**FINAL REPORT**
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## I. OVERVIEW

### Introduction

The University of Washington (UW) HEP neutrino group performed experimental research on the physics of neutrinos, using the capabilities offered by the T2K Experiment and the Super-Kamiokande Neutrino Observatory. The UW group included senior investigator R. J. Wilkes, two PhD students, four MS degree students, and a research engineer, all of whom are members of the international scientific collaborations for T2K and Super-Kamiokande. During the period of support, within T2K we pursued new precision studies sensitive to new physics, going beyond the limits of current measurements of the fundamental neutrino oscillation parameters (mass differences and mixing angles). We began efforts to measure (or significantly determine the absence of) the CP-violating phase parameter $\delta_{CP}$ and determine the neutrino mass hierarchy. Using the Super-Kamiokande (SK) detector we pursued newly increased precision in measurement of neutrino oscillation parameters with atmospheric neutrinos, and extended the current reach in searches for proton decay, in addition to running the most sensitive supernova watch instrument [Scholberg 2012], performing other astrophysical neutrino studies, and analyzing beam-induced events from T2K. Overall, the research addressed central questions in the field of particle physics. It included the training of graduate students (both PhD and professional MS degree students), and postdoctoral researchers. Undergraduate students also participated as laboratory assistants.

## II. T2K: Background

T2K (Tokai-to-Kamioka) is a long-baseline neutrino oscillation experiment [T2K 2011] whose primary goals are to make precise measurements of the appearance of electron neutrinos and the disappearance of muon neutrinos at a distance where the oscillation is maximal for the neutrino beam energy [Pascoli 2013] [Balantekin 2013] (Fig. 1). Improved precision in neutrino oscillation analyses requires improved knowledge of neutrino interaction cross sections [McFarland 2013]; as an integral part of the research program, T2K near detectors simultaneously function as fixed-target neutrino experiments to provide these measurements.

T2K consists of an accelerator-generated neutrino beamline [Shibata 2008], a near detector complex 280 m downstream of the neutrino beam target [ND280 2012, 2009], and a far detector, Super-Kamiokande (SK, to be described below), located 295 km away at an angle of 2.5° away from the axis of the neutrino beam (Fig. 2). Neutrinos are generated using the 30 GeV proton beam of the Japan Proton Accelerator Research Complex (J-PARC), located in Tokai-mura on the east coast of Japan [J-PARC 2005]. The near detector complex is composed of a detector on the axis of the neutrino beam, called INGRID, and a set of detectors located 2.5° off axis, as is SK, called ND280. INGRID is used primarily to measure the beam profile and stability, and the ND280 off-axis detector suite is used to measure neutrino fluxes and neutrino interaction cross-section properties.

Each proton beam spill has 8 bunches (6 prior to June, 2010) spaced 581 ns apart. The extracted protons are directed toward a graphite target installed inside a magnetic horn that collects and focuses the positively charged mesons (mainly pions and kaons) generated by proton interactions in the target. Two additional magnetic horns are used to further focus the selected charged mesons before they enter a 96 m long decay volume filled with He. The mesons decay predominantly into highly boosted muons and muon neutrinos, which propagate roughly in the direction of the decaying mesons. A beam dump stops most of the particles in the beam that are not neutrinos. Some high-energy muons pass through the beam dump and are observed by a muon monitor at its end, providing information used to track the beam direction and stability. The database available for analysis was taken in several running periods, beginning in January, 2010, , representing a total of $2.3 \times 10^{21}$ protons-on-target (POT) by early 2017, when beam power was at the 450 kW level, or more than $10^{14}$ protons per spill, at 2.5 s spill intervals (Fig. 3). The number of neutrino events in the near and far detectors is directly proportional to integrated POT. A main-ring upgrade in 2018 will raise the beam power toward its final Phase-I design level of 750 kW.

The UW group joined T2K at its inception, after participating in its predecessor, the K2K experiment [K2K 2006]. UW has contributed to T2K construction and operation in three areas: the pi-zero detector (P0D) component of ND280 [P0D 2012], construction of custom electronics for neutrino beamline monitors, and primary responsibility for the GPS time synchronization system at both near and far detectors. Two UW students will complete their PhD theses using T2K data in 2014, and four UW Professional MS degree students are contributing to and will write their capstone project reports on T2K.

**T2K: most significant results**

In July, 2013, the T2K Collaboration announced definitive observation of muon neutrino to electron neutrino transformation, at the 7.5 sigma level of significance [T2Knue 2013].

