GADZOOKS! How to Detect SN Neutrinos in SK... Next Year!

Mark Vagins

University of California, Irvine

ICRR - Kashiwa

June 29, 2005

A long time ago, in a (neighbor) galaxy far, far away…

A long time ago, in a (neighbor) galaxy far, far away…

Sanduleak -69^{o} 202 was gone, but not forgotten.

In fact, based on the handful of supernova neutrinos which were detected that day, approximately <u>one theory paper has been published every ten days</u>…

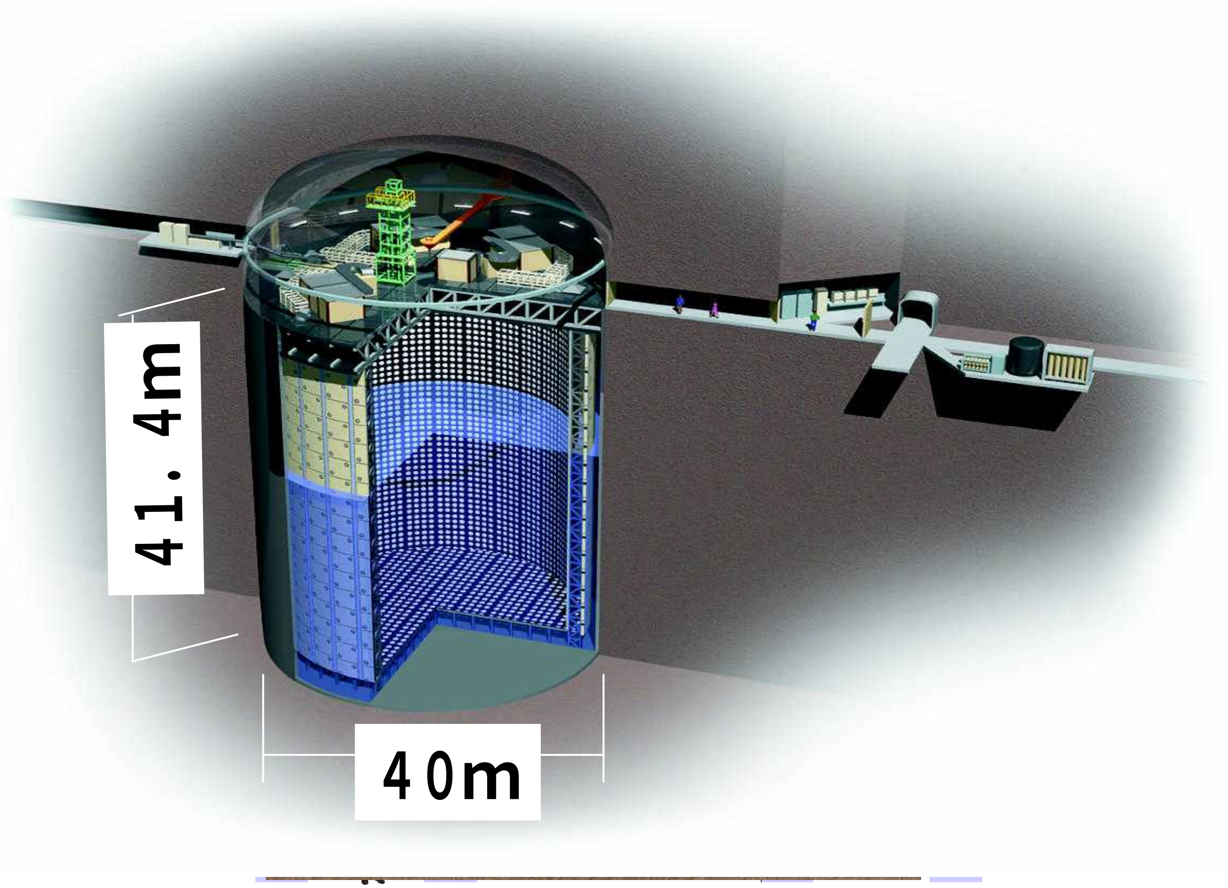
…for the last <u>eighteen years!</u>

Now, I shouldn't need to tell this crowd (at ICRR headquarters!) why neutrinos, particularly supernova neutrinos, are interesting.

