Neutrino Forecast: Mostly Sunny, with a Good Chance of Supernovas

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A very personal view of the near-term prospects for non-terrestrial neutrino detection is presented in this somewhat unconventional, conference-concluding talk. The bottom line: thanks to new technologies currently under development, a steady supply of supernova neutrinos should soon be available for study in the not-too-distant future.

1 Okay, Let's Get the Ground Rules Straight

This article is a record of what was presented as the concluding talk of the HAνSE 2011 supernova neutrino workshop, which was held at DESY in Hamburg, Germany, in July of that year. The final talk was not meant, intended, or expected to be a summary of what had been shown at the meeting up to that point, but rather was designated by the organizers to be a hopefully entertaining, definitely upbeat expression of my personal views on the prospects for supernova neutrino detection, circa mid-2011.

Therefore, in what follows I speak only for myself. For the purposes of that talk and this article I am not "Prof. Mark Vagins for the *XYZ* Collaboration"; rather, consider this to be merely the sound of a lone experimentalist's voice in the wilderness.

Fair warning: this article contains cartoons, sarcasm, and a dash of salty language. Proceed into these Proceedings at your own risk.

2 A Snide Aside

Now that we have the ground rules established, I would like to thank the organizers of this conference, not just for inviting me to give a sunny concluding talk, but also for setting a good example in the appropriate use of our beloved "ν".

Sure, the Greek letter *nu* rather looks like the English letter "v". However, as illustrated in Figure 1, it is most certainly pronounced with an "n" sound. You know, like that sound at the beginning of the word *neutrino*. And indeed, HAνSE is properly pronounced (and sometime written) as

Figure 1: "This just in: v and ν are not, as previously believed, interchangeable!"

"HANSE", a quite resonant word in Northern German history.

Why bother to point this out? Well, recently there has been an unfortunate tendency in our field to ignore the fact that "ν" is a proper Greek letter carrying a specific pronunciation. Instead, it is being used as if it's some clever, insider way to insert a "v" into an acronym. That's right, NOνA and MINERνA, I'm talking to you! Or perhaps I should say NONA and MINERNA. There will be more about acronyms later.

3 Why So Serious?

So, what's not to love about supernova neutrinos? They carry unique information about one of the most dramatic processes in the stellar life-cycle, a process responsible for the production and dispersal of all the heavy elements (i.e., just about everything above helium) in the universe, and therefore a process absolutely essential not only to the look and feel of the universe as we know it, but also to life itself.

As a gauge of the community's level of interest in these particular particles, it is worth noting that, based upon the world sample of twenty or so neutrinos detected from SN1987A (by Kamiokande, IMB, and BAKSAN), there has on average been a paper published once every ten days... for the last twenty-four years! After a quarter of a century, this handful of events remain the only recorded neutrinos known to have originated from a more distant source than our own Sun (by an easily-remembered factor of 10^{10}).

My talk was given on July 23$^{\mathrm{rd}}$, 2011. In other words, this decidedly optimistic presentation about seeing supernova neutrinos took place exactly 406 years and 287 days since a supernova was last conclusively observed in our own galaxy. That was SN1604, often known as "Kepler's supernova". Of course, no neutrino observatories were online that mid-October day in 1604, but it was probably a type Ia explosion, anyway.

Not surprisingly, the next nearby core collapse supernova is eagerly awaited by experimentalists, observers, and theorists alike. Unfortunately, over the last 1800 years there have been just six such explosions seen in our galaxy. So the really big question, of course, is: *when will the next one happen?* The most serious problem is that none of us has an unlimited time in which to wait, as I have quite helpfully (and graphically) depicted in Figure 2.

Figure 2: Regarding supernova neutrinos, the waiting is the hardest part... primarily because of, well, *death.* No one wants to be that guy on the right. The other guy's probably not having such a great time, either.

Yes, it has certainly been a long, cold winter for supernova neutrino watching. But I am here to tell you, to *testify,* my weakly-interacting brothers and sisters, that there is hope!

4 The Good News

Now, anyone who knows me knows that I am usually a pretty happy, optimistic guy, especially when there is cake in the vicinity (see Figure 3). Would I lie to you about cake? Never!