We observed 28 electron neutrino candidate events at the far detector, with 4.64±0.52 events expected for $\sin^2 2\theta_{13}=0.0$. A max likelihood fit assuming $\nu_\mu \rightarrow \nu_e$ oscillations, comparing number of observed events with MC predictions in terms of electron momentum and angle (pe, qe), and taking $\sin^2(2\theta_{23})=1.0$, $\delta_{CP}=0$ and $|\Delta m_{32}{}^2|=2.4\times10^{-3}$ eV$^2$, yields a value of $\sin^2(2\theta_{13})=0.152$ +0.041-0.034 (stat.+syst.). This is consistent with previous results [PDG 2012], and gives confidence that future work to measure $\delta_{CP}$ using long-baseline techniques will be feasible. Increased precision for $\Delta m^2{}_{32}$ and $\theta_{23}$ will be required for $\delta_{CP}$ studies. T2K capabilities in this regard were recently demonstrated in a paper reporting new results on $\nu_\mu$ disappearance [T2Knumu 2013]. Assuming three neutrino flavors, normal mass hierarchy and $\theta_{23} \leq \pi/4$ yields a best-fit mixing angle $\sin^2(2\theta_{23}) = 1.000$ and $|\Delta m^2{}_{32}| = 2.44 \times 10^{-3}$ eV$^2$/c$^4$. If $\theta_{23} \geq \pi/4$ is assumed, the best-fit mixing angle becomes $\sin^2(2\theta_{23}) = 0.999$ while the mass splitting remains unchanged. Thus, octant choice can significantly affect allowed-region contours; in future, results will give $\sin^2(\theta_{23})$ instead of $\sin^2(2\theta_{23})$.

UW contributed significantly to the data-taking and analysis effort. Goals included: (1) Increasing precision of measurements in $\nu_e$ appearance studies ($\theta_{13}$); (2) Resolving octant degeneracy ($\theta$<45°or >45°) ; (3) Increasing precision of measurements in $\nu_\mu$ disappearance studies ($\Delta m^2{}_{23}$, $\sin^2 \theta_{23}$), to reduce systematics and improve our $n_e$ appearance measurements (Fig. 4); (4) Performing a combined 3-flavor analysis on $\nu_e$ appearance and $\nu_\mu$ disappearance ; (5) Data-taking with the anti-neutrino beam; (6) Beginning R&D on future water targets for the P0D; (7) First studies of the CP-violating phase $\delta_{CP}$ , to exploit future beam intensity upgrades, near detector improvements, and (possibly) a megaton-scale far detector, Hyper-Kamiokande.

**T2K: UW contributions**

The UW HEP neutrino group was responsible for two critical subsystems in the T2K experiment. The P0D water target system design posed unusually difficult requirements: layers of water 3 cm thick but 2 m² transversely had to be inserted between scintillating bar tracking layers in the P0D. We helped to design, prototype, test, and construct the 25 water target layers required, along with the water supply, pumping, and monitoring system associated. Continuous monitoring while water is in the targets is required, due to the danger to other P0D components in case of water leaks.

UW group members play a leading role in operating, monitoring, and maintaining the time synchronization system that is critical to T2K far detector event identification.

The UW group also plays a leading role in the operation and maintenance of the T2K time synchronization system. We installed high-precision GPS receivers and associated equipment at both sites, and were responsible for monitoring and maintaining this equipment. The goal was to timestamp events in SK, and beam spill arrivals at the neutrino target at J-PARC, to nanosecond precision. (Fig. 5) The precision time system will permit T2K to take advantage of the fine bucket structure of the J-PARC beam spills to attempt a neutrino time of flight (TOF) measurement [Wilkes 2012]. The HEP community has been made well aware of the potential pitfalls (!) of such measurements [Opera 2013]. We worked with experts at US-NIST [Zhang 2013], and its Japanese counterpart NICT [Fujieda, 2010], to ensure that our measurements were as precise as currently practical.

Obtaining this level of precision required calibrations by transportation of atomic clocks between near and far sites. UW constructed the equipment necessary to house and operate laboratory Cs clocks in a stable thermal and power environment for the roughly 24 hr period required for a round trip, and UW students participated in several calibration expeditions. A team of four UW professional MS degree students, working for academic credit, made key contributions to this effort. The NICT group provided a Two-Way Satellite Time and Frequency Transfer (TWSTFT) calibration operation to confirm our calibrations.

