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Research Area : Experimental Physics

Kavli IPMU's Neutrino Forecast: Mostly Sunny, with a Good Chance of Supernovas

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-five 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}).

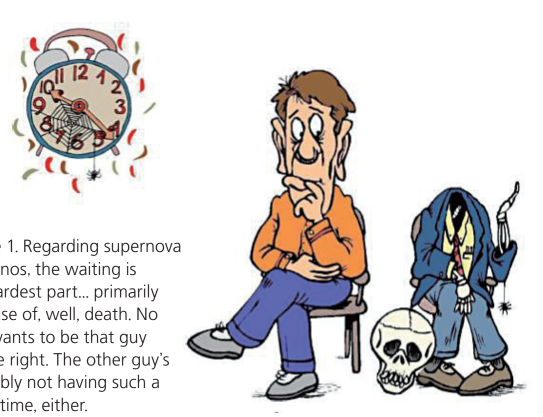

Figure 1. Regarding supernova neutrinos, the waiting is the hardest part... primarily because of, well, death. No one wants to be that guy on the right. The other guy's probably not having such a great time, either.

It has now been over 408 years 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. That type doesn't make very many neutrinos.

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 big question 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 1.

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!

The Good News

Now, anyone who knows me knows that I am usually a pretty happy, optimistic guy, especially when there is cake nearby (see Figure 2). 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 "non-zero 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.

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? Forget about all this waiting around stuff! I have a better idea...

Figure 2. A happy guy with cake at IPMU's 1st anniversary party. (Photo: Kai Martens)

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 that of 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; it 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 2012, a new Super–K relic paper came out sporting a new, improved analysis and much more data [4]. However, even with improved cut efficiencies and a lower threshold the backgrounds still dominated, and the resulting relic flux limits were 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!

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 3). As neutron capture on gadolinium produces an energetic gamma cascade, the inverse beta decay reaction, $\bar{\nu}_e + p \rightarrow e^+ + n$, 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.

The gadolinium must compete with the hydrogen in the water for the neutrons, as neutron capture on hydrogen yields a single low energy 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 4 is an artist's (okay, my) conception of how the gadolinium will be delivered. Due to a collapse in its price, adding this much gadolinium to Super–K should cost no more than $1,000,000 today, though it would have cost a staggering $400,000,000 back when SK was first designed.

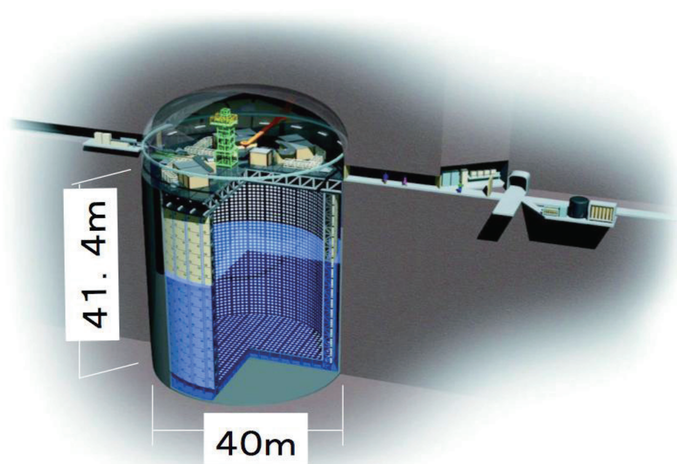

Figure 3. The Super–Kamiokande detector, located one kilometer underground in Mozumi, Japan. At 50,000 tons of water, it's large: the Statue of Liberty would fit inside.

Figure 4. "I got 1999 more of these here 50 kilo fellers out in the truck. Yup, it's a big truck."

Figure 5. 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 an acronym: Gadolinium Antineutrino Detector Zealously Outperforming Old Kamiokande, Super!. 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 5. Adding $Gd_2(SO_4)_3$ to Super–Kamiokande 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. Super–K with gadolinium should see about five of these supernova events every year. The net result? A steady stream of supernova neutrinos without the annoying wait!

Of course, 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. If we could be tag these events individually by their follow-on neutron captures then we could extract the time structure and neutrino flavor evolution of the burst precisely, gaining valuable insight into the dynamics of the explosion.

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

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. And there is another immediate challenge to making GADZOOKS! work: 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

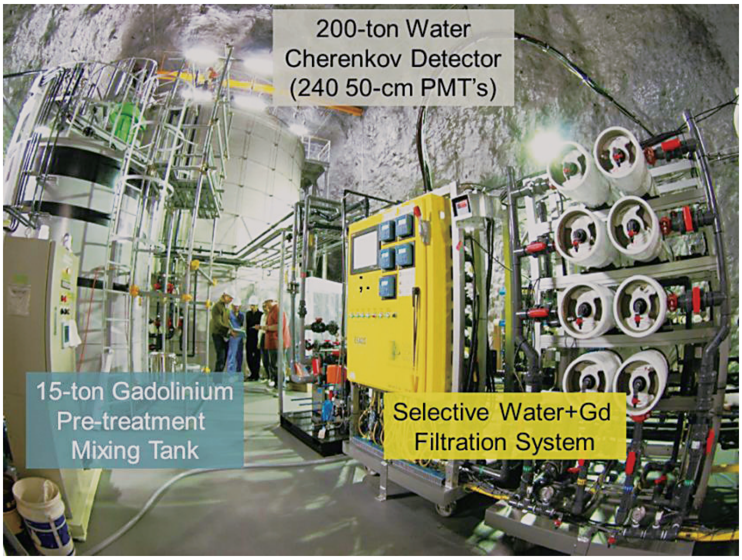

Figure 6. EGADS, the new large-scale gadolinium test facility in the Kamioka mine.

contaminants that are currently removed to maintain optical clarity. Crap!

To solve this crucial problem, in 2006 I hypothesized – a fancy science word for "guessed" – that a fundamentally new type of filtration system could be assembled. My "Molecular Band-pass Filter" would selectively extract $Gd_2(SO_4)_3$ from the water stream and return it to the tank, while simultaneously allowing all other impurities to be removed. In 2007 I put a prototype system together at the University of California, Irvine, where I continue to hold a joint appointment, and amazingly the damn thing worked! Then it was time for the next step.

In early 2008 I had the honor of becoming the first foreign professor to be hired by IPMU. My offer letter said, in essence, "Come make gadolinium loading work in Super-K!"

A new experimental chamber was 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) has been built as depicted in Figure 6. Known as EGADS (Evaluating Gadolinium's Action on Detector Systems), it is being 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 was 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. Now, with full gadolinium loading we are within 15% of the transparency of ultrapure water. This is probably already sufficient, but work continues to improve upon this result. Further comparative studies both with and without dissolved gadolinium in the 200 ton tank will take place during 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!

Finally, a few months ago I received a new Japanese Grant-In-Aid worth nearly $1,600,000. This will be used to convert the EGADS test facility into the world's most advanced supernova neutrino detector after the R&D phase is finished, and to tie it into a Japanese network of optical, X-ray, gamma-ray, infrared, and gravitational wave observatories.

My Fearless Extended Forecast

Already, 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 hundreds-of-kilotons scale and beyond, and at reasonable expense – adding no more than 3% 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 officially retained Gd-loading as an option (LBNE in the US [6]) or simply assumed it as part of their baseline design (Hyper–Kamiokande in Japan [7] and MEMPHYS in Europe [8]). Last year's Hyper-Kamiokande Letter of Intent [7] 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.

References:

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