But it is not only cake about which I am optimistic. I also feel quite certain that we will soon have some more supernova neutrinos to study. As a matter of fact, I expect a never-ending stream of them.

How can this be? There have been just six core collapse supernovas, i.e., the type which produce neutrinos, seen in our galaxy in 1800 years, right?

Well, first of all, one should not underestimate the power of six events. As luck would have it, there were exactly six events in my Ph.D. thesis experiment on the double Dalitz decay of the long-lived neutral kaon [1]. There were also just six fiducial events in the already famous nonzero-θ_{13} paper from the T2K experiment [2].

It should be remembered that those six supernova events were just the ones which could be seen with the naked eye for which records were made and, critically, whose records *survived* to the present day. Undoubtedly there were many, many more explosions during this time period, all of which would have been quite easily observed by a functioning neutrino telescope, had one but been available during, say, the Dark Ages.

Figure 3: A happy guy with cake at IPMU's 1^{st} anniversary party.

Indeed, it is believed that the core collapse supernova rate in the Milky Way galaxy is somewhere between one and three per century. Still not great, cheating death-wise, but considerably better than one per three hundred years, which would pretty much come up as a win in Death's column most of the time.

But you know what? Screw all this waiting around stuff! I have a better idea...

5 Having Your Cake and Eating It, Too

Supernovas in our galaxy may be relatively rare on a human timescale, but supernovas themselves are not rare at all. On average, somewhere in the universe *there is a supernova explosion once every second.* What's more, all of the neutrinos which have ever been emitted by every supernova since the onset of stellar formation suffuse the universe. These comprise the so-called "diffuse supernova neutrino background" [DSNB], also known as the "relic supernova neutrinos." They have not yet been seen, but if they proved to be observable they could provide a steady stream of information about not only stellar collapse and nucleosynthesis but also on the evolving size, speed, and nature of the universe itself.

And yet, in terms of the non-terrestrial neutrino forecast, there is no doubt that "sunny" is the key word. The flux of solar ^{8}B neutrinos is some 10^6 times the subtle DSNB flux.

In 2003, Super–Kamiokande [Super–K, SK] published the results of a search for these supernova relic neutrinos [3]. However, this study was strongly background limited, especially by the many low energy events below 19 MeV which swamped any possible DSNB signal in that most likely energy range, as well as by Michel electrons from sub-Cherenkov threshold muons produced by atmospheric neutrino interactions in the detector. Consequently, this previous SK study could see no statistically significant excess of events and therefore was only able to set the world's most stringent upper limits on the relic flux.

In the time between my talk at DESY and this article's writing, a new Super–K relic paper has come out sporting a new, improved analysis and much more data [4]. However, even with improved cut efficiencies and a lower threshold of 16 MeV the backgrounds still dominate, and the resulting relic flux limits are depressingly quite similar to those from eight years ago. Oy.

But didn't I say there would be cake at this party? All right then, one cake, coming up!

6 Doing Something About the (Neutrino) Weather

In order to finally see the elusive DSNB signal, theorist John Beacom and I are proposing to introduce a water-soluble gadolinium [Gd] compound, gadolinium chloride, $GdCl_3$, or the less reactive though also less soluble gadolinium sulfate, $Gd_2(SO_4)_3$, into the Super–Kamiokande detector (shown in Figure 4). As neutron capture on gadolinium produces an 8.0 MeV gamma cascade, the inverse beta decay reaction, $\overline{\nu}_e + p \rightarrow e^+ + n$, in such a Gd-enriched Super–K will yield coincident positron and neutron capture signals. This will allow a large reduction in backgrounds and greatly enhance the detector's response to both supernova neutrinos (galactic and relic) and reactor antineutrinos.