One student, Paul DeStefano, made such critical contributions that he received a part-time RA appointment in order to devote full time to this effort. As the MS students finish their degrees, new MS students were recruited to help. (Wilkes is faculty coordinator for the UW Physics Department's Professional MS Program).

During the last year of the grant period, most of the UW research activity involved J. Wilkes, and H. Berns, who had primary responsibility for monitoring and maintaining the GPS time synchronization system critical for T2K operations. Monitoring of the GPS equipment was also performed by unsupported volunteer MS students at UW, who performed daily checks of data quality.

Following closeout of the UW grant, primary responsibility for the T2K side of the GPS time synch system has been taken over by the Stony Brook University T2K group, as of late 2016.

## III. Super-Kamiokande: Background

Super-Kamiokande (SK, Fig. 6) is a 50-kiloton water Cherenkov detector located in the Kamioka Observatory in Japan, with ~1000 m of rock (2500 m water equivalent) overburden. Super-Kamiokande is contained in a cylindrical stainless steel tank, 39.3 m in diameter and 41.4 m in height, optically separated into two regions, an inner detector (ID), and an outer detector (OD). On the inner surface of the ID, 20-inch photomultiplier tubes (PMTs) are uniformly distributed to detect Cherenkov light radiated by relativistic charged particles. The OD, which surrounds the ID with a 2 m thickness of water and 1885 outward- facing 8-inch PMTs, is used to reject cosmic ray muon events and to tag exiting charged particles. The OD also serves as a shield from radioactivity from materials outside the detector wall. [SK 2003]. Detected “high energy” neutrino interactions (with estimated deposited energy greater than 100 MeV) come in several categories: fiducial-volume (FV, where the interaction vertex is reconstructed within the inner 22.5 kT of water volume); fully contained (FC, where the OD shows no significant signal, indicating the interaction products were contained within the ID); partially contained (where the OD shows exiting tracks); and upward-going muons (where the interaction vertex was in the rock beneath the detector). Fig. 7 shows an event display for a T2K beam-induced $\nu_e$ interaction categorized as FC-FV.

**Super-Kamiokande: most significant results**

The Super-Kamiokande experiment started data taking in April, 1996, and in 1998 announced the first undisputed evidence for non-zero neutrino mass [SK 1998]. Observations continued until detector maintenance began in July 2001. (This original configuration is called SK-I.) On November 2001, while refilling the tank with water after maintenance, an accidental implosion occurred which destroyed more than half of the PMTs. Surviving and on-hand spare PMTs were used to rebuild the detector with half the original density of photosensor coverage in the ID. Data-taking with this configuration (SK-II) ran from October 2002 to October 2005, when the full ID coverage was restored(SK-III). The reduced photomultiplier tube density during SK-II did not significantly affect data on high energy (atmospheric) neutrino interactions. Data-taking with the SK-III configuration started October 2006 and ended when the detector was upgraded with newly developed front-end electronics and online data systems, in September 2008 (SK-IV, currently ongoing).

To date, the SK collaboration has published its results in 130 papers in high-impact refereed journals (most of them in Phys. Rev. Letters, Phys. Letters, and Phys. Rev. D).

**Super-Kamiokande: UW contributions**

The UW HEP neutrino group contributed to the initial detector construction, its several reconstructions and upgrades, and its continuing operation, since it was commissioned in 1996. Our participation in data reduction and analysis lies primarily within the “atmospheric neutrino and proton decay” analysis subgroup.

Analysis effort at UW centered on two areas. One was the search for evidence of astrophysical point sources using the upward-going muon data set, the highest energy subset of neutrino interactions in SK (theses by K. Shiraishi and E. Thrane, leading to publications [Shiraishi 2008] [Thrane 2009]). The other was the search in SK fully-contained and upward muon data for evidence of non-standard neutrino interactions, and other exotic theoretical models that could mimic neutrino oscillation, such as the Mass Varying Neutrino (MaVaN) model developed by theorists Neal Weiner, Ann Nelson, and their students here at UW. The ability to interact closely with theorists interested in neutrinos and a team as powerful as that led by Ann Nelson is a great advantage for our experimental group, as well as for UW theory graduate students, who better understand the limitations of experimental measurements after working with us.

