is thinking.

2 ISOUP: The "Big Detectors"

We present a very brief description of the large underground detectors in the context of understanding the scientific sensitivity, possible upgrade paths, and current status.

LBNE/LBNO

LBNE and LBNO are both large liquid argon detectors. LBNE is a long-baseline experiment from Fermilab to the Sanford Underground Research Facility (SURF), a distance of 1300 km. A total of 34 kilotons (fiducial) of liquid argon Time Projection Chambers (TPCs) will be placed 4200 m.w.e. underground. The current LBNE design is a single-phase detector with electrons drifting from ionizing tracks to vertical collection and induction planes.

LBNO is similar to the LBNE design, but realized in a dual-phase design where electrons are drifted vertically to a liquid-gas interface then amplified for collection. It is being studied in 20, 50, and 100 kiloton configurations and would be located at a depth of 4000 m.w.e. at the Pyhsalmi mine in Finland. Alternative locations are also possible.

In general, liquid argon TPCs have mm scale track resolution, which makes them suitable for deciphering complex non-quasielastic interactions of neutrinos with the argon nucleus. The have other advantages for underground physics: (1) they can track kaons at the low energies relevant for proton decay searches, (2) they may be able to better reconstruct neutrino direction in atmospheric neutrino interactions, and (3) they have a significant cross section for electron antineutrinos at the energies of supernova bursts. Disadvantages include: (1) slow (ms level) response time, (2) a more complex nuclear target compared to water or liquid scintillator, and (3) high cost per kiloton. In addition, both detectors would have new neutrino beams built for mass hierarchy, CP violation, and precision oscillation measurements.

Status: LBNE in a first-phase configuration has been granted CD-1 and is in an advanced design stage. This includes a beam and 10 kton detector on the surface. International partners are being sought to help increase the scope to a larger detector underground. LBNO has completed a feasibility study and have proposed a small (300 ton) dual-phase demonstrator project to CERN. The possibility of LBNE and LBNO joining forces is being actively discussed.

JUNO/Hano-Hano/LENA/RENO-50

These are all large liquid scintillator detectors. JUNO (name change from Daya Bay II) is a 20 kiloton liquid scintillator located 1900 m.w.e. underground 53 km from the planned Yangjiang and Taishan nuclear power stations in southern China. It will have exceptionally good energy resolution (3-5 times Daya Bay) to make a mass hierarchy measurement, but is somewhat shallow for some low background physics. RENO-50 is an 18 kiloton detector with similar energy resolution requirements and physics goals. It will be located at one of three possible sites at a distance of 44-52 km from the Younggwang nuclear power station. Depth would be roughly 2000 m.w.e. at any of the sites. Both RENO-50 and JUNO will need to construct new laboratories. Hano-Hano is envisioned as a 10-50 kiloton underwater detector that would be movable (via barge) in order to study geo-neutrinos and monitor nuclear reactors at multiple locations. LENA is a 50 kiloton detector located either at the existing Pyhsalmi mine (4000 m.w.e.) or the LSM at Frejus (4800 m.w.e). LENA's depth makes it very sensitive to rare events where cosmic ray backgrounds can be a limiting factor.

[1] neutrino.physics.ucdavis.edu/indico/contributionDisplay.py?sessionId=12&contribId=25&confId=0

In general, liquid scintillator detectors have very low thresholds (<1 MeV), excellent energy resolution, moderately good timing resolution, and sensitivity to neutrons via capture or proton scattering. Advantages for underground physics include: (1) detection of kaons at proton decay energies, (2) separation of electron neutrino from electron anti-neutrino interactions in supernovae, (3) detection of reactor antineutrinos, and (4) detection of geo-neutrinos. Disadvantages include: (1) lack of good particle tracking and (2) moderate to high cost per kiloton.

Status: None of these four detectors have been approved for construction. JUNO is at the prototyping and design stage, with a decision on construction hoped for in the next few years[**?**]. RENO-50 is at a similar design stage, but still surveying possible sites. LENA is at a conceptual design stage, but may have to switch possible sites if Pyhsalmi is not available. Hano-Hano is at an early R&D stage due to the requirements of deep ocean deployment.

Hyper-Kamiokande/PINGU

Hyper-Kamiokande (Hyper-K) is a 560 kiloton (fiducial) water Cherenkov detector located at a depth of 1750 m.w.e. (although a deeper site at 2700 m.w.e. is also being investigated). The detector would have 25 times the fiducial mass of Super-Kamiokande, and similar physics goals (proton decay, atmospheric neutrinos, supernovae). It would have neutron-tagging capability via gadolinium loading. The unprecedented size makes the detector excellent for proton decay searches. It would also be possible to detect a supernova burst from the Andromeda galaxy. There is an existing neutrino beam from JPARC, but it would be desirable to upgrade the power by roughly a factor of two. Sensitivity to CP violation is similar to LBNE and LBNO, but mass hierarchy sensitivity can only be done with atmospheric neutrinos due to the short baseline ($\sim$300 km). The giant water Cherenkov detector IceCube is now completed and running well. The Precision IceCube Next Generation Upgrade (PINGU) is proposed in order to have a lower energy threshold and improved tracking.

In general, water Cherenkov detectors are the least expensive way to get very large mass detectors, and hence they can have excellent sensitivity to very rare events like proton decay. The relatively low threshold (few MeV) and potential for gadolinium loading also makes it possible to have a low-energy neutrino program (solar, reactor, supernovae). Disadvantages include: (1) difficulty in deciphering complex neutrino interactions above about a GeV, and (2) inability to directly detect kaons at proton decay energies due to the Cherenkov threshold.

Status: Hyper-K is in the conceptual design stage, with a decision expected on whether to proceed to a more advanced design expected this year. Site selection is well advanced but not finalized. PINGU is in the concept development and proposal stage.

3 ISOUP: Sensitivity to the “Big Questions”

In this section we present a summary of the sensitivity of experiments to the major scientific questions facing our field. The purpose is to show that the underground physics capabilities of these experiments are crucial to the program as a whole. Being underground also provides flexibility in the design of future experiments and/or upgrades, and this will also be discussed.

Do the parameters of the neutrino mixing matrix follow a pattern determined by a new symmetry?

Why is there a periodic table of elementary particles?

In our current thinking, these two questions are actually related. In the quark sector, the quark masses arise from Yukawa interactions with the Higgs field. However, the quark electroweak eigenstates are not identical with the strong interaction eigenstates, but are rather mixed in a pattern described by the Cabibbo-Kobayashi-Maskawa (V_{CKM}) matrix. By convention, V_{CKM} acts on the left-handed negatively charged quarks (d_L, s_L, b_L) and is represented by a complex unitary matrix, as shown in figures 1 and 2[2]. In this inherently unitary representation there are three angles (θ_{12}, θ_{13}, θ_{23}) and a CP-violating phase δ.

