# The Saga of Atmospheric Neutrinos

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A Saga? Yes, a great scientific tale of persistence, dead ends, serendipitous discovery, redemption and glory. Dictionary definition of a Saga: "a long story of heroic achievement, especially a medieval prose narrative in Old Norse or Old Icelandic." (OED). Indeed the tale of atmospheric neutrino studies has much of this. . . .

## 1 Neutrino Sources

From whence do neutrinos originate? The dominant sources we know are:

- Nuclear Reactors (power stations, ships, test reactors), known and observed since the 1950's.
- Particle Accelerators make them from collisions of beams of protons into targets and subsequent mesons decaying to muons and those allowed to decay in flight, as at Fermilab, CERN, KEK and Tokai.
- Atmospheric Neutrinos from GeV to TeV energies, produced by incoming cosmic rays colliding with air nuclei in the high atmosphere and then the secondary pions and kaons decaying in flight through the atmosphere.
- Geo-neutrinos from throughout Earth's mass from primordial Uranium, Thorium and Potassium decay chains, long predicted but hard to detect, and first observed in 2005.
- The Sun and indeed all stars produce vast numbers of electron neutrinos, bathing the Earth day and night. The flux of solar neutrinos at earth totally overwhelms the summed flux from all the rest of the Universe.
- Supernova (SN) neutrinos are the exception where a huge bursts may be seen from SN not much further away than out neighbor galaxies (SN1987A), with detectors in the class of $< 100\,\mathrm{kT}$. Attempts have been made to see the sum of all SN neutrinos, but that flux has been beyond reach as yet (maybe in a few years in Hyper-Kamiokande).

- Cosmic High Energy Neutrinos, now detected in the last few years by IceCube, with energies up to a few PeV. At present there seem to be several types of sources, some associated with cosmic jets.
- Big bang relic neutrinos are almost surely omnipresent at about 300 neutrinos/cm$^3$ but minuscule kinetic energy now, and with incredibly small interaction cross sections to boot. Nobody at present seems to have a good scheme for detecting these.

The previous categories have indeed all been observed and all are under active research with the exception of BigBang neutrinos. Herein we focus on the atmospheric neutrinos.

## 2 History, Neutrino Dreams

The journey to high energy neutrino astronomy starts with fantastic dreams in Russia and US in 1950's with pioneers such as Moisei Markov, George Zatsepin, in Russia and Ken Greisen, and Fred Reines in the USA, and who first articulated the dream of detecting cosmic neutrinos, hopefully permitting us to view the Universe in a very different light than photons [1].

Shortly after the 1956 initial detection of neutrinos by Reines and Cowan near nuclear reactors, there were soon the pioneer quests seeking natural atmospheric neutrinos in deep gold mines in India and South Africa in the 1960's (more about this later, and better detail in the accompanying talk by Paolo Lipari [2] with a more complete list of references).

## 3 Renewed Neutrino Activity in the 1970's

There followed years of struggle by small groups of true believers on little support in the 1970's. The DUMAND project got started in the mid 1970's with enthusiastic support by both Russians and Americans, including yours truly. Matters became more seriously considered with the landmark 1976 DUMAND Workshop in Hawaii (see ref. [3]), attended by an international cast of excited pioneers who would go on to found various initiatives going deep under the ground, water and even ice, and forming a direct lineage with almost all future large neutrino efforts, both experimental and theoretical. The 1976 DUMAND Workshop was particularly exciting to the participants because we had physicists from both the Soviet Union and the USA and Europe (and Japan), at a time when such contacts were generally difficult during the Cold War. The forbidden fruit aspect definitely added a spice to the interactions. Unfortunately international politics did enter in 1979 with the Russian intervention in Afghanistan and the US government forbidding US scientists to collaborate with the Russians if using any US government funds (see Igor Zheleznykh's contribution to this conference [4]). All the scientists involved were anxious to pursue our joint physics interests, and we did have some wonderful interactions such as the marvelous 1979 DUMAND workshop at Lake Baikal (see [5]). DUMAND USA went ahead for about 15 years, and with heroic efforts, the heroic parallel Russian DUMAND effort in Lake Baikal has moved ahead slowly, still operating today.

Overall the situation for neutrinos was saved in the late 1970's by theoritician magi who proposed the mystical quest for finding proton decay, in the form of the SU(5) grand unification scheme which predicted rates of nucleon decay accessible with a kiloton or more of closely observed material (see [6]). Because of cosmic rays making backgrounds, such searches required going deep (several thousand feet) underground. And of course many other research topics came along for free.

## 4 Atmospheric Neutrino Flux Calculations

These can be done via two methods. The ab initio process starts with assumed knowledge of the incoming cosmic ray spectrum and composition, and employs interaction modeling to produce pions and kaons from interactions high in the atmosphere, and then propagating these through decay in flight. The second, less used method starts with the observed cosmic ray muon spectrum from high in the atmosphere.

First calculations by M.A.Markov and Igor Zheleznykh[7], V.A.Kuzmin and George Zatsepin[8], and Ken Greisen[9] all around 1960, and Cowsik[10] in 1963. Other 1960's calculations were by Osborne, Wolfendale, Pal, Budagov and others (see Paolo Lipari's contribution for much more detail and references[2]).

These all needed information on composition and cross sections which were not yet available to any good precision... unknown errors were on the scale of a factor of two. But they agreed roughly with the first atmospheric neutrino observations in 1965 at the Kolar Gold Field (KGF in India)[11] and Case-Witwatersrand-Irvine (CWI in South Africa)[12]. It is noteworthy that indeed the first fluxes measure were a bit low (~35 % but possible systematic flux errors were on the order of a factor of two), but considering the huge uncertainties in flux calculations nobody made much of it until twenty years later in hindsight.

Atmospheric neutrino calculations remain difficult to this day. Top-down requires much knowledge of nasty hadronic physics as well as good incoming primary spectrum and composition. Using muon & kaon fluxes involves problems with the altitude of the observation, and that most muon spectrometer measurements are from ground level and not from balloons. Moreover the $K/\pi$ ratio even from accelerators and at an $x{\sim}1$, remains poor even to this day. Quark x distributions at $x=1$, which is where it counts for the neutrino spectrum calculation, are not well known. The geomagnetic field is not ignorable for neutrino energies $< 10\,\mathrm{GeV}$ or so and so the flux depends upon geomagnetic latitude. Likewise solar activity is not negligible either at energies up to around 10 GeV. And on top of all that the cross sections for $\nu$ observation remain far from perfect particularly in the few GeV region between quasi-elastic and deep inelastic regions (though this is an area of significant activity due to accelerator neutrino experiments). You can read much more from Tom Gaisser and Anatoli Fedynitch, and Morihiro Honda at the PANE2018 Meeting[13].

## 5 Broadening Interest in the late 1970's

After the early underground measurements of the 60's not much happened for around 15 years. Activity was rejuvenated in the late 1970's after the serious consideration of deep underground or underwater muon and neutrino detectors. DUMAND, got started by a group of physicists from Japan, Russia and the US, first from a gathering of like minds at the 1973 Cosmic Ray Conference in Denver. My recollection is that the attendees were Fred Reines (UCI), George Zatsepin (MSU), Saburo Miyake (ICRR), Howard Davis (OSU), Peter Kotzer (WSU), Maurice Shapiro (NRL), and me. An initial follow up meeting was held at Kotzer's venue in Bellingham, Washington in summer 1975, where with the help of oceanographers, we identified the best ocean location to be in the deep waters off the Hawaiian Islands (deep, extraordinarily clear waters, close to shore). This led to the first big international meeting arranged for 1976 in Hawaii. Well known experimentalist (and musician famed for his physics songs) Art Roberts of Fermilab organized this meeting, and locals Vic Stenger and Vince Peterson provided enthusiastic support.