Five UW students have written their PhD theses using SK data [UW 1998ff], and eight UW Professional MS degree students have contributed to and performed their capstone independent-study projects in SK.

## IV. Conclusion

During the period of grant support, the UW neutrino physics group led by Prof. R. Jeffrey Wilkes conducted research addressing contemporary central questions in the field of neutrino physics. Contributions to the field included construction, operation, and maintenance of critical components of both the T2K long baseline neutrino experiment, and the Super-Kamiokande Neutrino Observatory, as well as data reduction and analysis for both projects. A central feature of UW effort was the training of graduate students (both PhD and professional MS degree students), and postdoctoral researchers. Undergraduate students also participated as laboratory assistants.

## FIGURES

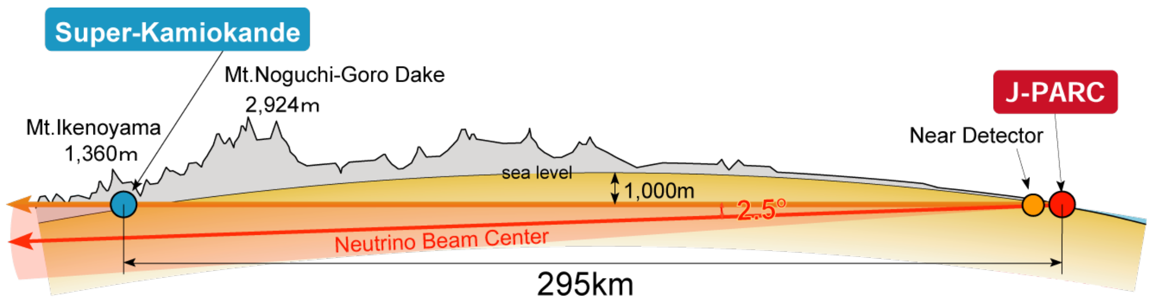


Figure 1: Overview of the T2K long-baseline neutrino experiment.

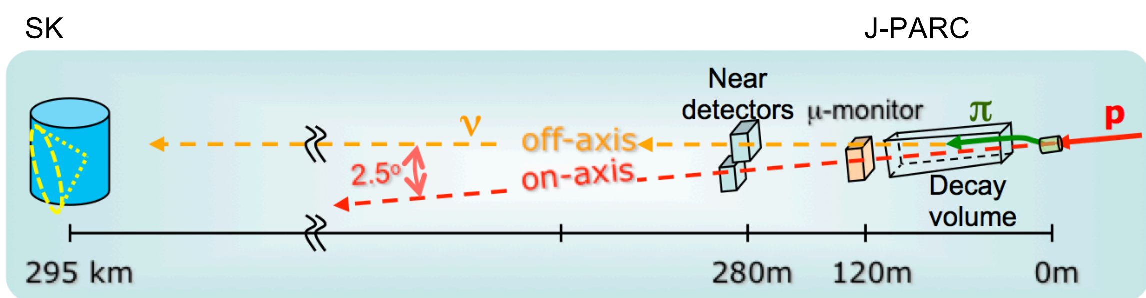


Figure 2: T2K neutrino production beamline, on- and off-axis near detectors, and far detector. (The potential Hyper-Kamiokande site is also located on the 2.5° off-axis cone.)

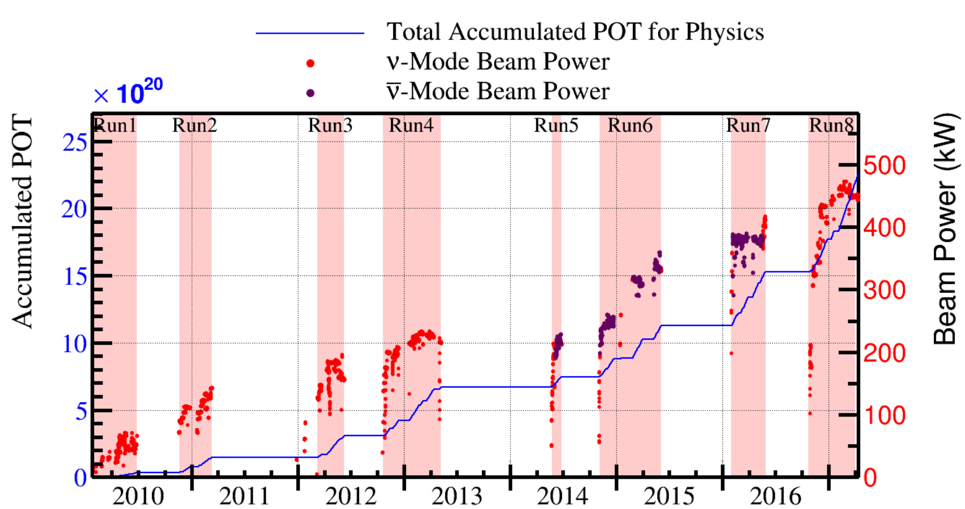

Figure 3: J-PARC proton beam intensity history, protons on target per pulse (red, right scale) and integrated POT (blue, left scale).