[2]from the Particle Data Group

$$\frac{-g}{\sqrt{2}}(\overline{u_L}, \overline{c_L}, \overline{t_L})\gamma^\mu W_\mu^+ V_{\rm CKM} \begin{pmatrix} d_L \\ s_L \\ b_L \end{pmatrix} + \text{h.c.}, \qquad V_{\rm CKM} \equiv V_L^u V_L^{d\dagger} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

Figure 1: The CKM quark mixing matrix

$$V_{\rm CKM} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23}-c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23}-s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23}-c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23}-s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix}$$

Figure 2: Representation of CKM matrix in terms of three angles and a CP-violating phase

While considerable effort has been expended measuring the individual elements of V_{CKM} the exact values are not predicted by the Standard Model. They do, however fall into a general pattern given by V_{CKM}= **1** + **C**, where **C** is a small perturbation from the unit matrix **1**, sometimes known as the "Cabibbo Haze."[3] This is best illustrated in the Wolfenstein representation of V_{CKM} in figure 3[4]. Here λ is a relatively small parameter (= 0.22535 ± 0.0065) such that deviations of the diagonal elements from unity are on the order of 2.5%.

$$V_{\rm CKM} = \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4)$$

$$s_{12} = \lambda = \frac{|V_{us}|}{\sqrt{|V_{ud}|^2 + |V_{us}|^2}}, \qquad s_{23} = A\lambda^2 = \lambda \left| \frac{V_{cb}}{V_{us}} \right|$$

Figure 3: The Wolfenstein representation of the CKM matrix

Figure 4 shows the current best numerical values for the magnitudes of the CKM matrix elements. The matrix is close to being a unit matrix and the underlying pattern is of the form V_{CKM} = **1** + **C**. Even though the reason for the departure from a pure unit matrix is not understood exactly, the framework is that **C** is a perturbation on zero mixing through perhaps rather complicated QCD processes breaking the symmetry.

$$V_{\rm CKM} = \begin{pmatrix} 0.97427 \pm 0.00015 & 0.22534 \pm 0.00065 & 0.00351^{+0.00015}_{-0.00014} \\ 0.22520 \pm 0.00065 & 0.97344 \pm 0.00016 & 0.0412^{+0.0011}_{-0.0005} \\ 0.00867^{+0.00029}_{-0.00031} & 0.0404^{+0.0011}_{-0.0005} & 0.999146^{+0.000021}_{-0.000046} \end{pmatrix}$$

Figure 4: Numerical values of the CKM matrix

One might assume that neutrinos would have very small mixings just like the quarks. In that case, deviation from a pure unit matrix could be expected to be very small. Indeed, that was the conventional wisdom prior to the unambiguous discovery of oscillations in atmospheric and solar neutrino experiments.

[3]see ISOUP talk of P. Ramond, "Fundamental Physics Underground"
[4]see talks by M. Diwan and A. Rubbia

Surprisingly, the neutrino mixing parameters (shown in figure 5)[5] give a very different picture.

NuFIT 1.1 (2013)

	Free Fluxes + RSBL		Huber Fluxes, no RSBL	
	bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range
$\sin^2\theta_{12}$	$0.306^{+0.012}_{-0.012}$	$0.271 \to 0.346$	$0.313^{+0.013}_{-0.012}$	$0.277 \to 0.355$
$\theta_{12}/^\circ$	$33.57^{+0.77}_{-0.75}$	$31.38 \to 36.01$	$34.03^{+0.81}_{-0.77}$	$31.78 \to 36.56$
$\sin^2\theta_{23}$	$0.437^{+0.061}_{-0.031}$	$0.357 \to 0.654$	$0.436^{+0.047}_{-0.032}$	$0.356 \to 0.653$
$\theta_{23}/^\circ$	$41.4^{+3.5}_{-1.8}$	$36.7 \to 54.0$	$41.3^{+2.7}_{-1.8}$	$36.6 \to 53.9$
$\sin^2\theta_{13}$	$0.0231^{+0.0023}_{-0.0022}$	$0.0161 \to 0.0299$	$0.0252^{+0.0022}_{-0.0023}$	$0.0181 \to 0.0320$
$\theta_{13}/^\circ$	$8.75^{+0.42}_{-0.44}$	$7.29 \to 9.96$	$9.13^{+0.40}_{-0.42}$	$7.73 \to 10.31$
$\delta_{CP}/^\circ$	341^{+58}_{-46}	$0 \to 360$	345^{+77}_{-46}	$0 \to 360$
$\frac{\Delta m^2_{21}}{10^{-5}\ eV^2}$	$7.45^{+0.19}_{-0.16}$	$6.98 \to 8.05$	$7.50^{+0.19}_{-0.17}$	$7.03 \to 8.08$
$\frac{\Delta m^2_{31}}{10^{-3}\ eV^2}$ (N)	$+2.421^{+0.022}_{-0.023}$	$+2.248 \to +2.612$	$+2.429^{+0.029}_{-0.027}$	$+2.256 \to +2.635$
$\frac{\Delta m^2_{32}}{10^{-3}\ eV^2}$ (I)	$-2.410^{+0.062}_{-0.063}$	$-2.603 \to -2.226$	$-2.422^{+0.061}_{-0.063}$	$-2.618 \to -2.239$

Figure 5: Best fit neutrino mass and mixing parameters [?]

The mixing angles are large compared to the quarks. Indeed, in one case (θ_{23}) it is near maximal at 41 + 3.4/-1.8 degrees. This leads to a mixing matrix (V_{PMNS}) far from a unit matrix (see figure 6) – compelling evidence against the idea that flavor mixing is a small perturbation from a unit matrix. Indeed, it may be that quark flavor and lepton flavor do not arise from the same underlying physics at all, despite the fact that we give them the same label. In this case, understanding of lepton mixing and its relation to quark mixing will profoundly influence our ideas on Grand Unified Theories. It is possible that neutrino mixing is such that the "Leading Order" (LO) mixing matrix reflects a new symmetry of Nature. An example of such a new symmetry is "TriBiMaximal" (TBM) mixing[?]. In this case, $\sin^2\theta_{23} = 1/2$, $\sin^2\theta_{12} = 1/3$, $\sin^2\theta_{13} = 0$. Figure 7 shows TBM mixing matrix. It is particularly interesting that mixing matrices like TBM can arise[?] via finite group family symmetries that seek to explain lepton flavor as a distinct phenomenon not related to quark mixing.

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$$|U|_{3\sigma} = \begin{pmatrix} 0.799 \to 0.844 & 0.515 \to 0.581 & 0.127 \to 0.173 \\ 0.218 \to 0.533 & 0.430 \to 0.719 & 0.591 \to 0.800 \\ 0.222 \to 0.534 & 0.431 \to 0.720 & 0.582 \to 0.793 \end{pmatrix}$$

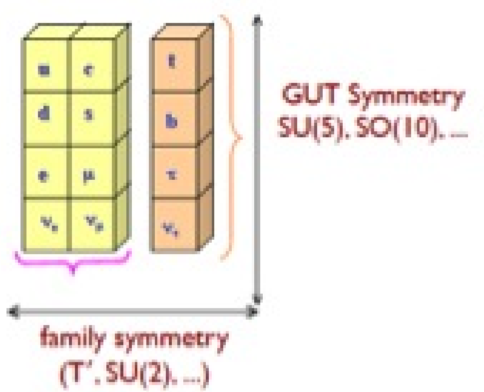
Figure 6: The 3 sigma range of the elements of the PMNS matrix

In formulating a Theory Of Flavor (TOF), it is a viable strategy to start with leptons. This is due to the fact that lepton mixing is in some sense easier to deal with than quark mixing. The charged leptons seem to have near zero mixing, while neutrino mixing seem to have a separate leading order symmetry. One then

[5] "Free Fluxes + RSBL" means that the reactor neutrino absolute fluxes have been allowed to float, and Reactor Short Base Line (RSBL, L¡100 m) experiments have been used in the fit. For "Huber Fluxes, no RSBL" the flux prediction from arXiv:1106.0687 has been used, and RSBL data are not used.

seeks group symmetries that naturally have diagonal charged leptons but highly mixed neutrinos. As in the case of the quarks, the basic neutrino symmetry has a "haze" due to "Next to Leading Order" (NLO) effects of the form $U_{PMNS} = \mathbf{T} + \mathbf{C}'$. In this case, $\mathbf{T}$ represents the matrix from LO family symmetry, while $\mathbf{C}'$ is the NLO correction[6].