The 1976 DUMAND Workshop has been widely heralded as the first time that astrophysicists, astronomers, particle theorists, cosmic ray experimentalists, particle physicists, oceanographers, ocean engineers, and Navy people got together to consider the attempt to start neutrino astronomy from the oceanic depths. There was a lot of excitement because of the attendance (in the midst of the Cold War) of Soviet scientists V.S. Berezinsky (Lebedev), A. E. Chudakov (Lebedev), B.A. Dolgoshein (MEPI), and A.A. Petrukhin (MEPI). L. V. Volkova and G. Zatsepin did many early neutrino flux and rate calculations at this time, and similar efforts picked up greatly after historic 1976 DUMAND conference[3].

Of interest perhaps to historians is the fact that we really did not know our specific goals.

We knew that we wanted to start looking for cosmic neutrinos, and we knew that the ocean deeps were a great place to start given large shielding from cosmic rays and unlimited available volume for target, but we knew neither the best energy range to aim for initially, nor the best detection technology and these discussions made the event most exciting.

We considered optical detectors employing the well understood photomultipliers, and possible new variations upon the glass bulbs (cylinders for example), but also new ideas about acoustic and radio pulse detection. Optical detection won out because the technology was already available and proven.

Radio detection depends upon the net ~30 % electron charge excess in a high energy interaction induced cascade. This has an $E^2$ energy dependence in pulse amplitude so becomes stronger at higher energies, but practical above noise only in the $>10^{17}$ eV range as yet. Zheleznykh was amongst the first[14] to make attempts at measuring Askaryan radiation, at the Vostok base near the South Pole.

There remain dreams of acoustic detection, which have even now not reached practicality. Funding for exploring the new detection mechanisms (optical, acoustic and radio) did not flow evenly, and they were pursued in an uneven multiplicity of efforts. Radio pulse detection has been developed (e.g. Anita) and has some exciting results though as yet not what was anticipated.

Ted Bowen led the discussions of acoustic radiation as a signal of high energy neutrino interactions at the 1976 Workshop. A task force was formed and ultimately acoustic signal measurements were made at Brookhaven and elsewhere, in which Larry Sulak, then of Harvard, played a seminal role. This line of work played out with experiments by Giorgio Gratta of Stanford, and colleagues in the SAUND project of the early 2000's, but continues to be explored sporadically such as for KM3NeT in the Mediterranean.

As to the science goals, we basically at first we did not know whether our initial prospects were best with lower energies from stellar burning and supernovae with MeV energies, or from the mysterious sources of ultra-high energy cosmic rays with energies ranging up to $10^{20}$ eV but unknown neutrino efficiencies. What was determined that, given the known cosmic ray spectrum, it would require a detector of the size of a full cubic kilometer surely to get into business; and this has finally been vindicated with the recent IceCube results. On the other hand we recognized that solar neutrinos and supernovae could be detected with more modest though still huge instruments with lower energy thresholds. (BTW, we knew about the potential for neutrinos to oscillate, but had no clues about what was likely to be found.)

This led to two major design branches, one of which was an open (billion tonne effective target volume) array of PMTs spaced apart by tens of meters in the deep ocean, and the other was for an underground instrument in the range of tens of meters in dimensions (thousands of tons), and with PMTs covering the walls looking inwards.

Follow up DUMAND activity involving both Soviet and American physicists, plus others from Switzerland, Japan, India, Italy, Germany and France. Much took place at summer DUMAND Workshops in Hawaii and at Scripps Institute of Oceanography from 1978 onwards through the 1980's. There were also DUMAND sessions at all of the biannual International Neutrino Conferences and International Cosmic Ray Conferences of that era. Of particular interest is the special DUMAND meeting that took place at the Pacific Science Congress in Khabarovsk in 1979, the first time that outsiders had been to this Soviet far West city, which was followed by a DUMAND Workshop at Lake Baikal with high level Russian physicists. I have written a short account of these exciting (both for physics and for personal interactions) meetings, which is included here as an Appendix.

Up until this time in the '70's astrophysicists studying energetic objects had thought little or not at all about neutrinos, and generally did not consider neutrino emission and hence we had almost no pre-existing estimates of cosmic neutrino fluxes. Berezinsky and Zatsepin realized that the GZK (Greisen-Zatsepin-Kuzmin) cutoff of $10^{20}$ eV cosmic ray protons interacting on cosmic photon backgrounds, inevitably led to neutrinos via the de-excitation of the protons with pion emission and subsequent decay[15]. In any case with the involvement of such persons as the prolific astrophysicist Dave Schramm, interest in astrophysical neutrinos grew. (Schramm and I became good friends and climbed mountains together too).

## 6 The Proton Decay Fueled 1980's

The arrival of the 1974 Georgi-Glashow SU(5) model[6] which permitted prediction of the decay of protons at a potentially detectable rate, with kiloton scale observed volumes. Within several years this prediction set off intense international activity to find the ultimate key to an elementary particle physics grand unification scheme. Unfortunately the model did not survive theoretical scrutiny long enough to get rejected by experiment. Yet miraculously it did survive long enough for us to get money to build these grand new deep mine proton decay search instruments!

Hence, in the early 1980's a few large underground instruments in the US, Europe, Japan, India, and Russia were built and came into operation.

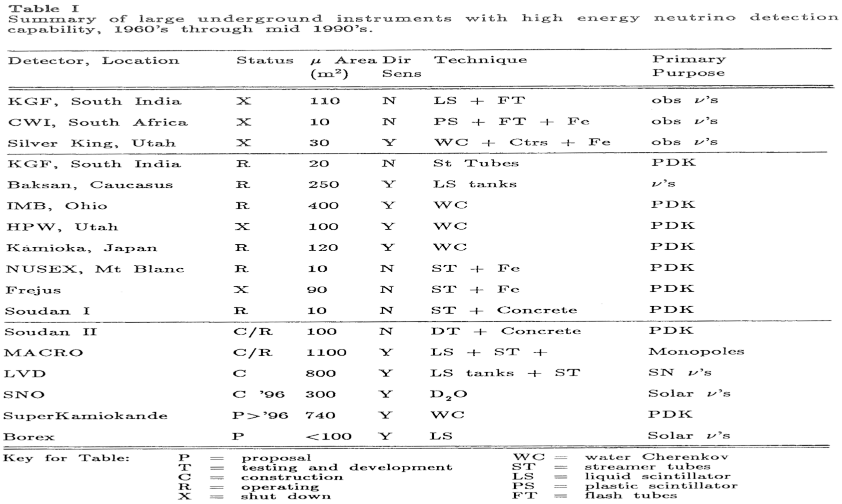


Table I
Summary of large underground instruments with high energy neutrino detection capability, 1960's through mid 1990's.