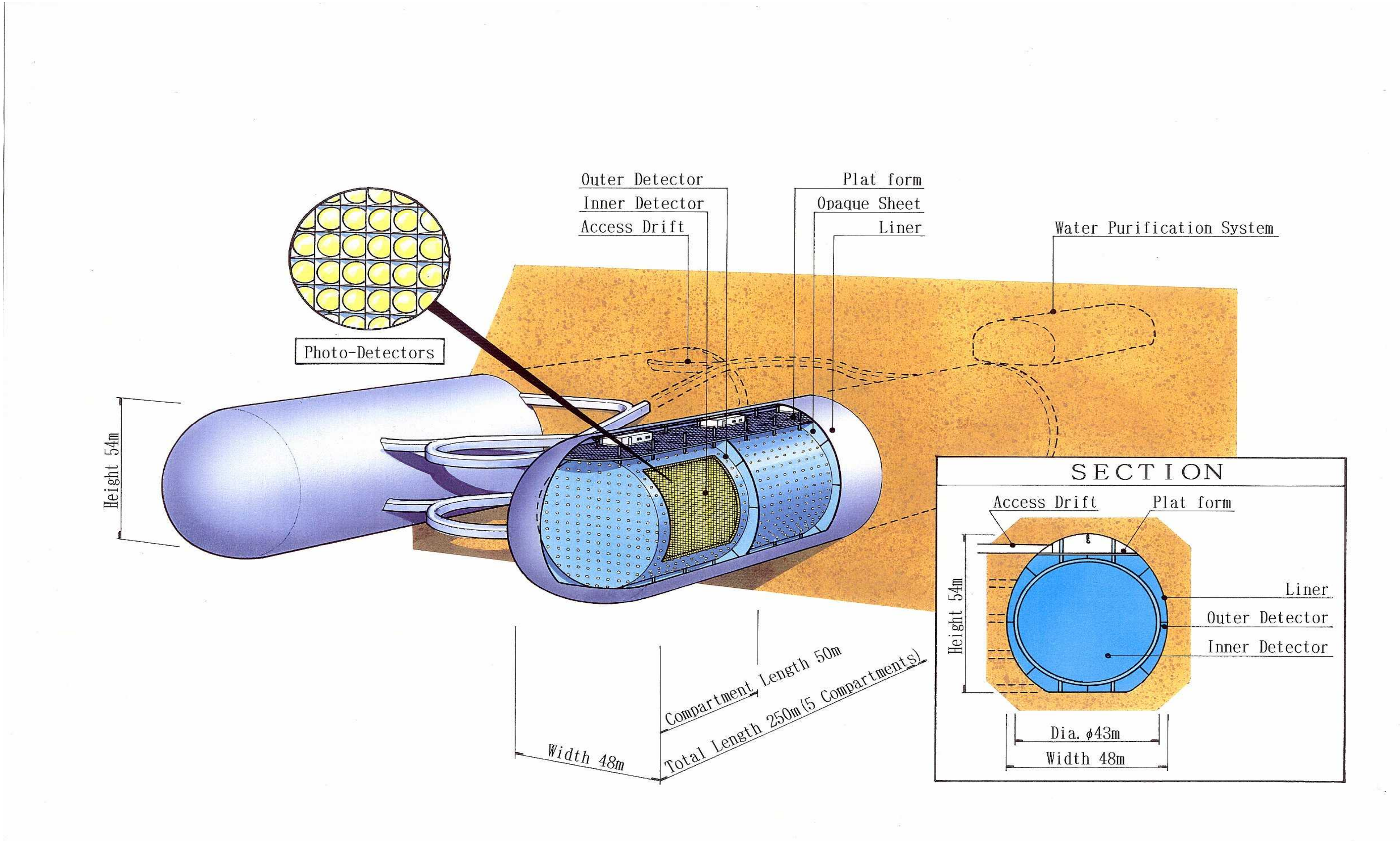
However, one little-noted fact is that at 170,000 light years, SN1987A remains the most distant source of neutrinos ever detected.