The first problem is then to consider family symmetries that lead to a viable $\mathbf{T}$. One such family symmetry is A4, the group of even permutations of four objects. We will use this example in a heuristic way to illustrate the general concept, since it can lead to TBM mixing. There are many mixing ideas, resulting in other symmetries such as the "Golden Ratio"[7] (GR), which predicts $\sin^2 2\theta_{12} = 1/\sqrt{5}\phi = 0.276$ (where $\phi = (1+\sqrt{5})/2$, the Golden Ratio). Current data gives a 2.5σ deviation from GR high, and a 2.3σ deviation from TBM low. Thus given the current 4% uncertainty in $\sin^2 2\theta_{12}$ it is not possible to determine if the data is closer to Leading Order (LO) GR or TBM mixing. This is strongly dependent on θ_{12}. To make progress here, $\sin^2 2\theta_{12}$ should be measured to high precision, 1% or better if possible.



$$U_{TB} = \begin{pmatrix} \sqrt{2/3} & 1/\sqrt{3} & 0 \\ -1/\sqrt{6} & 1/\sqrt{3} & -1/\sqrt{2} \\ -1/\sqrt{6} & 1/\sqrt{3} & 1/\sqrt{2} \end{pmatrix}$$

Figure 7: Family symmetry models versus GUT symmetry models (left). TBM mixing matrix (right).

What about NLO corrections? A4 group has 12 elements and can be visualized as the symmetry associated with rotations of a tetrahedral[8]. It can be shown that see-saw versions of A4 can lead to TBM mixing for light neutrinos, with NLO corrections giving relationships between the three mixing angles, neutrino mass sum rules, and limits on the possible ranges of δ_{CP} and m_{ee} in neutrinoless double beta decay. One example of a model[9] that relates measured quantities predicts $\sin^2 2\theta_{23} = 1/2 + 1/\sqrt{2}\cos\delta_{CP}\sin\theta_{13}$. Thus measuring the mixing angles θ_{23} and θ_{13} gives a prediction for δ_{CP}. Current uncertainties on $\sin^2 2\theta_{23}$ (+14%/-7%) and $\sin^2\theta_{13}$ (+/- 5%) do not significantly restrict δ_{CP} under this model, sinceδ_{CP} in the range (100°, 160°) would be consistent with the model to 1σ. If, however current uncertainties on these angles could be reduced by a factor of 5, this range shrinks to (122°, 134°). This is just to illustrate the close connection between mixing angles, CP violation, and mass hierarchy. Similar kinds of correlations exist for many other models [10] and one can assume there will be significantly more theoretical activity in this area as new results become imminent. Thus measurements of δ_{CP} should be accompanied by more precise measurements of mixing angles in order to maximize their usefulness in testing models. **A simple measurement of any one of the mixing parameters, mass hierarchy, or δ_{CP} should not be viewed out of context of the true goal: finding a theoretical framework for lepton flavor.**

As an example of the power of such measurements, the measurement of a large value of θ_{13} ruled out many models that predicted small deviations from zero. This is illustrated in figure 8, where all models to the left of the line are essentially ruled out at more than 3σ[**?**]. Some of these measurements are best done underground, and for beam measurements this should be a consideration in addition to mass hierarchy and

[6]Note: such discrete family symmetries are distinct from the "Grand Unified" groups proposed for quarks and leptons (discussed further below), also shown in figure 7

[7]See for example [**?**].

[8]See ISOUP talk by M-C. Chen

[9]In this example we use [**?**] as an illustration of the general idea. There are in fact a number of possible models that can be tested in a similar fashion.

[10]For an excellent review, see [**?**].

CP violation measurements. A brief summary of potential improvements is given below, especially in regards to underground experiments.

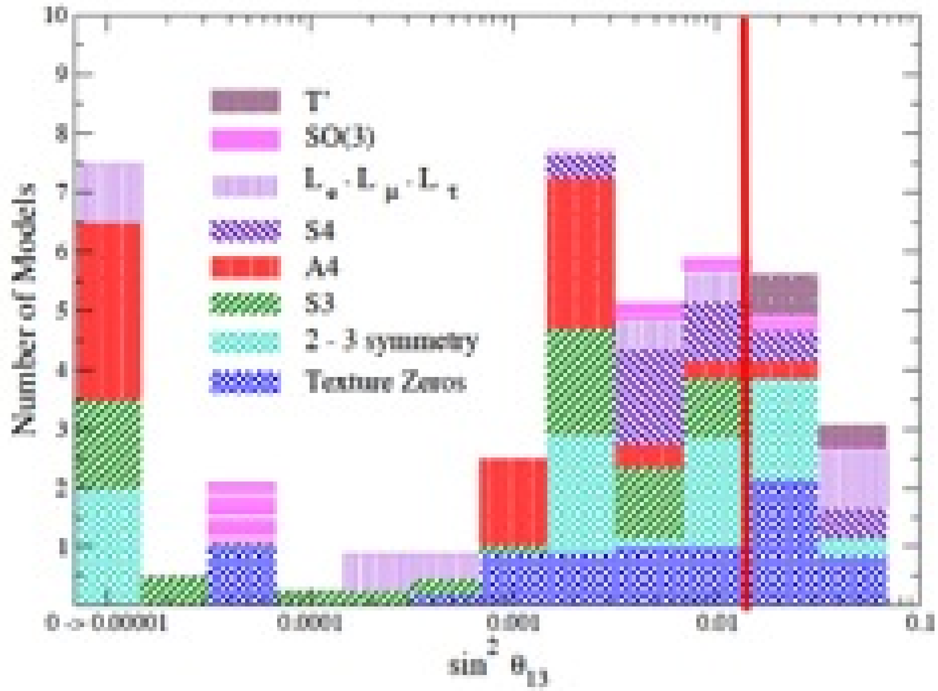


Figure 8: Models ruled out by a large value of θ_{13}

What are the prospects for measuring these parameters in the future? This was a major topic of ISOUP experimental talks.

Mass Hierarchy: LBNE/LBNO will be able to do a 3σ determination of the mass hierarchy within three years independent of δ_{CP}. Underground experiments like Hyper-K, INO, LBNE/LBNO, and PINGU will be able to determine the mass hierarchy to 3σ using atmospheric neutrinos over a period of 5-15 years (depending on the value of $\sin^2 2\theta_{23}$). In addition, reactor experiments like JUNO and RENO-50 could determine the mass hierarchy to 4 in $\sim$6 years if uncertainties on Δm^2_{32} can be reduced to the 1% level. The comparison of results using atmospheric, beam, and reactor neutrinos will be a powerful tool in confirming the interpretation of the observed effects as being due to neutrino mass hierarchy.