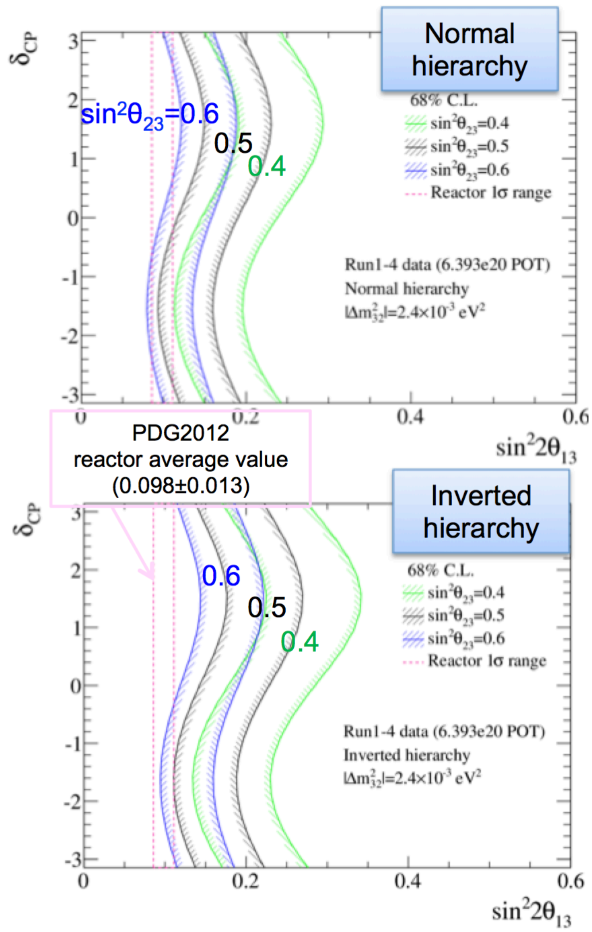


Figure 4: T2K sensitivity (using only data *already acquired*) to $\delta_{CP}$ vs $\sin^2 2\theta_{13}$ , showing how $\sin^2\theta_{23}$ and mass hierarchy (upper: normal; lower: inverted) affect results. Increased precision in $\theta_{23}$ will be critical.

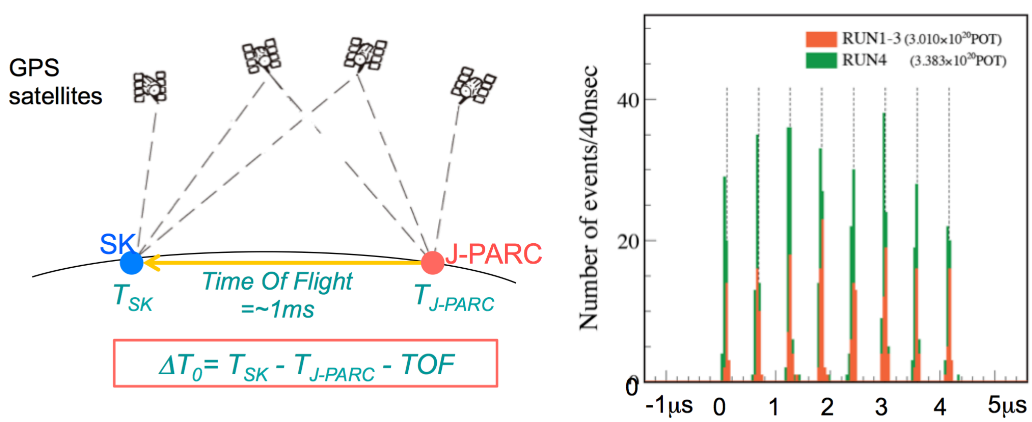


Figure 5: left: T2K GPS time synchronization scheme; right: beam-induced events in SK – timing accuracy displays the proton beam's bucket substructure.