It's still the only recorded neutrino source more distant (by an easily-remembered factor of 10^{10}) than our own sun.

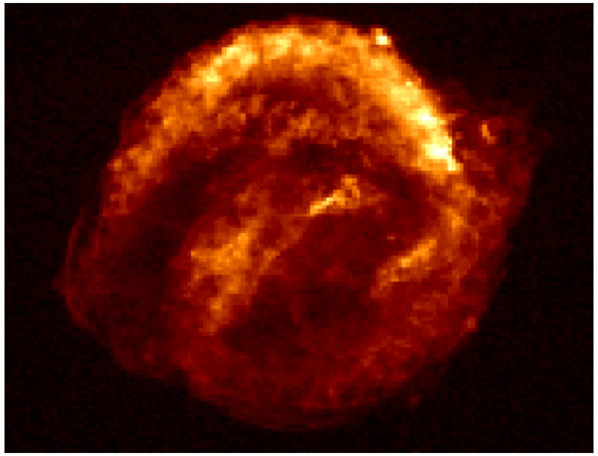
An array of impressive experiments stand ready to observe the neutrinos of the next galactic supernova.



More SN neutrino-capable detectors, some quite fantastic, are planned or being built.

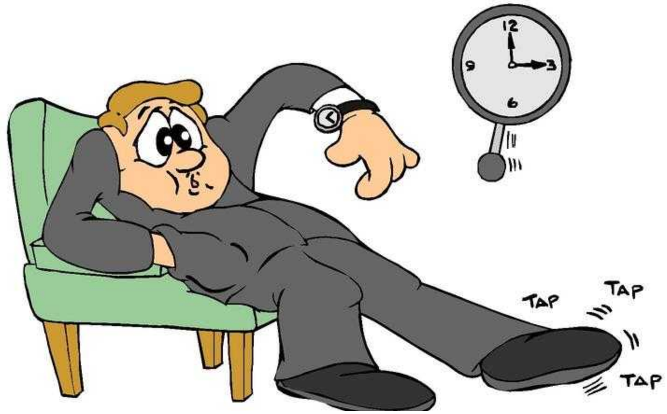


On the other hand, we've recently observed a big anniversary!



As of last October 9th, it has been exactly 400 years since a supernova was last definitely observed within our own galaxy.

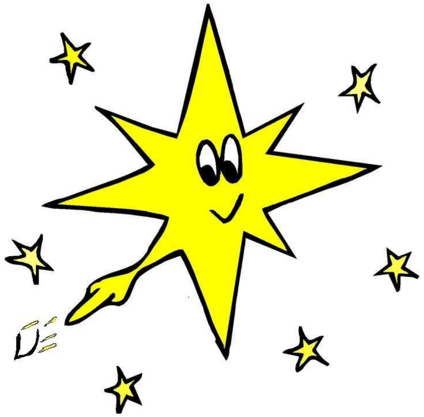
So, what’s a supernova neutrino-loving scientist to do?



Well, galactic supernovas may be somewhat rare on a human timescale, but supernovas are <u>not.</u>

On average, there is <u>one supernova explosion</u> somewhere in our universe <u>every second!</u>