It is especially critical that liquid argon experiments like LBNE/LBNO be located underground. They have a truly unique feature in that the precision tracking may allow the atmospheric neutrino direction to be determined to unprecedented precision. This would allow an enormous range of L/E to be explored. Figure 9 shows the expected L/E range for and precision to be expected for a 34 kton LBNE detector at SURF. Figure 9 also shows[11] the expected sensitivity to determining the mass hierarchy with 350 kton-years of exposure assuming expected reconstruction performance. *The sensitivity using atmospheric neutrinos is comparable to the beam neutrinos, and provides a complementary way to make the measurement in the same detector.*

δ_{CP}**:** Hyper-K and LBNE/LBNO will be able to determine δ_{CP} with a 1σ resolution of 8°-10° (15°-30°) for a δ_{CP} value of 0 ($\pi/2$) radians with roughly a decade of operation using beams in the range of 700 kW[12]. The resolution depends in part on the final systematic uncertainties achieved on the beam signal and backgrounds. Current goals are 5%[13] , which will require a well-characterized beam. Note that upgrade

[11]See ISOUP talk by H. Gallagher and A. Blake. Also [?].
[12]See ISOUP talks by M. Bishai, M. Ikeda, and A. Rubbia.
[13]LBNE uses 1% signal normalization uncertainty in their estimates.

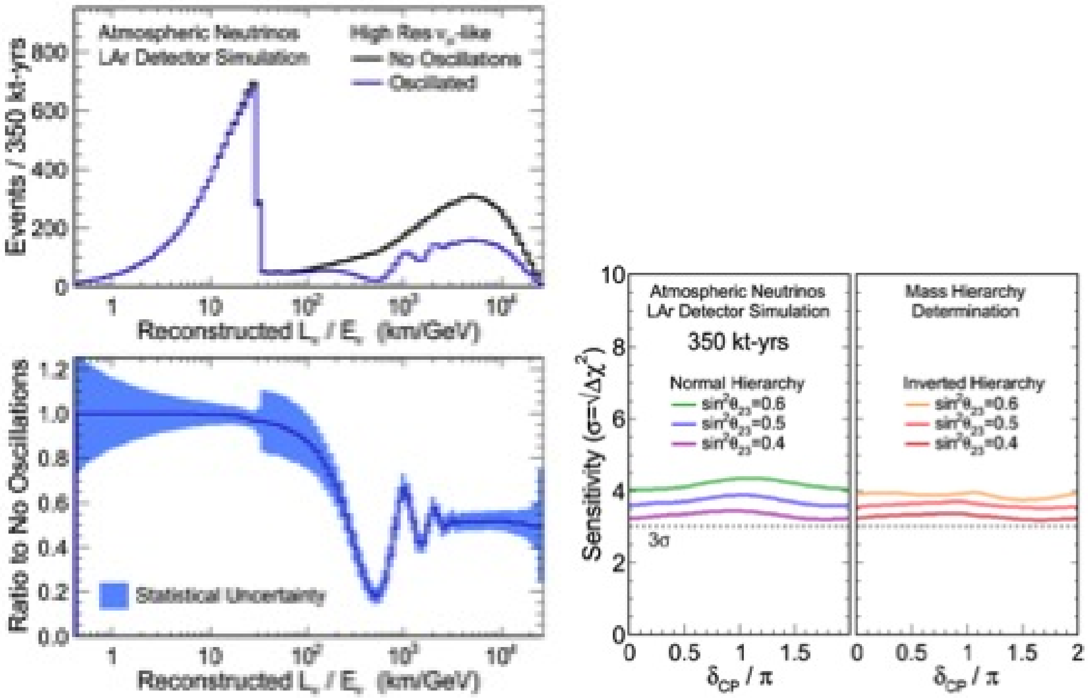


Figure 9: The L/E range and statistics expected for 350 kton-years of LBNE (left). The sensitivity for mass hierarchy using atmospheric neutrinos only (right).

of LBNE beam power to 2 MW is required to improve sensitivity into this range. Figure 10 shows the CP phase angle resolution for Hyper-K as a function of integrated beam power. Figure 11 shows the LBNE sensitivity as a function of kton-years of exposure at three separate beam powers.

Mixing Angles: While measuring θ_{13} with reactors and beams is important due to the very different techniques used, the ultimate precision will be with reactor experiments, as the systematic uncertainties of a near/far detector experiment are typically less than those of neutrino beams. The expected final precision on $\sin^2 2\theta_{13}$ for current reactor experiments is in the range of 0.003-0.010. None of the existing or proposed long-baseline or reactor experiments will reach a precision that is significantly better. Hence best precision on $\sin^2 2\theta_{23}$ will likely remain at a level of 3-5% for the foreseeable future.

For $\sin^2 2\theta_{12}$, the current precision is at a level of 5%, mainly from solar neutrino experiments and KamLAND. It can be expected that JUNO and RENO-50 could reach a precision of ~1% or better. This is much better than the expected precision on δ_{CP} or the other mixing angles, and of the order needed to address which lowest order models fit the observed data better.

Currently, $\sin^2 2\theta_{23}$ is known to be >0.957 at 90% c.l.[14] If the systematic goals on beam characterization can be achieved, LBNE would have a 1σ resolution on this quantity of 0.021 if the true value was actually 0.50. Hyper-K will achieve similar or better sensitivity[15] using standard analysis cuts. Thus one can expect roughly a factor of 2-3 improvement in the uncertainty which essentially comes for "free" with the CP violation measurement.

Are the forces of Nature unified at high energy?

With the observation of the energy-dependent variation of the coupling constants for the strong, weak, and electromagnetic forces, the idea that these couplings could be low energy manifestations of a overall "Grand Unified" symmetry has intrigued us. There are several popular SM extensions, including SUSY, grand unification models, the "see-saw" mechanism, and so on. These extensions link the observed low-energy