| Detector, Location | Status | $\mu$ Area ($m^2$) | Dir Sens | Technique | Primary Purpose |
|---|---|---|---|---|---|
| KGF, South India | X | 110 | N | LS + FT | obs $\nu$'s |
| CWI, South Africa | X | 10 | N | PS + FT + Fe | obs $\nu$'s |
| Silver King, Utah | X | 30 | Y | WC + Ctrs + Fe | obs $\nu$'s |
| KGF, South India | R | 20 | N | St Tubes | PDK |
| Baksan, Caucasus | R | 250 | Y | LS tanks | $\nu$'s |
| IMB, Ohio | R | 400 | Y | WC | PDK |
| HPW, Utah | X | 100 | Y | WC | PDK |
| Kamioka, Japan | R | 120 | Y | WC | PDK |
| NUSEX, Mt Blanc | R | 10 | N | ST + Fe | PDK |
| Frejus | X | 90 | N | ST + Fe | PDK |
| Soudan I | R | 10 | N | ST + Concrete | PDK |
| Soudan II | C/R | 100 | N | DT + Concrete | PDK |
| MACRO | C/R | 1100 | Y | LS + ST + | Monopoles |
| LVD | C | 800 | Y | LS tanks + ST | SN $\nu$'s |
| SNO | C '96 | 300 | Y | $D_2O$ | Solar $\nu$'s |
| SuperKamiokande | P>'96 | 740 | Y | WC | PDK |
| Borex | P | <100 | Y | LS | Solar $\nu$'s |

Key for Table:
P = proposal
T = testing and development
C = construction
R = operating
X = shut down
WC = water Cherenkov
ST = streamer tubes
LS = liquid scintillator
PS = plastic scintillator
FT = flash tubes

Figure 1 – Summary of Large Underground Instruments with High Energy Neutrino Detection Capability, 1960's through mid-1990's[16].

Figure 1 illustrates the situation as I reviewed it in February 1990[16]. At that time the first three listed (KGF in India, CWI in South Africa and Silver King in Utah had been shut down for nearly two decades, whereas there were 8 projects which were operating for some period of the 80's. The 90's saw Soudan II, MACRO (monopole search experiment), and LVD (supernova neutrinos) all come into operation.

It should be mentioned that greatly improved computer calculational ability was taking off in this era, with the first large simulation programs enabling much improved atmospheric neutrino flux calculations.

I also note that while I cannot now document the exact sequence, many of us felt that there was somewhat of a trend for new measurements to be made, and then flux calculations validating them, with incipient discrepancies painted over and possibly showing the recognition of the muon neutrino anomaly.

## 7 The Contentious Neutrino Anomaly

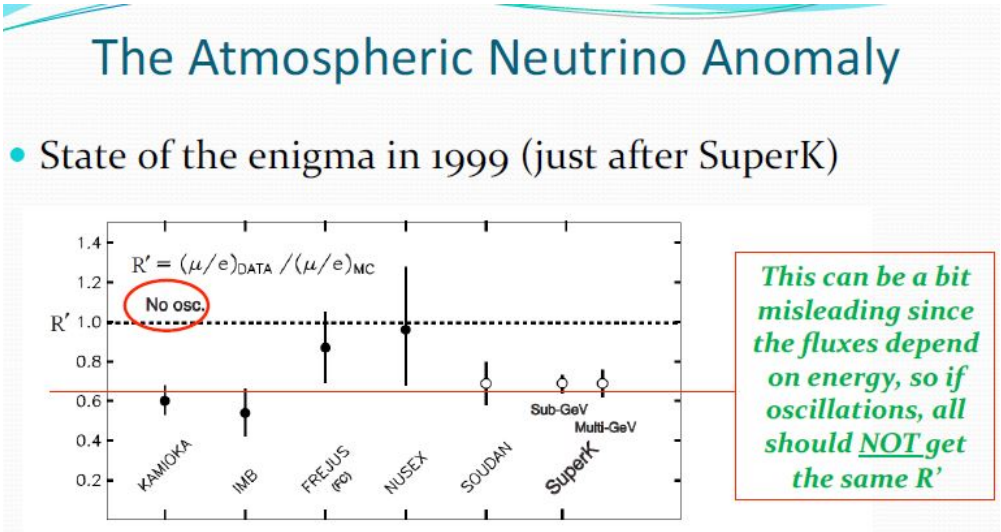
Serious hints of something awry with the atmospheric neutrino generated muon to electron ratio, christened the "muon neutrino anomaly" developed from 1983 in the IMB experiment and onwards in others. (These first serious pieces of evidence ultimately leading to the discovery of neutrino oscillations are documented in detail in the IMB dissertations of Bruce Cortez and (now US Congressman!) Bill Foster, Eric Shumard, Geoff Blewitt and Todd Haines). The IMB group was nervous about making any inflammatory claims about neutrino oscillations, particularly since Fred Reines had made a huge blunder in claiming neutrino oscillations from reactor experiments in 1980[17].

There was much struggle to make sense of hints, and contrary results, and there arose even animosity amongst explorers with seemingly contradictory results. Confusion, contradiction and dispute sometimes even leading to harsh words, reigned about the "neutrino anomaly" for about a decade. However by the later 1980's Kamiokande and IMB made the anomaly clearer after they developed particle identification techniques, discriminating the Cherenkov rings produced by electrons versus muons. (The anomaly became a moot question a decade later, after the 1998 Super-Kamiokande results were released, see T. Kajita's contribution[18].)

The deficit of atmospheric muon neutrino events in the ~ 1 GeV energy range was long seen, but not appreciated at first. In summary the ratio of $\nu_\mu$ events seen/expected was[19]:

| | | |
|---|---|---|
| CWI | 66 ± 14 % | 1965 |
| KGF | 64 ± 24 % | 1965 |
| IMB mu-decays | 76 ± 10 % | 1986 |
| Fréjus | 75 ± 27 % | 1988 |
| Kamiokande | 59 ± 7 % | |

Early experiments observing atmospheric neutrino interactions underground did not detect electron neutrino events, and the ratio above is rather different than "R" in following table, the ratio of muons to electrons, observed / expected (in some experiment). This "ratio of ratios" depends on observed energy range of the experiments if it is not unity, which it is not, see Figure 2.



The Atmospheric Neutrino Anomaly

- State of the enigma in 1999 (just after SuperK)

This can be a bit misleading since the fluxes depend on energy, so if oscillations, all should NOT get the same R'

Figure 2 – The state of the neutrino anomaly in 1999, just after the Super-Kamiokande discovery paper[20] (double ratio of muon to electron events, data divided by expectations).

By the end of the IMB-1 run we had 401 events 104 with a $\mu$ decay. Expected was 34 ± 1 %, seen 26 ± 2 %, a 3.5 $\sigma$ problem. Many possible causes were hypothesized, including oscillations, but... NUSEX in the Mont Blanc Tunnel reported 28 ± 11 % and Kamiokande reported 36 ± 8 %. This was the situation in 1986.

By 1988 the anomaly became clearer in the IMB and Kamiokande data with the development of "showering" vs "non-showering algorithms" (discriminating electron neutrino interactions versus muon neutrino interactions).

Matters were made more confusing due to the under-prediction of the electron neutrino flux (still the case, BTW), wherein there were too many electron events and too few muon events seen, and so early oscillation speculation was $\nu_\mu \leftrightarrow \nu_e$. See John LoSecco's contributions[21].