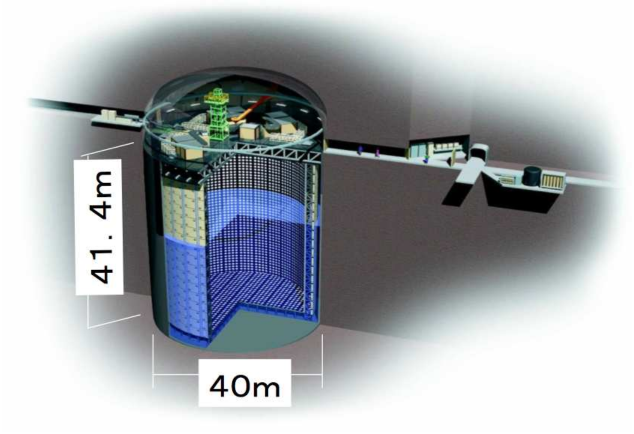


Figure 4: The Super–Kamiokande detector, located one kilometer underground in Mozumi, Japan. At 50,000 tons of water, it's large: the Statue of Liberty would fit inside.

The gadolinium must compete with the hydrogen in the water for the neutrons, as neutron capture on hydrogen yields a 2.2 MeV gamma, which is essentially invisible in Super–K. So, by using 100 tons of gadolinium compound we would have 0.1% Gd by mass in the SK tank, and just over 90% of the inverse beta neutrons would be visibly caught by the gadolinium. Figure 5 is an artist's (okay, *my*) conception of how the gadolinium will be delivered.

Due to a collapse in the price of gadolinium as a result of large-scale production facilities operating in Inner Mongolia, adding this much gadolinium to Super–K should cost no more than $600,000 today, though it

Figure 5: "I got 1999 more of these here 50 kilo fellers out in the truck. Yup, it's a pretty big truck."

would have cost a staggering $400,000,000 back when SK was first designed. This is primarily due to the fact that the rare earth elements are found blended together in nature, and when refining one of them the others are inevitably produced, with or without an accompanying commercial market demand (see Figure 6).

Figure 6: Where rare earths are concerned, if you've refined one, you've refined 'em all.

Figure 7: Mark Vagins and John Beacom working on GADZOOKS!. In case you're wondering, this drawing shows us as we appeared back in 2003. Sigh.

We call this new project "GADZOOKS!". In addition to being an expression of surprise as well as an archaic swear word dating back to 1694 (but as such *still* nearly a century more recent than the last galactic supernova), it's also a sweet acronym: Gadolinium Antineutrino Detector Zealously Outperforming Old Kamiokande, Super!

People tend to either love this name or hate it, but no one forgets it, which is important when promoting a new idea. The basics of this load-SK-with-Gd proposal are detailed in our *Physical Review Letters* article [5], the creation of which I've whimsically depicted in Figure 7. The relationship between gadolinium loading and the percentage of neutrons which the Gd will capture is plotted in Figure 8.

7 Supernova ν Signals? We Gotcha' Signals Right *Here!*

7.1 DSNB Signal: Betting On a Sure Thing

Adding $Gd_2(SO_4)_3$ to Super–Kamiokande will make it possible to look for coincident signals, i.e., for a positron's Cherenkov light followed shortly – within 50 microseconds – and in the same spot – easily within SK's best vertex fitter's position resolution – by the gamma cascade of a captured neutron. Once this happens, then troublesome spallation singles backgrounds could be eliminated and the analysis threshold lowered far below the old 19 MeV cutoff or even the present one at 16 MeV. This would be accomplished by simply applying most of the same techniques used in SK's usual solar neutrino analysis [6], the only major difference being that a search for pairs of correlated events would allow extraction of the inverse beta signal.

Note that without neutron tagging, after the normal cuts are applied only three neutrino-like singles events per cubic meter per *year* remain (see Figure 9), so requiring pairs of events to fall within 50 μs and 50 cm will essentially wipe out most non-inverse beta backgrounds.