[14] see ISOUP talk by H. Tanaka
[15] Hyper-K LOI

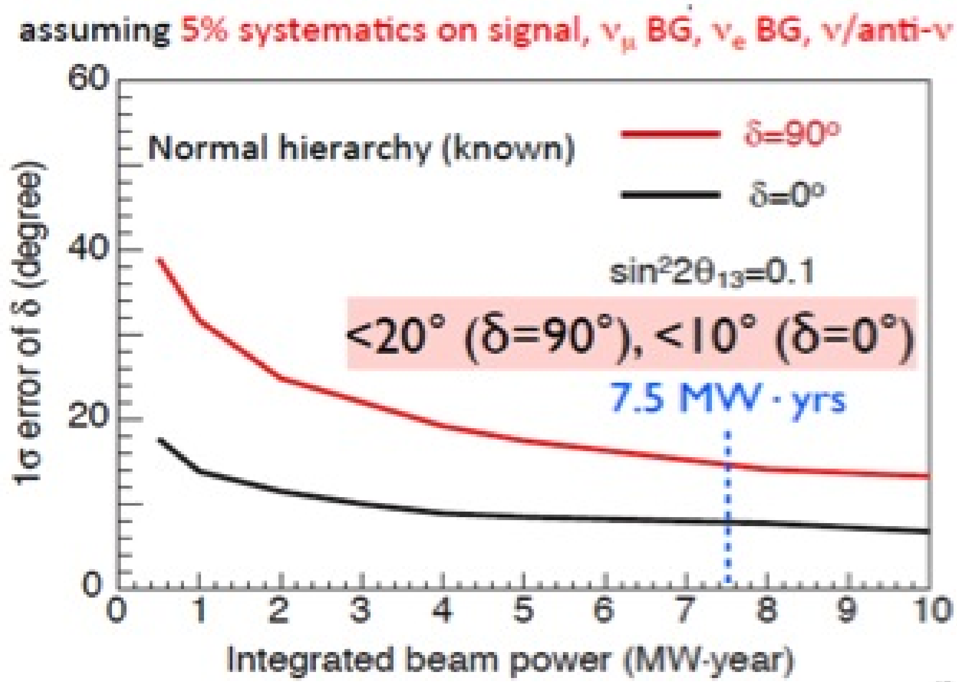


Figure 10: CP phase angle resolution for Hyper-K as a function of integrated beam power

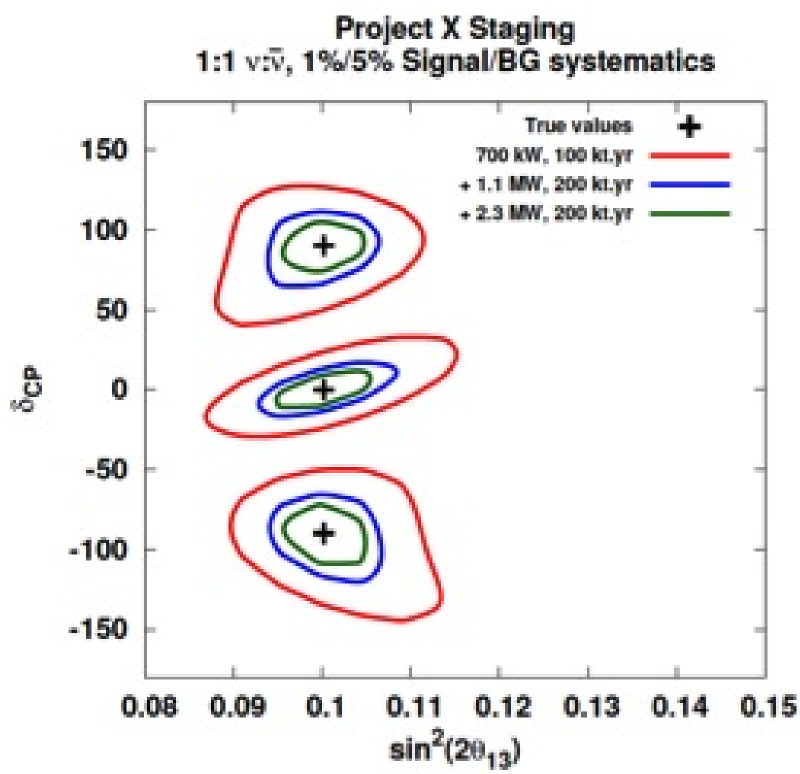


Figure 11: LBNE CP phase resolution as a function of combined exposure and beam power

phenomenon such as the baryon asymmetry of the universe, the existence of stable, neutral dark matter, and the running of coupling constants to more general principles. It is particularly attractive to imagine that these coupling constants actually become unified at very high energy scales ($\sim 10^{16}$ GeV) and that neutrino masses may be a result of massive right-handed partners.

The most direct and experimentally feasible way to test this idea is through the observation of proton decay. Such an observation would have profound implications beyond testing the validity of Grand Unified Theories (GUTs)[16]:

1. It would provide unambiguous evidence of baryon number (B) violation
2. It would provide confirmation of an essential element of Big Bang cosmology, namely non-conservation of baryon number
3. It would provide evidence that quarks and leptons are part of the same unified multiplet and help determine the structure of such a multiplet
4. It would tell us the ultimate fate of the universe
5. It would allow us to probe into the fundamental laws of nature at truly high energies $\sim 10^{16}$ GeV, beyond the reach of any conceivable future accelerator.

In most grand unification models ,with or without supersymmetry, one primary mechanism for proton decay involves dimension 6 (d=6) operators, induced by exchange of leptoquark gauge bosons. These lead to decay modes satisfying $\Delta B = \Delta L$, so modes like $p \to e^+\pi^0$ and $n \to e^+\pi^-$ are allowed, but $n \to e^-\pi^+$ (satisfying $\Delta B = -\Delta L$) is forbidden. Furthermore, in most SUSY grand unification models, proton decay also proceeds through d=5 operators involving exchange of superheavy color triplet higgsinos, which favor a strange antiquark in the final state. These decays also satisfy $\Delta B = \Delta L$, leading to decay modes like $p \to \nu K^+$. Figure 12 shows representative decays via the d=6 and d=5 operators. In general, these are not the only possible decay schemes, however. Proton decay also appears in models with "extra dimensions" and in D-brane formulations. Indeed, determination of the proton decay modes along with the rate can help select between opposing theories.

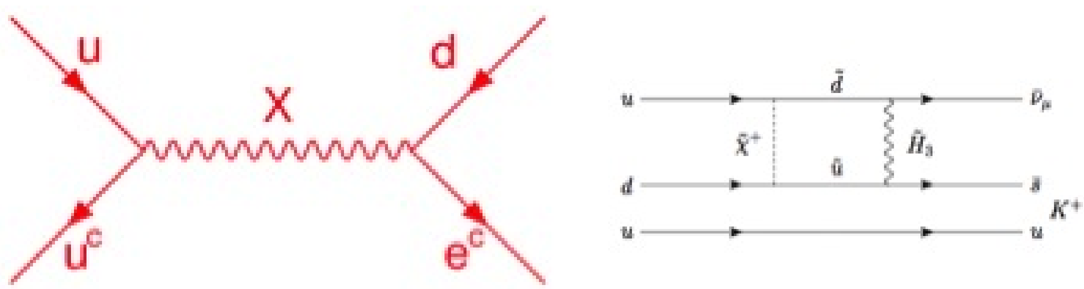


Figure 12: Proton decay via leptoquark excahnge (left) and SUSY particle exchange (right)

Figure 13 shows the range of expectations for two representative proton decay modes (for d=6 and d=5). Current experimental limits are also shown[17].

For SUSY decay modes similar to d=5 modes shown in figure 12, the lifetime of the proton depends sensitively on the mass of the SUSY spectrum. Thus detection of proton decay via this mode with a lifetime of 10^{34} years would imply relatively light sfermion spectrum. Thus proton decay may give a first hint of SUSY at energies above the LHC, and could be our only way of probing above these energies for some time. In a class of well-motivated SO(10) GUT models, both the νK^+ and $e^+\pi^0$ modes have lifetimes within an order of magnitude of the current limits, and are therefore within reach of experiments like LBNE and Hyper-K.