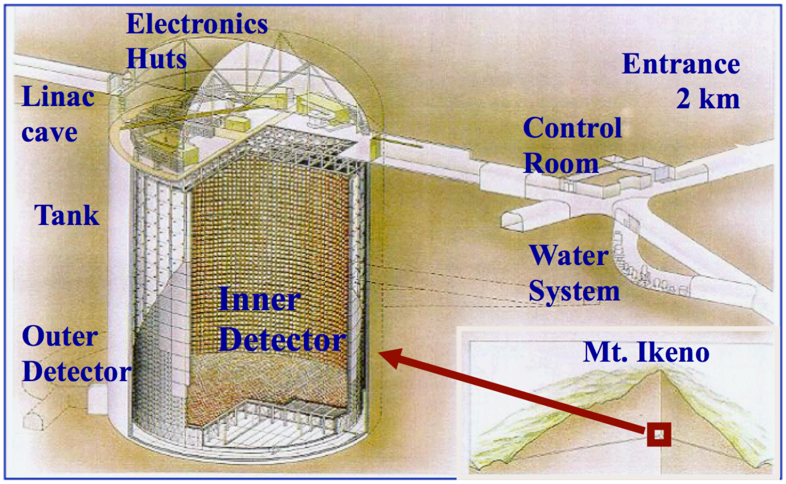


Figure 6: Super-Kamiokande underground neutrino detector.

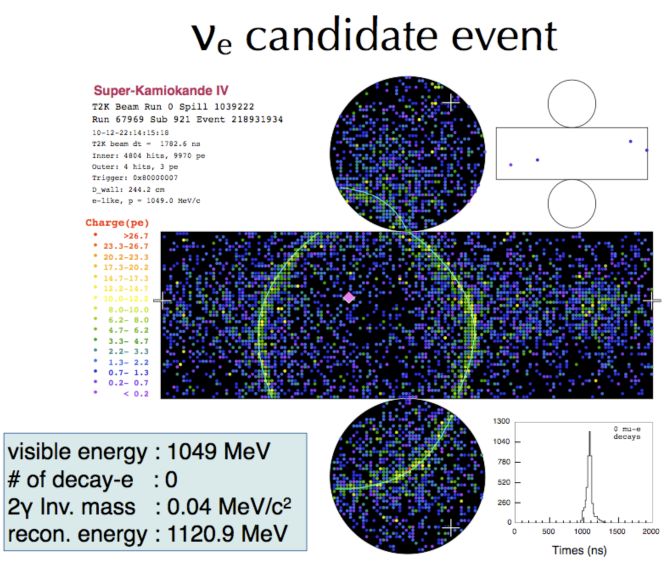


Figure 7: SK event display for a T2K electron neutrino appearance event.