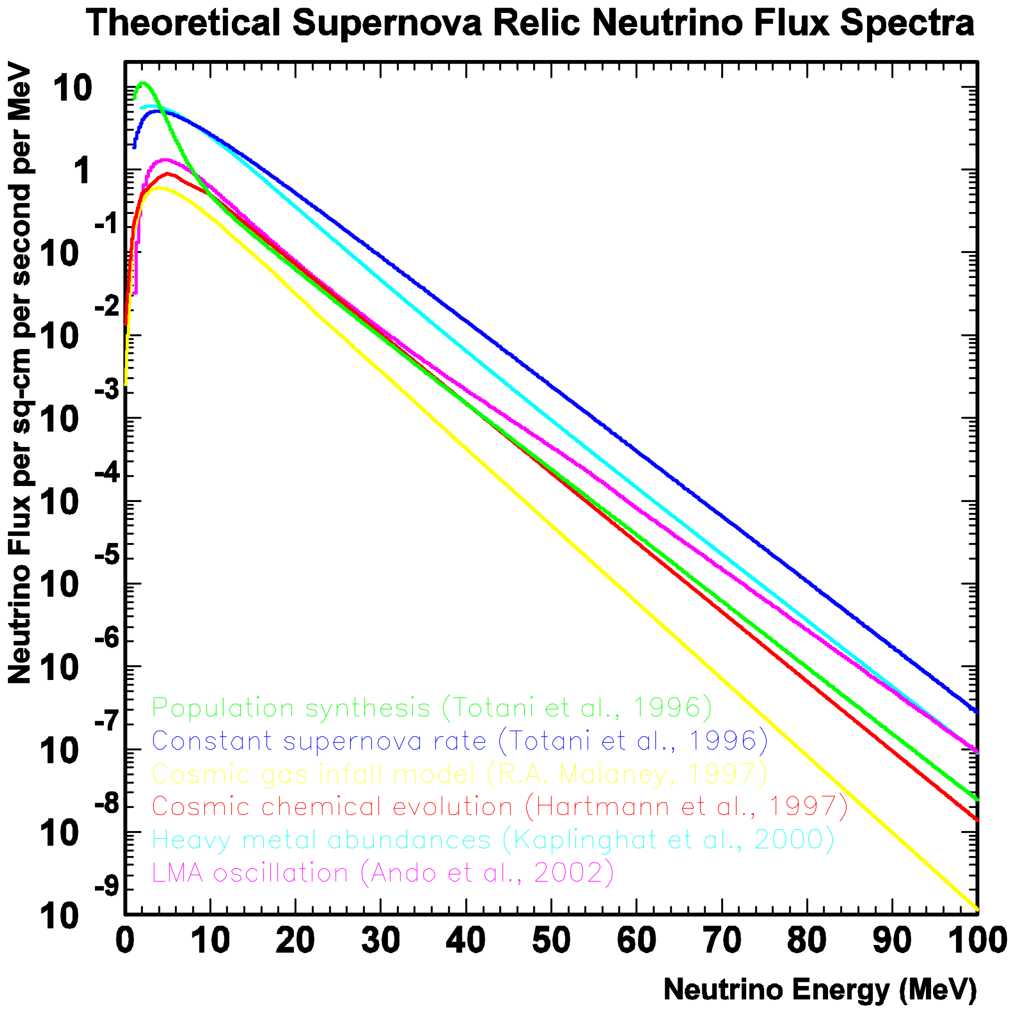
These constitute the diffuse supernova neutrino background [DSNB], also known as the “relic” supernova neutrinos.