[16]see ISOUP talks by K.S. Babu, P. Nath and S. Raby
[17]from ISOUP talk by K.S. Babu

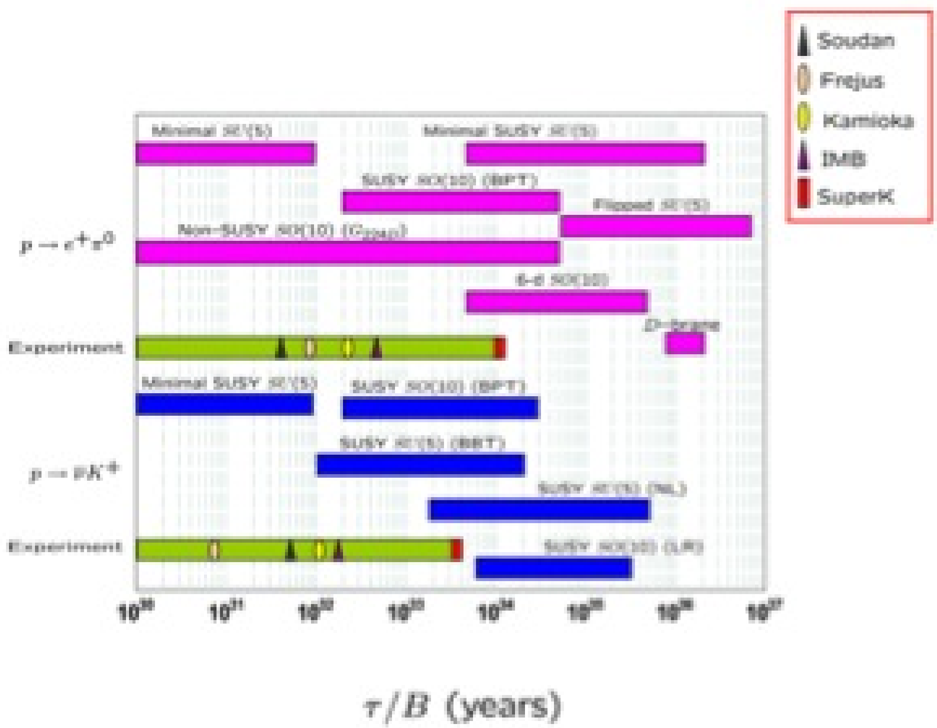


Figure 13: The range of expectations for proton decay from several theories. Current experimental limits are also shown. A new generation of experiments would improve these by a factor of 10-20.

What are the experimental prospects for finding proton decay in next generation detectors? There are three basic types being considered, as shown in figure 14.[18]

Technique	Examples	Comments
Water Cherenkov	22.5 kton Super-K 560 kton Hyper-Kamiokande	Best for $e^+\pi^0$ Good for all modes
Liquid Argon	34 kton LBNE LAr TPC 20 kton LBNO 2-phase TPC	Best for $K^+\nu$ Good for many other modes
Scintillator	50 kton LENA Next gen. reactor (DB2) ? Water-based LSc ?	Specific to $K^+\nu$

Figure 14: Characteristics of the three types of new detector being considered

Water Cherenkov detectors are the most robust proton decay detectors, in that they are good for almost all modes. A recent 20%[19] improvement in detection efficiency for the νK^+ mode in Super-Kamiokande (SK) has further enhanced prospects for future water Cherenkov detectors to improve upon the current SK 90% c.l. limit of 5.9×10^{33} years for this mode. There is also the possibility of reduction of backgrounds via the addition of a neutron capture detection capability, in that few proton decay modes would produce neutrons in the final state, whereas SK has found that many atmospheric neutrino events do produce neutrons above 1000 MeV (see figure 15). Hyper-K at 560 kilotons represents the future of this type of detector. HK could reach a 20-year sensitivity of 6×10^{34} years[20] the νK^+ mode with SK backgrounds, and about double that if neutron tagging can reduce backgrounds by a factor of five. This would be an order of magnitude beyond current limits.

Liquid argon detectors like LBNE/LBNO have the advantage that they have excellent tracking and the ability to see particles below the Cerenkov threshold (see figure 16). Thus they have a high efficiency for modes with kaons (∼97%), about five times higher than SK. Backgrounds are also expected to be smaller for these modes - essentially dominated by real kaons generated from cosmic ray muons outside the detector. There is also the potential for single event discovery given the small backgrounds expected. The main disadvantages of liquid argon detectors are that they are more expensive per unit volume and therefore smaller. Note that the backgrounds increase dramatically as the depths get shallower - thus it is critical that LBNE be located underground to have any sensitivity for proton decay. LBNE with a 34 kton detector would be able to reach a 20-year sensitivity of about 6×10^{34} years, an order of magnitude better than existing limits[21]. In addition, LBNE would be about 10 times more sensitive than SK to other SUSY modes such as $p \to e^+/\mu^+ K^0$.

A summary of existing limits and 10-year sensitivity estimates is given in figure 18. The LBNE sensitivity assumes it is 34 ktons built underground.

What surprises might be in store for us with new measurements in neutrino astrophysics?

Many important scientific discoveries have been made by experiments exploiting new technology or new capabilities to look at the universe in a new way[22]. With the advent of comprehensive Cosmic Microwave Background (CMB) measurements (ν mass limits, N_{eff} determination), 10 meter adaptive optics telescopes (dark energy/matter measurements, structure history), large Gravitational Wave (GW) detectors, and new

[18] see ISOUP talk by E. Kearns

[19] from 15.8% to 18.9%

[20] The current limit from SK for $p \to e^+\pi^0$ is 1.3×10^{34} years.

[21] The current limit from SK is 5.9×10^{33} years

[22] A good example is the chlorine solar neutrino experiment. Other examples are the proton decay detectors that incidentally, could also measure atmospheric and supernova neutrinos.

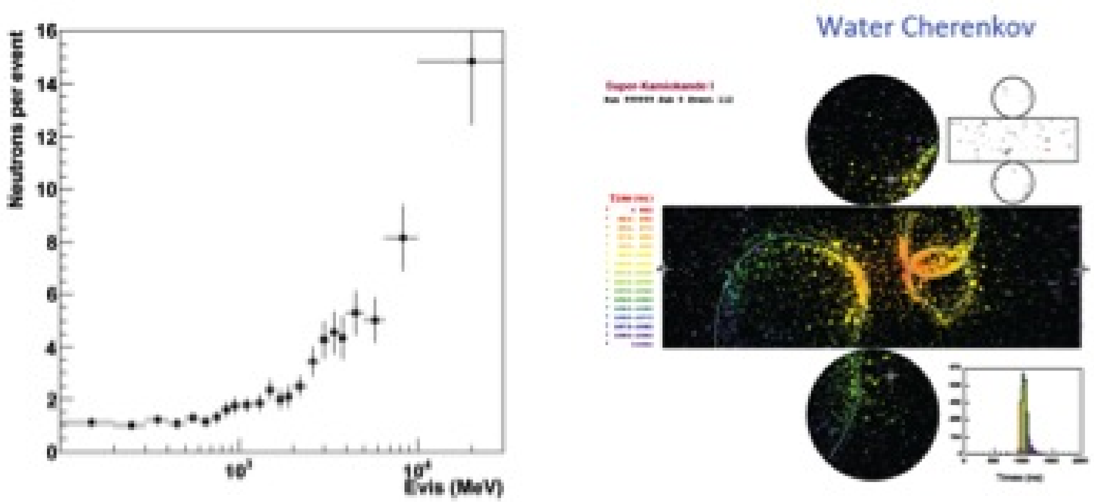


Figure 15: A simulated proton decay event in SK (right). The measured neutron multiplicity in SK as a function of atmospheric neutrino E_{vis} (left)