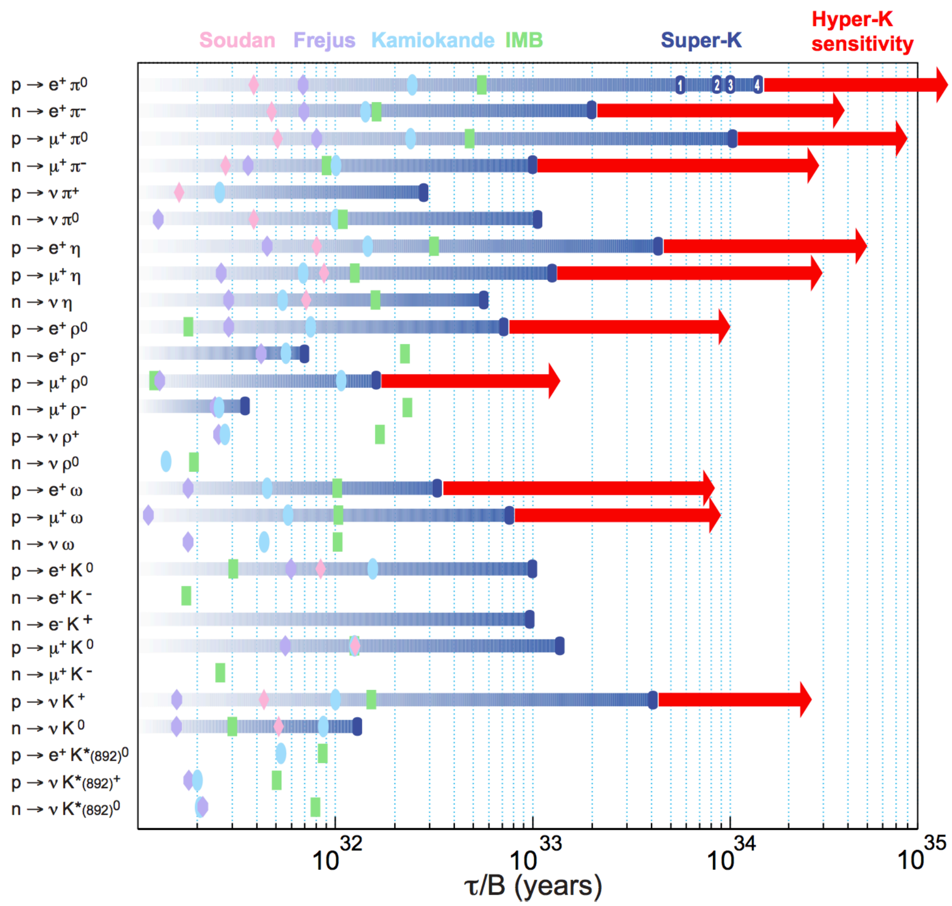


Figure 8: Super-K results on nucleon decay (latest 220 kt-yr data release), with potential for megaton-scale Hyper-K shown.

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## V. Appendices

### A. Super-Kamiokande Publications

Papers published in refereed journals only.

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**C. Theses by supported students**

Paul DeStefano, The T2K Precise Time System, MS Thesis, University of Washington, 2015.

Kevin Connolly, Development Towards a Model-dependent Measurement of the $\nu\mu$ Charged Current Single $\pi$+ Pion Momentum Spectrum, PhD Thesis, University of Washington, 2014

Scott Davis, Relative Cross Section Measurement of the Inclusive Charged Current Multiple Pion Production to Inclusive Charged Current from \numu at the Near Detector of the T2K Experiment, PhD Thesis, University of Washington, 2014

Eric Thrane, A Search for Astrophysical Neutrino Point Sources with Super-Kamiokande PhD Thesis, University of Washington, 2008

Kiyoshi Keola Shiraishi, Super-Kamiokande Atmospheric Neutrino Analysis of Matter-Dependent Neutrino Oscillation Models
PhD Thesis, University of Washington, Aug. 2006

Michael R. Dziomba, Study of neutrino Oscillation Models with Super-Kamiokande Atmospheric
Neutrino Data, PhD Thesis, University of Washington, Aug. 2012

Andrew L. Stachyra, A Search for Astrophysical Point Sources of Neutrinos with Super-Kamiokande
PhD Thesis, University of Washington, Feb 2002

Jeffrey S. George, Experimental Study of the Atmospheric \nu_\mu / \nu_e Ratio in the Multi-GeV Energy Range
PhD Thesis, University of Washington, Jun. 1998

## D. MAJOR EQUIPMENT

Major items of equipment acquired for this project (as of 2017):

### High-performance computer system

Location: Physics-Astronomy Building, University of Washington, Seattle, WA
Capabilities: rapid processing of extensive monte carlo and physics analysis data. Two host computers with associated high-capacity data storage. Part of a nationwide T2K computing network managed by U. Colorado collaborators.

### Super-Kamiokande Water Cherenkov Detector and Laboratory

Location: Kamioka Observatory, Higashi-Mozumi, Gifu Prefecture, Japan
Capabilities: World's largest underground neutrino detector; capable of observing interactions of neutrinos from 4 MeV to >100 GeV energies; detector for solar, atmospheric and supernova neutrinos. Laboratory includes large-scale computing and data-storage facilities.

### T2K Pi-Zero detector (part of ND280 near detector complex)

Location: J-PARC Laboratory, Tokai, Ibaraki Prefecture, Japan
Capabilities: Accurate tracking and reconstruction of neutrino interactions in water target layers.

### Precise GPS time synchronization system

Location: J-PARC Laboratory, Tokai, Ibaraki Prefecture, Japan, and Kamioka Observatory, Higashi-Mozumi, Gifu Prefecture, Japan
Capabilities: Provides time stamps for local events (proton beam spills at J-PARC, and neutrino interaction triggers at SK) with accuracy relative to UTC on the order of 30 ns, and using supplementary precision GPS receivers and offline processing, corrections to provide ~1 ns precision.