It should be noted that starting around 1986 the Kamiokande group began to make claims of the anomaly being due to oscillations, though the mass difference-squared range they deduced has now been rejected. The IMB group was well aware of this possibility of oscillations, but felt the claims were not justified and that oscillations was not necessarily the only solution. Even worse, the IMB group published a paper rejecting muon neutrino oscillations including the presently accepted range in $\Delta m^2$ . As John Lo Secco has published at this meeting, this erroneous result was due to employing a flux calculation later rejected. Note that these experiments did not have useful neutrino direction information and only depended on muon and electron neutrino rates.

Here follows a quick review of various confusing evidence about possible neutrino oscillations in atmospheric neutrinos from the 1980's era evidence (from a slide I showed many times during that era). Some the confusions about the muon neutrino anomaly:

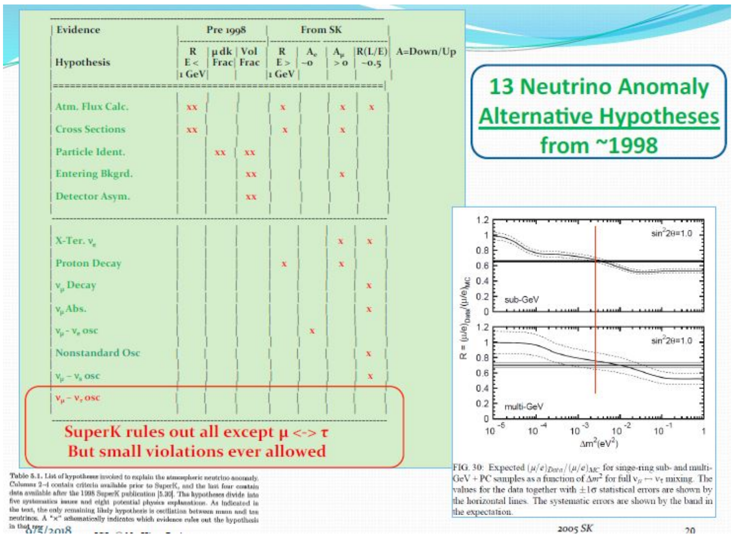
- Under-prediction of the electron neutrino flux: too many electron events + too few muon events, ⇒ early oscillation speculation was $\nu_\mu \leftrightarrow \nu_e$ .
- Tendency to be see the anomaly in water detectors and not with iron targets.
- Cherenkov cone resolution in e vs $\mu$, in 1980's was not yet demonstrated (until at done by the IMB/SuperK group at KEK in the 1990's).
- Cross sections and fluxes, could be wrong (and are still somewhat problematic).
- Possibility of detector up/down or e/$\mu$ biases?
- Possibility of new source of electron neutrinos?? (raising low energy e/$\mu$).
- Cosmic rays, not great reputation (enhanced by claims of PDK observation by Miyake and even Koshiba, and by Reines's 1980 blunder, often discussed!)
- IMB paper on entering-stopping events rejecting oscillations (incorrect since it employed a neutrino flux model now known to be wrong).
- Early oscillation claims from Kamiokande (and some others)were not credible and got $\Delta m^2$ in nowadays disallowed region in any case.

See Figure 3.

## 8 Supernovae

Supernova Neutrino studies got a great boost when SN 1987A yielded physics gold for Kamioka, IMB and Baksan. The observation of the only visually detectable supernova in our galactic neighborhood (in the Large Magellanic Clouds at 50 kpc) in 200 years garnered much scientific and public attention, and spawned much activity in the theory community. It should be noted that until that event we did not know that the imagined scenario of end of life stellar collapse to a neutron star actually took place. But now we knew that collapsing stars do indeed go through a phase of being dominantly neutrinos. And we also knew that neutrinos thus made survive and fly at the speed of light for 150,000 years, including being slightly deviated by the mass of our Galaxy to be successfully detected on Earth.

It was an exciting period for all of us involved, though not without controversy due to the apparently incorrect 4 hour earlier observation of a very low energy burst of "neutrinos" by LSD



13 Neutrino Anomaly Alternative Hypotheses from ~1998

| Evidence<br>Hypothesis | Pre 1998<br>R E < 1 GeV | <br>μ dk Frac | <br>Vol Frac | From SK<br>R E > 1 GeV | <br>$A_e$ ~0 | <br>$A_\mu$ > 0 | <br>R(L/E) ~0.5 |
|---|---|---|---|---|---|---|---|
| Atm. Flux Calc. | xx | | | x | | x | x |
| Cross Sections | xx | | | x | | x | |
| Particle Ident. | | xx | xx | | | | |
| Entering Bkgrd. | | | xx | | | x | |
| Detector Asym. | | | xx | | | | |
| X-Ter. $\nu_e$ | | | | | | x | x |
| Proton Decay | | | | x | | x | |
| $\nu_\mu$ Decay | | | | | | | x |
| $\nu_\mu$ Abs. | | | | | | | x |
| $\nu_\mu - \nu_e$ osc | | | | | x | | |
| Nonstandard Osc | | | | | | | x |
| $\nu_\mu - \nu_s$ osc | | | | | | | x |
| $\nu_\mu - \nu_\tau$ osc | | | | | | | |

A=Down/Up

SuperK rules out all except μ <-> τ
But small violations ever allowed

Table 5.1. List of hypotheses invoked to explain the atmospheric neutrino anomaly. Columns 2–4 contain criteria available prior to SuperK, and the last four contain data available after the 1998 SuperK publication [5.30]. The hypotheses divide into five systematics issues and eight potential physics explanations. As indicated in the text, the only remaining likely hypothesis is oscillation between muon and tau neutrinos. A "x" schematically indicates which evidence rules out the hypothesis in that row.

FIG. 30: Expected $(\mu/e)_{Data}/(\mu/e)_{MC}$ for singe-ring sub- and multi-GeV + PC samples as a function of $\Delta m^2$ for full $\nu_\mu \leftrightarrow \nu_\tau$ mixing. The values for the data together with $\pm 1\sigma$ statistical errors are shown by the horizontal lines. The systematic errors are shown by the band in the expectation.

2005 SK

9/5/2018

20

Figure 3 – List of Hypothetical explanations of the neutrino anomaly from about 1996, just prior to the Super-Kamiokande announcement of discovery of muon neutrino disappearance. After exposition of Super-Kamiokande data in 1998, the only viable option remained as $\nu_\mu \leftrightarrow \nu_\tau$.

in the Mont Blanc tunnel, which went undetected by the other three instruments (Kamiokande, IMB and Baksan). As of yet nobody understands these results, which this author personally investigated without finding any experimental problem. My best guess is an incredibly unlucky background fluctuation (at the level of less than once per year). To have been real and not seen elsewhere the flux (of what?) would have to have been restricted to less than several MeV, and due to the small size of the LSD detector to have been large compared to the later detected SN neutrino flux, and hence incredibly powerful. While most physicists have dismissed these strange results, and while I remain very skeptical, we can only await the next SN to find out is any such strange phenomena accompany the burst.