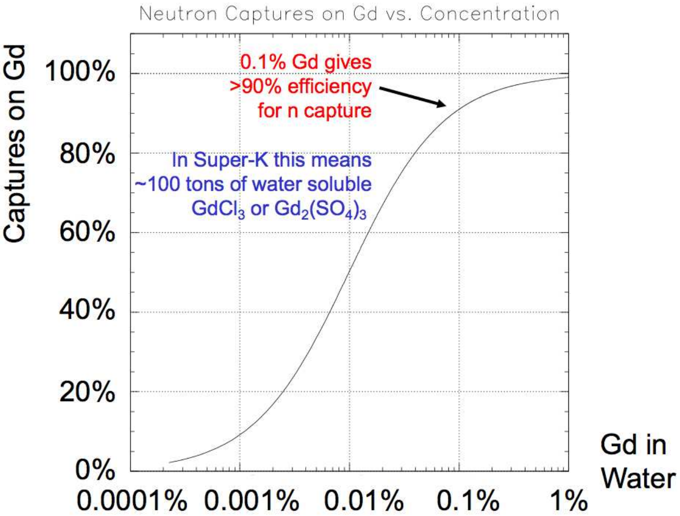


Figure 8: (color online) Neutron capture efficiency vs. gadolinium loading. The remaining neutrons get caught by the H in all that H_2O.

Figure 9: After the usual solar cuts, Super–K is left with only three neutrino-like events per cubic meter per year. That's all, folks!

Going lower in energy will not only allow a detection of the so-far unseen DSNB flux, but it will also allow the extraction of important – and unique, barring a galactic supernova – information regarding the neutrino emission parameters of supernovas. The sparse SN1987A data is in disagreement regarding the average luminosity and energy of the supernova $\overline{\nu}_e$'s.

DSNB models vary, and there is in fact some tension between the models (and their proponents), but according to a rather definitive modern review of the topic, Super–K with gadolinium should see about five of these supernova events every year [7]. This rate, if correct, would allow a rather prompt (within one year) discovery of the DSNB by SK [8] and hence lead to correspondingly rapid solutions to a number of long-standing questions, including the seemingly incompatible SN1987A neutrino data sets, the actual rate of optically dark explosions, the correct heavy metal production model, and the average supernova neutrino emission parameters. Furthermore, with fresh supernova neutrino data in hand for the first time in a generation, such an observation will undoubtedly stimulate new theoretical (and perhaps even experimental) developments in the neutrino and cosmology communities.

Figure 10 shows the expected spectrum of neutron-tagged positrons – signal and background – in a Gd-enriched Super–K. The width of the band labeled "DSNB" reflects the remaining allowed range of theoretical flux predictions for the relic signal. The scale of the expected reactor signal is uncertain at best right now, as what is shown assumes normal operations of all Japanese reactors, which is probably unlikely (to say the least) anytime soon. However, note that the lower bound on the DSNB window would be only marginally reduced by up to a 90% cut in reactor flux; even if all the Japanese reactors are turned off there will still be some operating on the Korean peninsula... yes, on both sides of the DMZ!

At any rate, we expect to see a (few?) thousand or so coincident reactor antineutrino events in a gadolinium-enriched Super–K each year, along with about five coincident supernova relic neutrinos events. Remaining coincident backgrounds from atmospheric neutrinos which contribute to the DSNB flux will be small, less than one a year, and their number decreases with falling energy while the flux of supernova neutrinos rises. The remaining spallation background will lie under the huge reactor flux and will therefore be negligible.

The net result? A steady stream of supernova neutrinos without the annoying wait!

7.2 Galactic Supernova Signal: Hey, It's Gotta Happen Eventually

If we are fortunate enough to observe a nearby supernova in the coming decades, it would be most beneficial to have $Gd_2(SO_4)_3$ in the water of the large water Cherenkov detectors which are online when the resulting neutrino wave sweeps across the planet. This is primarily because their most copious supernova neutrino signal by far (~88%) comes from inverse beta events. These are only produced by one of the six species of neutrinos and antineutrinos which are generated by a stellar collapse, and so if we could be tag them individually by their follow-on neutron captures then we could extract the $\overline{\nu}_e$ time structure of the burst precisely, gaining valuable insight into the dynamics of the burst. What's more, we could then subtract them away from the more subtle non-$\overline{\nu}_e$ signals, uncovering additional information that would otherwise be lost from this once-in-a-lifetime (we should be so lucky) happening.