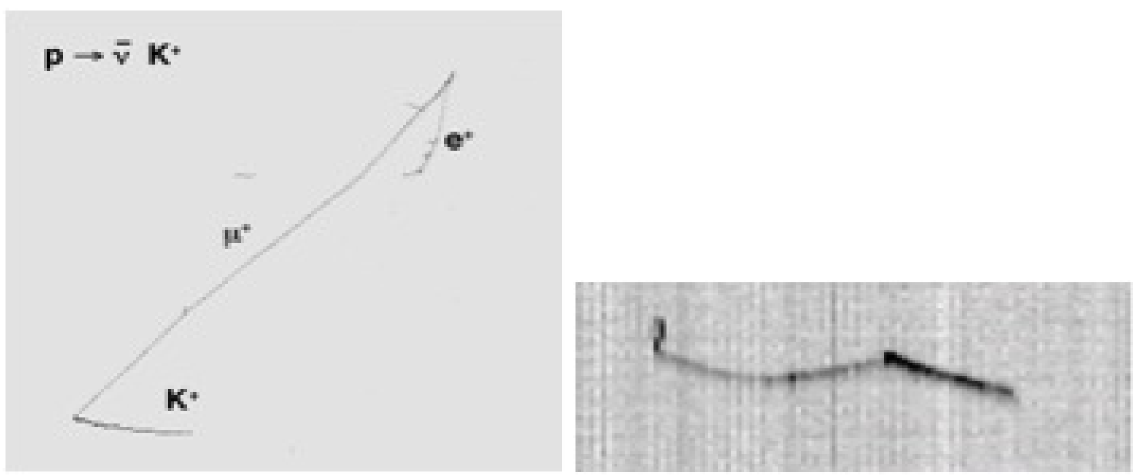


Figure 16: A simulated (left) and real (right) K^+ event in a liquid argon TPC

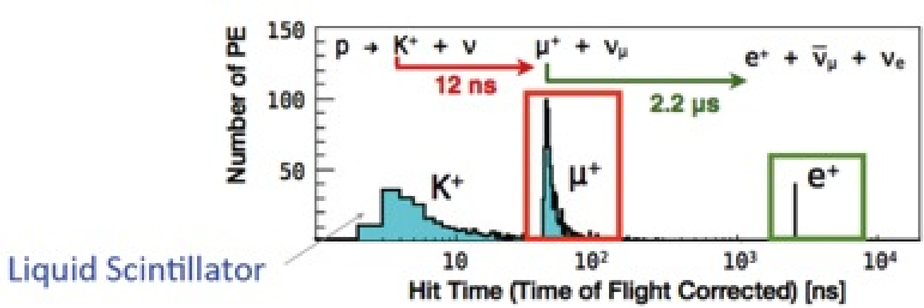


Figure 17: The deposited energy versus time sequence for a proton decay in liquid scintillator

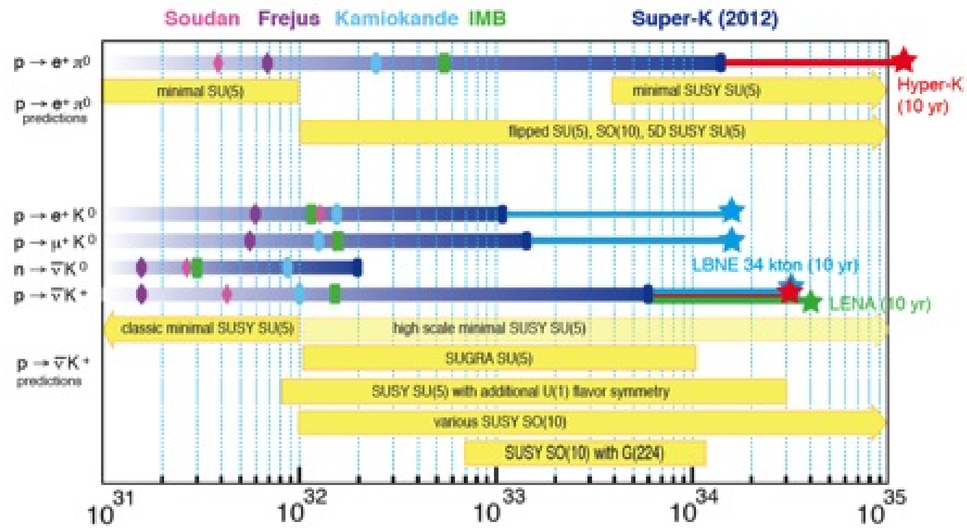


Figure 18: Proton lifetime in years (x-axis) versus decay mode (y-axis), showing potential improvements over existing sensitivity. Also shown are some theoretical estimates

large neutrino detectors - an over determined situation is developing in which Beyond the Standard Model (BSM) effects may first show themselves[23].

Supernovae (SN) are expected to occur in our galaxy every 30-40 years[24]. About half should be Type II core collapse SN, which are known to emit neutrinos based on measurements of SN1987A. It is not expected that SN Type I (of the type used to determine the accelerated expansion of the universe) would emit significant numbers of neutrinos, but this has not yet been experimentally verified. The neutrino production takes place in an environment that is a relatively cold, high electron number degenerate environment. The density of neutrinos is so large, that neutrino-neutrino interaction effects are significant and cannot be ignored. SN are therefore very sensitive to lepton flavor changing effects, including collective oscillation effects that are predicted but not possible to see in any terrestrial experiment. Figure 19 shows the "oscillogram" for neutrino and antineutrino survival probability as a function of energy and the neutrino trajectory angle from the neutron star. Plots for both inverted and normal mass hierarchy are shown, as well as for neutrinos and antineutrinos.

The boundary line around 10 MeV in the spectra is known as a "spectral swap" and is due to collective oscillation brought on by neutrino-neutrino interactions (as opposed to "normal" matter effects on electron neutrino survival due to electron density). This plot shows that a measurement of supernova neutrinos that can extract fundamental physics requires: (1) high statistics, (2) sensitivity to neutrinos and antineutrinos, and (3) good flavor sensitivity and separation.

Both liquid scintillator and water Cherenkov detectors are very sensitive to anti-electron neutrinos due to the high cross section for inverse beta decay (IBD) on hydrogen. On the other hand, liquid argon detectors are most sensitive to electron neutrino interactions via $\nu_e + ^{40}Ar \rightarrow ^{40}K + e^-$.[25] In addition, water Cherenkov detectors of the size of Hyper-K can detect significant numbers of electron scattering events and separating them out from IBD events either via direction or neutron tagging. Liquid scintillator detectors have a very distinct neutral current signature in the form of a 15 MeV monoenergetic gamma from neutrino carbon interactions. Thus the combination of different detector types is a powerful tool towards untangling the neutrino astrophysics from basic neutrino parameters. Figure 20 gives a summary of expected event rates at 10 kpc for the largest existing and proposed neutrino detectors in a class[26].