## 9 Solar Neutrinos

A bonus not expected from the 1980's proton decay searches and attendant atmospheric neutrinos studies was the observation of solar neutrinos at Kamioka. Those of us building the big underground experiments did not at first think we had the sensitivity to see the few MeV solar neutrino interactions, and hence this quest was ceded to the radiochemical investigations, beginning with Ray Davis' cleaning fluid detector in the Homestake mine. However, (U. Michigan Visiting Prof.) Tegid Jones of UCL carried out careful solar neutrino calculations in an attempt to engage the IMB experiment. However we abandoned the quest since the IMB threshold of about 10 MeV was simply too high for solar neutrinos, and the depth (and thus background) of the IMB detector was not sufficient. Bruce Cortez, who had been an IMB graduate student went to work for Al Mann at U. Penn, and transported the idea (and much IMB software) to the Kamioka group. Fortuitously the Kamiokande detector had been designed by Masatoshi Koshiba to rely upon topological recognition of nucleon decay events (and initially without regard for fast timing) and the group had pioneered the development of the grand 20" Hamamatsu PMTs (huge compared to the initial 5" PMTs in IMB). They did achieve a threshold low enough to detect solar neutrinos. Their subsequent observation of solar neutrinos, facilitated by the Al Mann of U. Penn. supplied nanosecond timing electronics, was a great coupe, and initiated counting experiments for solar neutrinos (and a Nobel for Koshiba). That is a great story but not our topic here however, and yet it formed both a distraction to the pursuit of proton decay and atmospheric neutrinos and an attraction to community interest in neutrinos generally.

## 10 The 1990's

Early in the decade IMB was shut down as having completed its mission by the US DOE, High Energy Physics. This was after a major leak event but which was recoverable at manageable costs. But DOE, with their usual quarterly profit mentality said the initial mission of IMB was complete and that we could ask NSF or elsewhere for support if we wanted to continue. (This is in sharp contrast to what I heard in 1992 at the Japanese major agency review for approval of SuperK construction, see discussion session).

The long running US DUMAND project, of which I was the spokesman, was terminated after failure of the deployed junction box off Keahole Point, at 4 km depth on the West side of the Big Island of Hawaii. Actually the DUMAND group did accomplish an unprecedented 45 km of deep ocean cable laying, by physicists using an oceanographic vessel. A short circuit in the ocean bottom junction box and a faulty fuse which arced over, made recovery and repair of the j-box required. Such operations were common amongst communications cable laying operations and could have been accomplished at small fractional cost. Perhaps due to the termination of the US Texas based SSC around the same period, there was timidity at the DOE, which at that time was not at all used to non-accelerator science (now greatly changed in the era of the LSST). The review committee from DOE had not a single ocean technology expert but consisted of mostly accelerator based researchers. Hence the DUMAND program was terminated.

Take note that the Baikal based Russian DUMAND project continued, and on the most meager support. They were aided in survival by help from East German physicists, of whom Christian Spiering was key. Although progress has been slow, that team was carried by unsung heroes, keeping at it over 30 years and slowly working ahead with very minimal resources. (It is a great pity that we in the US were forbidden to keep working with this group in 1979.)

The deep ocean line of work was only restarted later in the decade with the NESTOR project in Greece, ANTARES in France, and NEMO in Italy. The DUMAND group worked hard to transfer experience and even hardware to both NESTOR and ANTARES. ANTARES was the most successful and began about where DUMAND had left off about a decade later with a detector about the same size as that which DUMAND had been preparing to deploy. Those three Mediterranean projects coalesced into a European effort called KM3NeT which as of this time has not advanced to the cubic kilometer scale.

## 11 The Super-Kamiokande Revolution

Super-Kamiokande was completed and brought redemption to the field, fame and fortune in 1998 with the discovery of muon neutrino oscillations (and not electron neutrinos). SuperK had been under construction from 1992 to 1996, starting operations exactly on schedule on 1 April 1996 with a switch thrown by leader Yoji Totsuka. Without much wasted time getting the electronics and data collection into order, useful data began to accumulate within several months. (Big experiments often spend a year getting everything working and calibrated and the data analysis stream stabilized, but not SuperK).

After DUMAND was shut down, I was working on upcoming muon events in SuperK as well as with the group studying the contained events more than 100 MeV. In fact the story of the discovery of muon neutrino oscillations was not so much of a struggle to find the signal, but to wrap our heads around what we were seeing. Most prominent was the zenith angle distribution of the muon neutrino induced events of energy in the 1 GeV energy range which exhibited a dramatic 2:1 up-to-down effect. This of course is due to the upcoming neutrinos travelling distances of order an earth radius, and down-going neutrinos travelling tens of kilometers, and having a large nearly maximal mixing angle and a $\Delta m^2$ of about 2-$3\times10^{-3}$ eV$^2$ which makes the oscillation transition near the horizontal direction.

The Super-Kamiokande discovery paper of 1998 became the most cited paper in all experimental neutrino physics. This landmark observation set off an exponential increase in neutrino studies, and led to the award of the Nobel to analysis group leader Takaaki Kajita in 2015 along with Art McDonald of SNO for clearing the solar neutrino quandary. Neutrino studies multiplied until at the present time they engage a significant fraction of the particle physics community outside of the LHC.

## 12 Atmospheric Neutrinos

Let me go back to the title topic and talk a bit about atmospheric neutrinos. As a neutrino source they are wonderful... the beam is always on, the range of energies goes from $\sim$10 MeV to $\sim$100 TeV, seven orders of magnitude. If we include astro-neutrinos as seen by Ice Cube that goes up to a few PeV. There is a lovely up/down symmetry with atmospheric neutrinos, which is broken by oscillations. The earth provides a variable absorber, $\sim$0-$10^{10}$ g/cm$^2$, determined by looking for neutrinos from various nadir angles. The muon to electron neutrino ratio at around 1 GeV is determined by the well known pion, kaon and muon decay constants, and is reliably 2:1. The atmospheric neutrino beam also has small but useful tau neutrino content about $\sim$10 GeV. And of course, it was from observing atmospheric neutrinos that we first learned about muon neutrino oscillations (and in which this author participated heavily).

The initial SuperK results of 1998 with a statistical significance or order 19 sigma, which number is so large as not to be meaningful... The remaining possibilities are only that muon neutrinos are disappearing consistently with oscillations, or something is grossly wrong with the SuperK data in magnitude and angle (and also as not shown, in momentum).

(A historical aside, it was to my friend John Bahcall's great disappointment, he who had labored so long and hard on solar neutrino predictions, that this was a larger and far more convincing discrepancy than in solar neutrinos at the time, and moreover was very soon accepted by the community which had been uncomfortable with the solar problem. Sadly John did not live to see that in fact his solar neutrino predictions were within 20 % and his long effort justified. Ray Davis lived to see his often doubted Homestake radiochemical experiment validated, and he did go to Stockholm.)

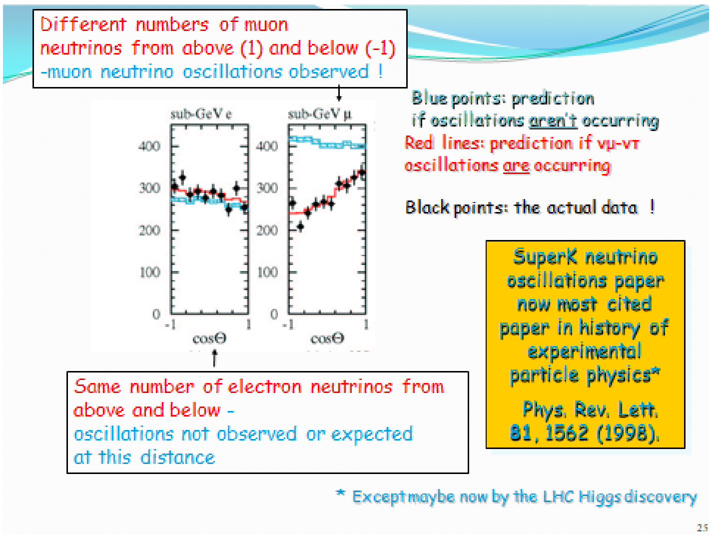
I do note however, that even with what most physicists considered gold plated results from Super-Kamiokande (see Figure 4), there were some doubting physicists. In particular one grand old man of CERN refused to believe any cosmic ray results until they were corroborated by an experiment at an accelerator. But probably 99 % of the community was quickly convinced that we had demonstrated muon neutrino disappearance. It did take several years however to confirm that the oscillation was to mostly to tau neutrinos. This was not so easy but came about mostly through elimination of alternatives. Tau neutrino appearance was detected at Super-Kamiokande but not with great statistics (see ref. [22]).