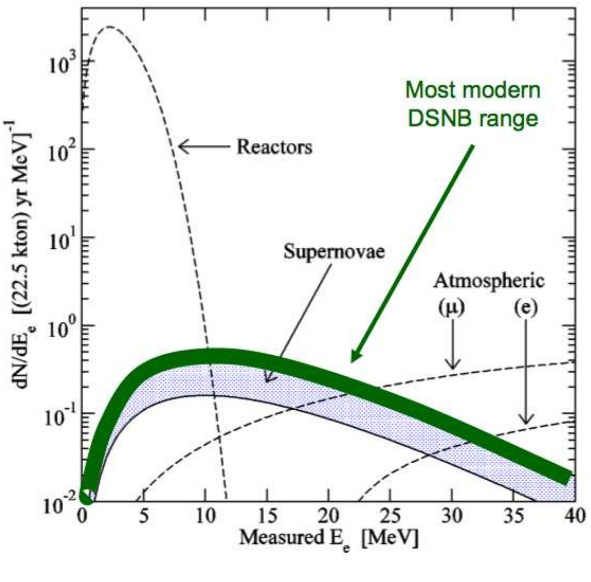


Figure 10: (color online) Expected positron spectrum tagged by neutron captures in a Gd-enriched Super–Kamiokande. One year of data is shown, with SK's energy resolution and all known backgrounds taken into account. Note the clear window for observing the relic supernova neutrinos between the reactor and atmospheric neutrino events.

For example, being able to tag the $\overline{\nu}_e$ events would immediately double SK's pointing accuracy back to the progenitor star. This is merely the result of statistics, since the elastic scatter events (about 3% of the total) would no longer be sitting on a large background in angular phase space [9]. Super–Kamiokande is the only running detector with useful neutrino pointing capability; reducing the error on this quantity by a factor of two would reduce the amount of sky to be searched by a factor of four. This could prove quite important for the narrow-field astronomical instruments which would be attempting, assuming of course that Super–K can get the word out in time, to see the first light from the new supernova.

At the same time, this event-by-event subtraction would allow identification of the initial electron neutrino pulse from the neutronization of the infalling stellar matter, a key input in understanding supernova dynamics.

Oh, and here's a really neat trick: if

the exploding star was big and rather close (~two kiloparsecs or less) we would get an early warning of its impending collapse [10]. Approximately a week before exploding, the turn-on of silicon fusion in the core would raise the temperature of the star sufficiently that electron-positron annihilations within its volume would begin to produce $\overline{\nu}_e$ just above inverse beta threshold. The sub-Cherenkov positrons would be invisible, but in SK the captures of the resulting neutrons on gadolinium would result in a sudden, dramatic, and monotonically increasing singles rate. As early as six days before collapse there would be a five sigma excursion in SK's low energy singles rate in the case of Betelgeuse nearing the end of its lifetime. The continuing increase in singles rate would clearly indicate a coming explosion, ensuring that no one would intentionally turn off Super–K for calibration or maintenance and thereby miss the big event. Only Super–K with effective neutron tagging can receive this early warning; no other existing detector can do this.

In addition, a gadolinium-enriched Super–K would be sensitive to very late black hole formation following a supernova explosion anywhere within our galaxy, since the distinctive coincident inverse beta signals from the cooling phase could be distinguished from the usual singles backgrounds. An abrupt cutoff of these coincident signals occurring even many minutes or hours after the main burst would be the conclusive signature of a singularity being born. Direct observation of such an event – witnessing (and thereby measuring) the actual moment of a black hole's creation – would clearly be of great value, especially when eventually correlated with electromagnetic signals from X-ray or gamma-ray observatories, or gravitational wave signals.

8 Gadolinium R&D – Or, How I Became a Plumber

8.1 Selective Water Filtration in Sunny Southern California

Since maintaining the excellent light transmission of a water Cherenkov detector is a crucial requirement, the insertion of any chemical compound is a challenging task. Simply put, we want to shovel 100 tons of something into ultrapure water without screwing up its clarity. And there is another immediate challenge to making GADZOOKS! work in the real world:

In detectors such as Super–Kamiokande, the long mean free path of light (~100 meters) is maintained by constant recirculation of the water through a water purification system. The existing SK purification system would dutifully and rapidly eliminate any added gadolinium along with the contaminants that are currently removed to maintain optical clarity. Crap!