[23]see ISOUP talks by G. Fuller and G.Raffelt

[24]Hyper-K would be expected to detect ∼10 events from a Type II SN in Andromeda also.

[25]The neutrino argon cross section has not been measured at this energy, and is complicated by the fact that the g.s.→ g.s. transition is highly forbidden. There are proposals to measure this cross section at stopped pion sources.

[26]see ISOUP talk by F. Cavanna

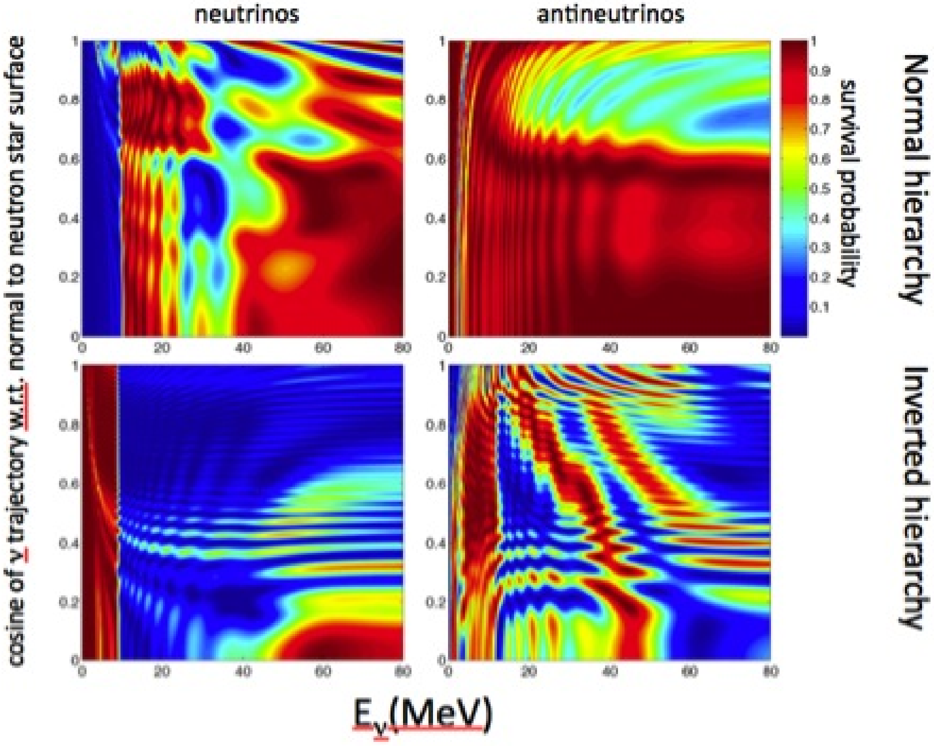


Figure 19: Oscillograms showing oscillation probability as a function of neutrino energy and trajectory

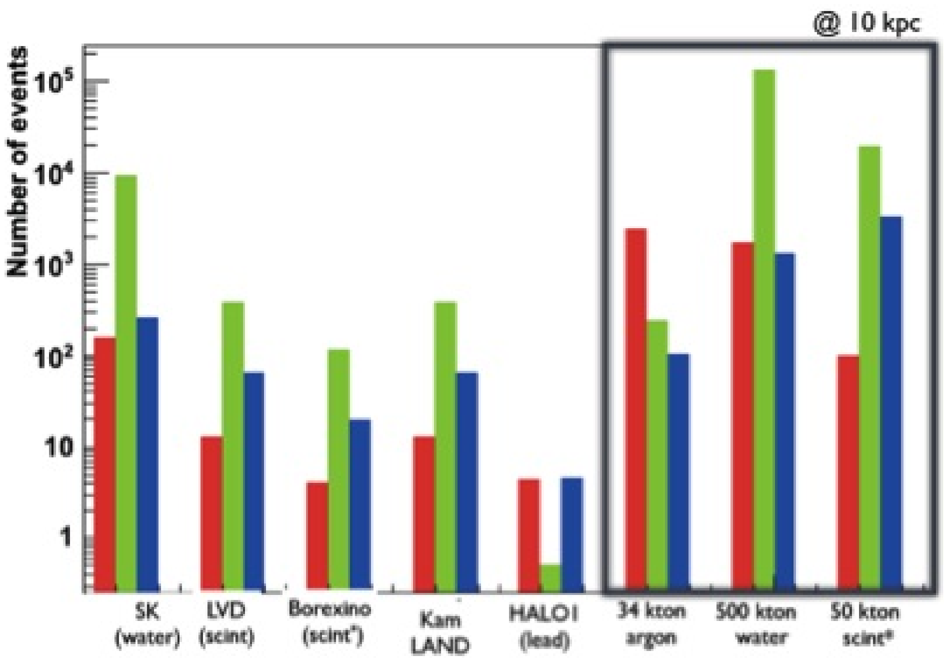


Figure 20: Event rates for largest detectors in a class. Red are electron neutrinos, green are electron anti-neutrinos, and blue are mu and tau neutrinos and anti-neutrinos

It is clear from figure 19 that the contribution of LBNE/LBNO liquid argon detectors is critical due to the dominance of e interactions. Figure 19 also makes it obvious that although the neutrino and anti-neutrino spectra extend up to 30 MeV and beyond, much of the "action" is taking place below 15 MeV. Since $^{40}Ar(\nu_e, e^-)^{40}K^*$ has an effective threshold of about 5 MeV, outgoing electron energies will be *small*, less that 10 MeV in the region of interest. In addition, unlike neutrino-electron scattering events, the electrons are isotropic in direction.

The upshot is that, while a surface liquid argon detector might be able to detect the presence of a supernova, the science that could be extracted would be compromised by the fact that backgrounds on the surface are expected to be very significant in the energy range of interest. For example, the n-p reaction on ^{40}Ar produces ^{40}Cl, which has a 90 second half-life and is expected to produce kilohertz levels of 7.5 MeV endpoint betas on the surface. *It is critical that detectors like LBNE/LBNO be located underground in order to be sure that they can contribute meaningfully to a supernova neutrino burst detection.*

4 ISOUP: Panel Discussion Session

The Panel members were: JoAnne Hewett (SLAC), Antonio Masiero (INFN), Marzio Nessi (CERN), Piermaria Oddone (FNAL), Yasuhiro Okada (KEK), Jogesh Pati (SLAC), Georg Raffelt (MPI), Natalie Roe (LBL), Hank Sobel (UCI). The discussion questions (solicited from attendees) were:

1. What is the compelling motivation for continuing the search for proton decay beyond Super-Kamiokande sensitivity?
2. How important is an underground physics program for a long baseline experiment? Is measurement of CPV by itself motivation enough without going underground?
3. What is the scientific motivation to have both water Cherenkov and Liquid Argon detectors to do the underground science?
4. What could we do to foster more international collaboration in these large experiments?
5. Is there theoretical guidance for the precision goal for measurement of PMNS matrix parameters?

The complete audio of the discussion is available at:
neutrino.physics.ucdavis.edu/indico/contributionDisplay.py?contribId=25&sessionId=12&confId=0.