## 13 The Yellow Brick Road

A comment on science teaching: we usually teach a logical progression from one theoretical notion or experiment to another, making the progress appear to students to be clear and logically neat. However real time life in science has many oft forgotten distractions, culs-de-sac, and even confusing wrong results. On the bleeding edge of science, most of the time we do not know where we stand, what is the best course, or even if our questions can be answered. For example, the road to discovery of muon neutrino oscillations and neutrino mass included:

- First off we had no idea if neutrinos had mass or if they did would the phases change in flight causing flavor oscillations. Particle "shape shifting" in flight remains a bizarre phenomenon with no macroscopic equivalent.

- In the early 90's also much confusion over solar neutrinos.



Different numbers of muon neutrinos from above (1) and below (-1) -muon neutrino oscillations observed !

Blue points: prediction if oscillations aren't occurring

Red lines: prediction if νμ-ντ oscillations are occurring

Black points: the actual data !

Same number of electron neutrinos from above and below - oscillations not observed or expected at this distance

SuperK neutrino oscillations paper now most cited paper in history of experimental particle physics*

Phys. Rev. Lett. 81, 1562 (1998).

* Except maybe now by the LHC Higgs discovery

Figure 4 – Summary of atmospheric electron and muon zenith angle distributions as reported in the Nobel Prize winning publication of 1998.

- There were incorrect claims of oscillations from reactors and some accelerators (the 1995 LSND) results and later from MiniBOONE.

- Theorists and some experimentalists loved the MSW solution with small (and probably undetectable) Cabbibo angles. (JGL and Sandip Pakvasa loved vacuum oscillations for example.) All were wrong.

- Every turn in the neutrino story has been by experimental evidence since there has been little or no guidance from a more fundamental theory.

- Most neutrino mass speculations were wrong as mass differences and mixing angles were surprisingly large.

- Recall that the (minimal) Standard Model assumption was of zero neutrino mass.

- Atsuto Suzuki's gamble on KamLAND payed off, which could have been a null experiment if MSW or vacuum oscillations were correct.

- Only after decades of confusion and wrangling over solar models and various solar neutrino experiments, was the solar neutrino disappearance made clear by SNO in 2001 and 2002.

- There was a general prejudice in the particle community that non-accelerator results were untrustworthy (see following).

- We are in the same situation today with CP violation in the neutrino sector, and Majorana neutrinos... theorists have prejudices mainly based on aesthetics and analogies, but these have a poor track record. Ditto about sterile neutrinos. We do not even know if we are even in this game!

It is this challenge that makes such exploratory physics so fascinating, and for people like me the best game around.

## 14 Sociology/Science Comment

Cosmic Ray (CR) studies, were slow to modernize and lacked credibility, but have come to the top of elementary particle physics unquiries.

- Starting in the 1950's particle physics progress began to shift to accelerators, and more precisely controlled experiments.
- The International Cosmic Ray Conference (ICRC) became somewhat of a backwater, and hot shots tended to go elsewhere.
- CR studies and early neutrino works were not very attentive to error estimates (not easy) (but true in many other areas as well).
- In any event many quantities like input CR fluxes, cross sections, etc. only good to 10-20 %, or worse.
- The W mass was not known until 1983, and hence earlier ideas about high energy neutrino interactions were large under-estimates.
- And no fancy computer simulations to study acceptance, fluctuations, fitting … until 1980's.
- The precision era in CRs did not arrive until 1990's and progressed until now in the second decade of the second millennium, the neutrino game is top notch.
- Since around 1990 non-accelerator experiments have led the way, with the exception of the (not unexpected) Higgs observation.

## 15 Aside: The Curious Luck in Neutrinos (The gods like neutrino hunters?)

- Distance ∼1000 km between arrival direction hemispheres, between full oscillation upcoming and negligible for down-going for atmospheric $\nu$'s ∼1 GeV.
- Mixing angle for $\nu_\mu \leftrightarrow \nu_\tau$ near max $45^o$ (if were tiny: would remain unseen).
- 4 MeV $\nu_e$ oscillation lengths ∼2 km and 150 km, and mixing angle not tiny (very convenient for human terrestrial measurement).
- Wolfenstein Matter-Effect distance ∼ radius of Earth.

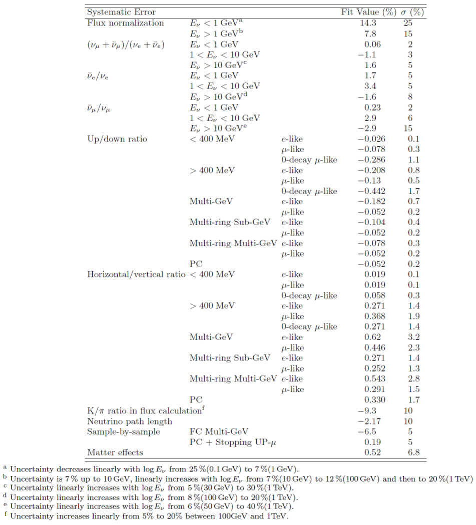
See more about this in Maury Goodman's talk at this meeting. We do seem to have incredible luck with neutrino parameters which could have been anything.

## 16 Direct Production Not Yet Seen and Other Unsettled Issues

- Neutrinos from short lived heavy states produced at high energies should have isotropic zenith angle distribution, not peaked near the horizontal.
- (Recall late '60's flap about false hint of W production seen in Utah, the "Keuffel" effect.)
- Predicted cross over with normal $\pi$/K flux at ∼100 TeV.
- Even with much IceCube data, Direct Production remains not found today.

Also (as heard in detail in other talks at this symposium…):

- Mass order not yet settled but leaning towards "normal".
- CP violation, maybe (but who really cares, since we have no model to test and it does not tell us anything about heavy neutrino involvement in baryogenesis?)
- Majorana or Dirac? Theorists favor Majorana, but no other particle is seen as Majorana.