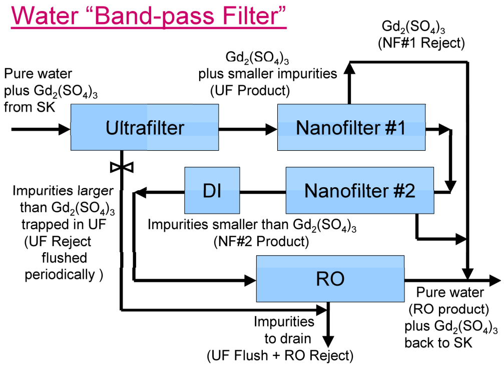
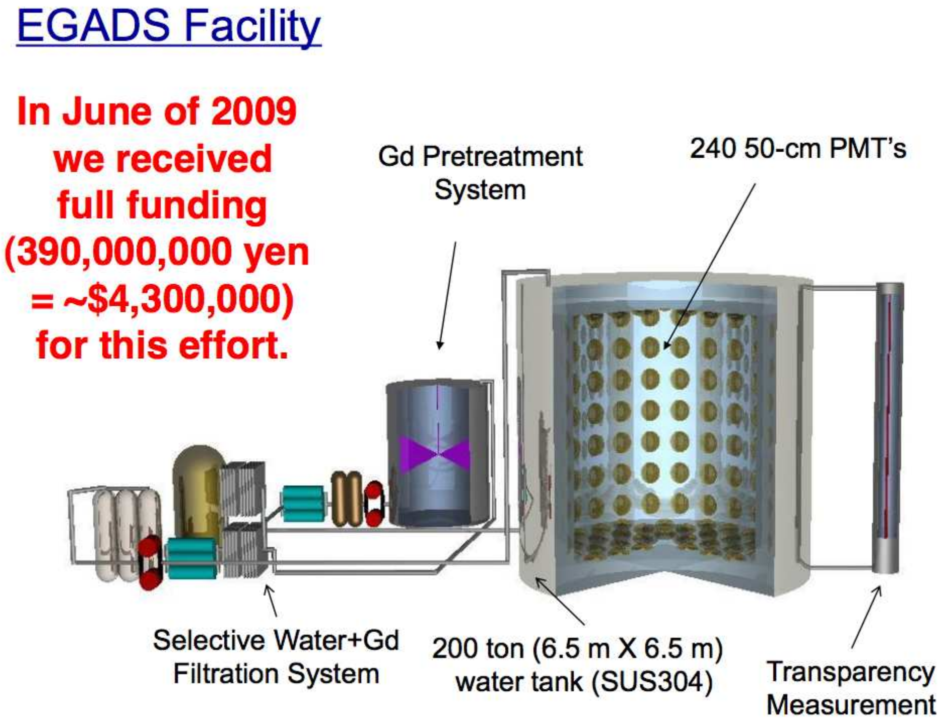


Figure 11: Selective water filtration conceptual design. Looks pretty simple, huh?

To solve this fundamental problem, I had to do something which had not been done before: invent a molecular "Band-pass Filter," a system capable of *selectively* filtering the water to retain the Gd while removing the impurities. To this end, a scaled-down version of the SK water filtration system was built under my direction at the University of California, Irvine [UCI], where I hold a joint appointment. The essential idea is as follows: there are a variety of commercially produced, membrane-based filters on the market. Rated by the size of pores in the membrane, they



EGADS Facility

In June of 2009
we received
full funding
(390,000,000 yen
= ~$4,300,000)
for this effort.

Figure 12: EGADS, the new large-scale gadolinium test facility in the Kamioka mine.

reject contaminants larger than these holes, while passing those which are smaller into the product water stream. By using a suitable sequence of filters, and by introducing nanofiltration, a new membrane intermediate in pore size between reverse osmosis (which rejects all gadolinium and everything larger) and ultrafiltration (which passes all gadolinium and everything smaller), I hypothesized – a fancy science word for "guessed" - that a fundamentally new type of filtration system could be assembled. It would selectively extract $Gd_2(SO_4)_3$ from the water stream and return it to the tank, while allowing all other impurities to be removed via the usual combination of reverse osmosis [RO] and deionization [DI]. This concept is shown schematically in Figure 11.

Amazingly, the damn thing worked. Chemical analysis on the prototype system at UCI showed that a particular two-stage nanofilter separated all Gd and SO_4 ions from the main water stream and allowed de-ionizing of that main water stream while maintaining the transparency of the water. Even after one thousand passes of the water through the system there was no detectable drop in gadolinium concentration – holy crap! Then it was time for the next step.

8.2 EGADS: In the Hall of the Mountain King

Although a small, sealed, gadolinium-loaded calibration device has already been deployed in Super–Kamiokande to verify the detector's predicted response to Gd neutron capture gammas [11], before Gd can be introduced into SK itself I must first demonstrate that the selective

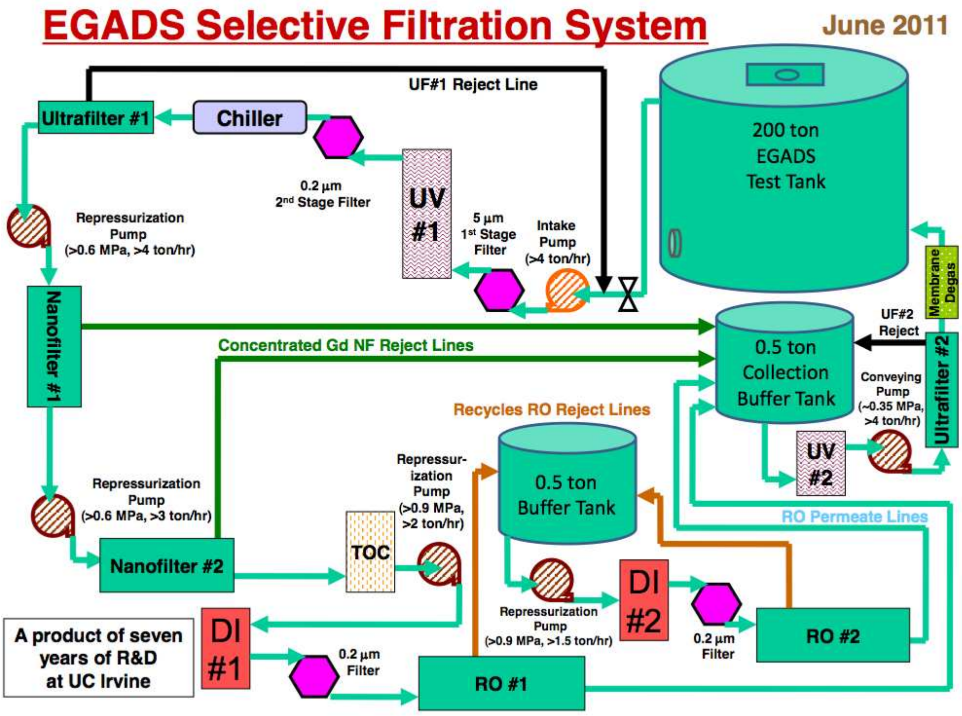


Figure 13: The selective filtration water system for EGADS. It will be capable of processing 100 tons of gadolinium-loaded water each day.

water recirculation technique works on a massive scale and that light transmission will only be marginally reduced by the presence of dissolved $Gd_2(SO_4)_3$. To this end, a new experimental chamber has been excavated in the Kamioka mine, located close to Super–Kamiokande. There, a dedicated, large-scale gadolinium test facility and water Cherenkov detector (essentially a ∼200 ton scale model of Super–K) is being built as depicted in Figure 12.

Known as EGADS (Evaluating Gadolinium's Action on Detector Systems), it will be used to make absolutely sure that the introduction of Gd will not interact with the detector materials and to certify the viability of the Gd-loading technique on a large scale, closely matched to the final Super–K requirements.