| Systematic Error | | | Fit Value (%) | $\sigma$ (%) |
|---|---|---|---|---|
| Flux normalization | $E_\nu < 1$ GeV[a] | | 14.3 | 25 |
| | $E_\nu > 1$ GeV[b] | | 7.8 | 15 |
| $(\nu_\mu + \bar{\nu}_\mu)/(\nu_e + \bar{\nu}_e)$ | $E_\nu < 1$ GeV | | 0.06 | 2 |
| | $1 < E_\nu < 10$ GeV | | −1.1 | 3 |
| | $E_\nu > 10$ GeV[c] | | 1.6 | 5 |
| $\bar{\nu}_e/\nu_e$ | $E_\nu < 1$ GeV | | 1.7 | 5 |
| | $1 < E_\nu < 10$ GeV | | 3.4 | 5 |
| | $E_\nu > 10$ GeV[d] | | −1.6 | 8 |
| $\bar{\nu}_\mu/\nu_\mu$ | $E_\nu < 1$ GeV | | 0.23 | 2 |
| | $1 < E_\nu < 10$ GeV | | 2.9 | 6 |
| | $E_\nu > 10$ GeV[e] | | −2.9 | 15 |
| Up/down ratio | < 400 MeV | $e$-like | −0.026 | 0.1 |
| | | $\mu$-like | −0.078 | 0.3 |
| | | 0-decay $\mu$-like | −0.286 | 1.1 |
| | > 400 MeV | $e$-like | −0.208 | 0.8 |
| | | $\mu$-like | −0.13 | 0.5 |
| | | 0-decay $\mu$-like | −0.442 | 1.7 |
| | Multi-GeV | $e$-like | −0.182 | 0.7 |
| | | $\mu$-like | −0.052 | 0.2 |
| | Multi-ring Sub-GeV | $e$-like | −0.104 | 0.4 |
| | | $\mu$-like | −0.052 | 0.2 |
| | Multi-ring Multi-GeV | $e$-like | −0.078 | 0.3 |
| | | $\mu$-like | −0.052 | 0.2 |
| | PC | | −0.052 | 0.2 |
| Horizontal/vertical ratio | < 400 MeV | $e$-like | 0.019 | 0.1 |
| | | $\mu$-like | 0.019 | 0.1 |
| | | 0-decay $\mu$-like | 0.058 | 0.3 |
| | > 400 MeV | $e$-like | 0.271 | 1.4 |
| | | $\mu$-like | 0.368 | 1.9 |
| | | 0-decay $\mu$-like | 0.271 | 1.4 |
| | Multi-GeV | $e$-like | 0.62 | 3.2 |
| | | $\mu$-like | 0.446 | 2.3 |
| | Multi-ring Sub-GeV | $e$-like | 0.271 | 1.4 |
| | | $\mu$-like | 0.252 | 1.3 |
| | Multi-ring Multi-GeV | $e$-like | 0.543 | 2.8 |
| | | $\mu$-like | 0.291 | 1.5 |
| | PC | | 0.330 | 1.7 |
| K/$\pi$ ratio in flux calculation[f] | | | −9.3 | 10 |
| Neutrino path length | | | −2.17 | 10 |
| Sample-by-sample | FC Multi-GeV | | −6.5 | 5 |
| | PC + Stopping UP-$\mu$ | | 0.19 | 5 |
| Matter effects | | | 0.52 | 6.8 |

[a] Uncertainty decreases linearly with $\log E_\nu$ from 25 %(0.1 GeV) to 7 %(1 GeV).
[b] Uncertainty is 7 % up to 10 GeV, linearly increases with $\log E_\nu$ from 7 %(10 GeV) to 12 %(100 GeV) and then to 20 %(1 TeV)
[c] Uncertainty linearly increases with $\log E_\nu$ from 5 %(30 GeV) to 30 %(1 TeV).
[d] Uncertainty linearly increases with $\log E_\nu$ from 8 %(100 GeV) to 20 %(1 TeV).
[e] Uncertainty linearly increases with $\log E_\nu$ from 6 %(50 GeV) to 40 %(1 TeV).
[f] Uncertainty increases linearly from 5% to 20% between 100GeV and 1TeV.

Figure 5 – An image of the table of the flux-related systematic errors and normalizations in the 2017 Super-Kamiokande. The second column shows the best fit value of the systematic error parameter $\epsilon_j$ in percent and the third column shows the estimate 1-$\sigma$ error size in percent. Note that the the overall normalization uncertainty decreases linearly with log $E_\nu$ from 25% (0.1GeV) to 7% (1 GeV). Also note other large uncertainties ranging from 5% to 40% as energy increases[23].

## 17 Still some oddities in Atmospheric Neutrino Flux Calculations

- Over the years most flux calculations under-predicted the observed ($\mu$ & e) neutrino interaction rate. Typically 20 %. See Figure 5.
- (This contributed to consideration of $\nu_e \leftrightarrow \nu_\mu$ early on... 90's).
- Something going on which we have not recognized? Separate issues?

## 18 And more, so much to do and understand about atmospheric and other neutrino correlated phenomena.....

- Still waiting for that next SN, and will there be early events? (as claimed for SN1987A by Mont-Blanc group, weird but not obviously wrong).
- And where are the BZ and Glashow Resonance events? (Glashow events maybe now seen in IceCube?)
- And then there is the Reactor Neutrino Anomaly, including the "5 MeV Bump", still not gone away (reaffirmed this year...).
- And the unexplained LSND and MiniBone anomalies (steriles??) (reaffirmed by MiniBoone Group this year).
- And due to neutron lifetime enigma, speculations about n → DM +? Or?? Astrophysical neutrino implications?
- And nice suggestion about DM Balls ~$10^{23}$ $m_n$, which can explain solar coronal heating, but which should make lots of (not seen) neutrinos (Gorham says no however).
- And the ANITA observation of two ~$30^o$ upcoming showers that appear to be tau-like neutrino showers ~500 PeV for which the earth is opaque.

## 19 Finally, Some Conclusions on the Saga of Atmospheric Neutrino Studies

- Atmospheric neutrino studies have led to much surprising science and great scientific fun.
- Definitive absolute flux and cross section calculations not yet, but getting better every year.
- Neutrino Oscillations, and small but finite mass, the crowning achievement, keep on giving, and presenting many open questions and mysteries. Still no fundamental theory to explain let alone predict… not in Standard Model.
- Not even a hint of PDK! (yet, it paved the way for big detectors) (HyperK?)
- Initial major motivation for starting atmospheric neutrino studies, high energy neutrino astronomy is finally underway thanks to Ice Cube! (And hopefully KM3NeT and Baikal soon).

## 20 Conclusions about Atmospheric Neutrino Studies

The neutrinos produced in the atmosphere have presented us with a cornucopia of neutrino study opportunities, in part facilitated by our marvelous luck with respect to the cosmic ray spectrum, the dimensions of the earth and the properties of slightly massive neutrinos about which we have learned so much unanticipated news. Note that our discovery of the oscillations parameters was entirely without guidance from more fundamental theory… we had no useful idea of expected masses and mixings, only prior experimental limits. I note that great progress has been made in calculations of the atmospheric neutrino flux, which is a very tricky business, but we do not yet have definitive predictions at the few percent level.

Note that the major outcomes of the atmospheric neutrino studies, as well as much of solar neutrino studies (as in Kamiokande and Super-Kamiokande), and the observation of neutrinos from SN1987A, were made possible by (useful though wrong) theoretical predictions of nucleon decay, a beautiful example of serendipity.

The arc of research has come round at last after 50 years, of studying atmospheric neutrinos in order to find neutrinos from the cosmos. The fun goes on with no end in sight!

### Acknowledgments

Many thanks to organizers, in Trieste and Paris for inviting this review!