Funding for the new facility has been obtained in Japan to the tune of 390,000,000 yen (about $4,300,000 at the current exchange rate); construction began in September of 2009. Within nine months we had gone from solid rock to an excavated hall with a total volume of about 2.5 kilotons ready for physics occupancy, complete with a 200 ton stainless steel tank. Six months after that a significantly scaled-up version of my UCI selective water filtration system had been assembled and installed. It started running with pure water in January of 2011, and has been filtering dissolved gadolinium sulfate since August of that year.

The flow chart of the EGADS selective filtration system can be seen in Figure 13; it has certainly gotten a bit more complicated than the conceptual design shown in Figure 11, but this is what it takes to make things work in the real world. An additional requirement which the underground EGADS version of my system had to meet was that it do its job in a nearly lossless fashion – and indeed, note that there are no drain lines in Figure 13. Instead, all rejected water is cleaned and recycled. But guess what? This lossless design works, too!

A custom data acquisition system is currently being assembled and tested, and in the spring of 2012 a total of 240 calibrated 50-cm photomultiplier tubes, the same design as those being used in Super–K, will be installed in the tank.

Comparative studies both with and without dissolved gadolinium in the 200 ton tank will take place during 2012 and 2013. If all goes well, we should be ready to introduce gadolinium into Super–Kamiokande sometime within the next few years. The ultimate goal is to be able to make the world's first conclusive DSNB observation by 2016. Gadzooks, indeed!

9 My Fearless Extended Forecast

Figure 14: Got a kilo of Chinese white gadolinium powder concealed in your carry-on bags at the airport? Hey kids, don't try this; it might not end well.

As one who has spent, over the last eight years, many a long day and longer night covered with gadolinium dust (don't worry, it's [mostly] harmless), I can state with certainty that it has been a long, strange trip trying to get Gd into Super–Kamiokande. There have been exciting breakthroughs and discoveries along the way.

A series of important discoveries I made: a) it is an exceedingly bad idea to put any large quantity of gadolinium in your carry-on bags when traveling internationally, because b) Gd is opaque to X-rays, and c) airport personnel get very upset indeed (see Figure 14) when they find a kilogram of mysterious white powder from China in someone's luggage. Oh, and d) it will not improve your situation one bit to cry out to the security folks who are pointing automatic weapons at you and pawing your precious container of highly-refined gadolinium, "Don't open that! It's very pure!"

This incident took place, I kid you not, at John Wayne Airport (yes, named after the actor who usually played gun-toting cowboys) in Orange County, California. At any rate, I was eventually released from police custody, and progress on enriching Super–K with Gd could continue.

The Japanese-backed funding and rapid construction of EGADS, not to mention its very promising early results, indicates that the goal is finally within sight. If adding gadolinium to Super–K is a success, then I am convinced that – almost overnight – selective filtration will become part of the standard technology suite for all future water Cherenkov detectors, taking its place alongside such venerable components as phototubes and high voltage supplies.

Already, as I have been laboring away deep underground, the GADZOOKS! concept has gained significant traction around the world. Note that this is the only method of detecting neutrons which can be extended to the tens-of-kilotons scale and beyond, and at reasonable expense – adding no more than 2% to the capital cost of detector construction – as well. Given the additional physics reach neutron detection makes possible (for supernova studies as well as other, unrelated topics like proton decay), getting this capability for minimal extra cost is an enticing possibility.

This is probably why all of the major proposed next-generation water Cherenkov detectors either are officially retaining Gd-loading as an option (LBNE in the US [12]) or simply assume it as part of their baseline design (Hyper–Kamiokande in Japan [13] and MEMPHYS in Europe [14]). The recent Hyper-Kamiokande Letter of Intent [13] even went so far as to include the benefits of gadolinium in its Executive Summary.

Any one of these new detectors, once enriched with gadolinium, will be able to record on the order of *one hundred relic supernova neutrinos every year.* They will therefore accumulate statistics comparable to the total number of events seen from SN1987A by Kamiokande every single month they are in operation.

As if that's not enough to make one giddily optimistic, having one or more such giant, Gd-enhanced detectors awaiting the next galactic supernova is also a truly exciting prospect. In other words: delicious cake for everyone!

So, I think it is safe to predict that the extended outlook for supernova neutrinos is remarkably bright and sunny indeed.

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