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## Appendix: Khabarovsk and Lake Baikal in August 1979

This being a Neutrino History meeting, and those who attended the seminal 1979 meetings being few now, I thought it worthwhile to write down some tales of two very interesting meetings in the summer of 1979. The first DUMAND meeting that summer was held at the 16th International Cosmic Ray Conference in Kyoto, 6-18 August, and records of those sessions can be found in Volume 10 of the Proceedings. That year represented a high point in our enthusiasm for the initiation of a grand deep water project to initiate high energy neutrino astronomy, and there was much interest from Japan, the Soviet Union, Europe and the USA. The Soviet and the US groups were soon partitioned due to the Soviet activity in Afghanistan and the US government forbidding our collaboration ("you can collaborate but do not ask for any US government funds to do so"). Whence came the DUMAND in the Pacific (Hawaii centered) and Soviet group working towards deployment in Baikal, which two projects continued as distinct but friendly projects.

**Khabarovsk.** There was a strong contingent of neutrino aficionados at the 14th Pacific Science Congress in Khabarovsk, hosted by the Academy of Sciences of the USSR. Khabarovsk is the largest city in the Eastern most tongue of Siberia, close to the border with Manchuria, and on the meandering Amur River. This was the first time an outside (non-Soviet) group had been in this area for many years and we occupied a new Intourist hotel, complete with the missing floor where the KGB kept track of things (we discovered their private back entrance). This meeting series, not so well known in physics, has been convening since the first session in Honolulu in August 1920!

There was terrific multi-disciplinary camaraderie at this meeting, with heightened enthusiasm since this was during the Cold War and interactions with our academic (and other) brethren in the Soviet Union were infrequent, and somewhat "forbidden fruit", with people being cautious about political discussions, and curiosity about lifestyles from both sides. I recount two incidents which remain as strong impressions.

First, we had rapidly made new friends amongst attendees from around the Pacific basin and from Russia. Somehow a number of us, perhaps 20, wound up in a small hotel room of an interesting Russian scientist, perhaps a geologist. With much lubrication from vodka, the topic became rather political, and the host spoke out strongly about failures of the Soviet system. The phone rang and it was for the occupant, but he waved it away, indicating here was not present. This happened twice more, and he started to look worried. Then came a rap on the door, and two burly fellows escorted him away. Nobody I knew, even later, of what became of him. This was my first instance of seeing the (presumably) KGB in action. (Later we learned that all hotel rooms had a special modification to the telephones which left the microphones active for remote monitoring.).

Second, I was walking with a friend, anthropologist Annette Weiner, along the winding Amur River front one evening, and we noted a comfortable looking river boat moored along the quay which had a large semicircular dining room at the stern, with obvious dinner activity. There was however a gangplank with a guard holding a submachine gun at the entrance. We gathered our courage and walked past the guard, mumbling "tovarisch", and into the maze of passageways. We were fumbling about when another armed guard asked if we needed help, in Russian of course and neither of us spoke enough Russian to get out of this. By a miracle along came one of the English-Russian translators, who immediately stepped up and said we were her friends coming to dinner, and whisked us away. Indeed this ship was the lodging for the conference translators and we were greeted in the aft lounge with great enthusiasm. Many of the translators had never had a conversation with a native English speaker. Soon people started dragging their tables to be contiguous with ours until practically the whole room was linked. As you may imagine, food, liquor, story telling, singing and dancing followed, lasting until the wee hours. Somewhat after midnight we departed for the hotel and practically the whole group escorted us, holding hands and singing. It was a marvelous and unforgettable experience, and really made us think how well people can get along if only given a chance. It was one of the best experiences of my life.

Two different experiences, but heightened, even made possible by the craziness of the Cold War.

**Baikal.** Our DUMAND Colleagues in the Soviet Union organized a meeting at Lake Baikal in the middle of Siberia in a dramatic and historical location. In fact we were meeting near the dacha where Premier Khrushchev and President Eisenhower had planned to meet, except for the unfortunate incident with Gary Powers' U-2 plane being shot down over Russia (May 1960). Anyway there were good facilities and an unusually nice highway from the airport in Irkutsk.

I do not have a written record of all the Russian attendees of this meeting, which I vaguely recall was intentionally left out of the Proceedings (of which I was the Editor, 1980). In fact some of the very best of Russian physicists did attend, headed by Secretary of the Academy M. A. Markov, who I came to admire greatly as a scientist and a fine person. In those days a Head of Delegation was required, and though young (39), bearded, pony-tailed, and Levi wearing, I was designated to be the person interacting with high ranking Academician Markov, who was elderly and dignified. I had expected him to be somewhat dismissive of this relatively young, irreverent, hippy looking American, but he was friendly, open and generous, and we got on famously!

In fact dear Markov had facilitated the participation of my friend Annette Weiner, a cultural anthropologist who was then faculty at U. Texas, Austin. My recollection is that in Khabarovsk I asked Markov if she could come with us to Baikal, and he said something like "make it happen" to his assistant, and that was that… no troubling visas and such, she just went along as an accompanying person. At my suggestion she wrote a little paper about her experience, which I included in the Proceedings. (See DUMAND 1979 Summer Workshop at Khabarovsk and Baikal, p.367, Pub. Hawaii DUMAND Center, 1980). This caused some anxiety among my Russian friends, since it did have some mild observations beyond just physics, but in the end I think there were no serious repercussions.

Other physics attendees from Russia were George Zatsepin, Venya Berezinsky, Igor Zheleznykh, Lev B. Okun, Arkady B. Migdal, Alexander Chudakov, V. F. Yakovlef, A. Z. Gazizov, L. B. Bezrukov, E.V. Bugaev, A. A. Petrukhin, Yu. N. Vavilov.

The USA participants were as listed as authors in the Proceedings. Notable, aside from the usual DUMAND suspects, was retired Admiral Nathan Sonenshein, then of the Global Marine Corporation. One afternoon after sessions, we were invited down to the pier where the oceanographic vessel was birthed, and sailed out a short way into the lake to view the sunset, and raise a few toasts. This toasting included the crew, and apparently even the engineers below decks. As we returned, carefully approaching the pier, instead of slowing the ship began suddenly to accelerate. There was a disconcerting crunching of dock timbers as we slid alongside. But the shoreline had a gentle gravel slope and the ship came to rest without much shock and little or no damage (except for the pier). Apparently due to some tippling, the engine telegraph was mistaken between full astern and full ahead. What I recall most was the horror on the old Admiral's face… a pity I did not catch it on film. Of course the Russian crew was embarrassed, but we all had a huge laugh and that was that.

BTW, for the record, at this meeting I did have very private conversations with one important Soviet physicist about defecting to the West, while walking in dense birch woods. After coming home I was interviewed by CIA and FBI about our trip (as was usual in those times), and I refused to tell the agents who was considering defecting because I did not trust the agencies… as was later proved to be the case.

For the science content of the gathering at Baikal, I refer the reader to the Proceedings, which has lots of interesting material. Browsing through them some 40 years later, it is impressive both at how well we did in predicting some future activities (such as the necessity of going to 1 $\mathrm{km}^3$ to really begin the cosmic neutrino science and also how naïve were some prognostications. Note that we were playing with ideas not only for the large optical detectors later realized underground and under water and ice (though we did not seriously consider ice then as we knew nothing of its optical transmissivity). There were serious considerations of acoustic and radio detection, both later studied but with acoustic sensing still not realized while radio detection both in ice (ARA) and from the air (ANITA) are now doing well. The spirit of those meetings remains most with me… our enthusiasm for launching a new astronomy from the deep ocean pervaded all. We all knew well about the cold war but we were all brothers in our quest (there were no women amongst the physicists, as usual at that time). We all departed with a special bond as participants in a higher calling, one going beyond political impediments. It was a wonderful time.