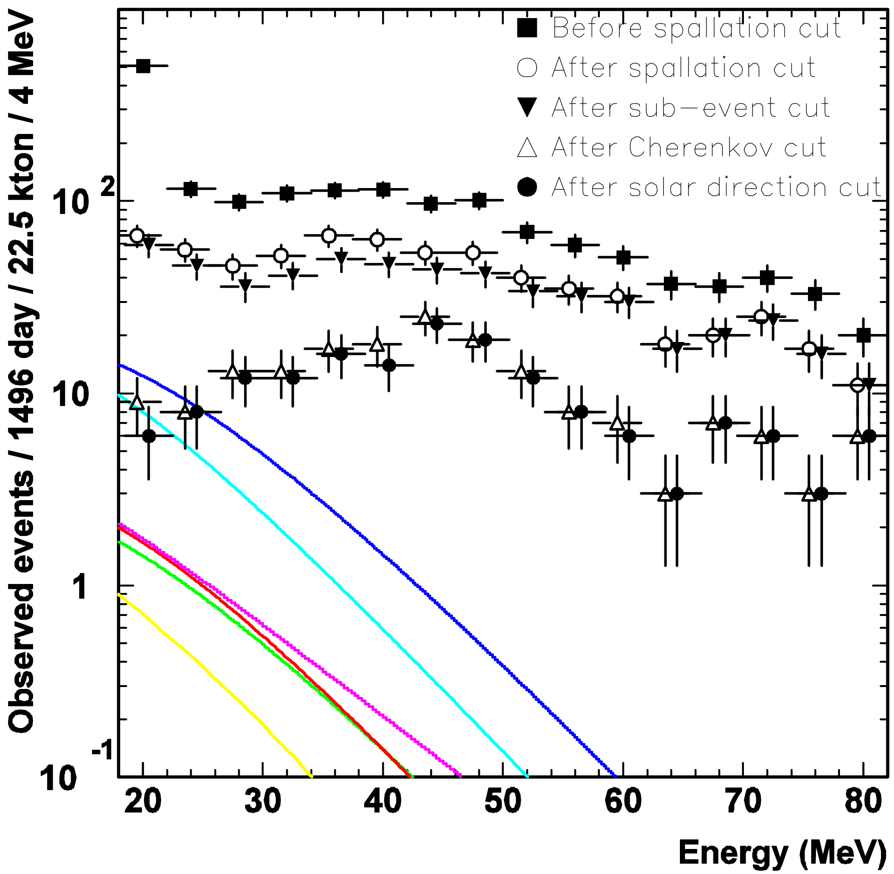
After traveling an average distance of

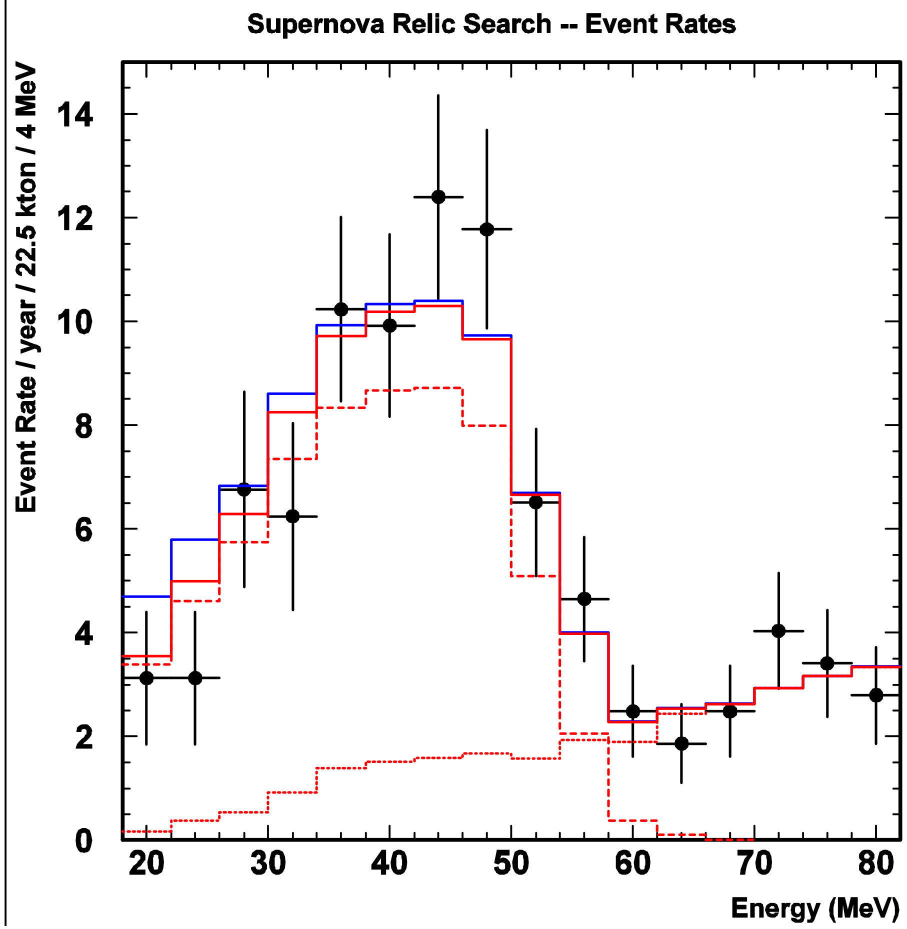
six billion light years, about 100,000 of these genuine supernova neutrinos pass through our bodies every second.

As of 2002, here's what the various predictions of this flux looked like:



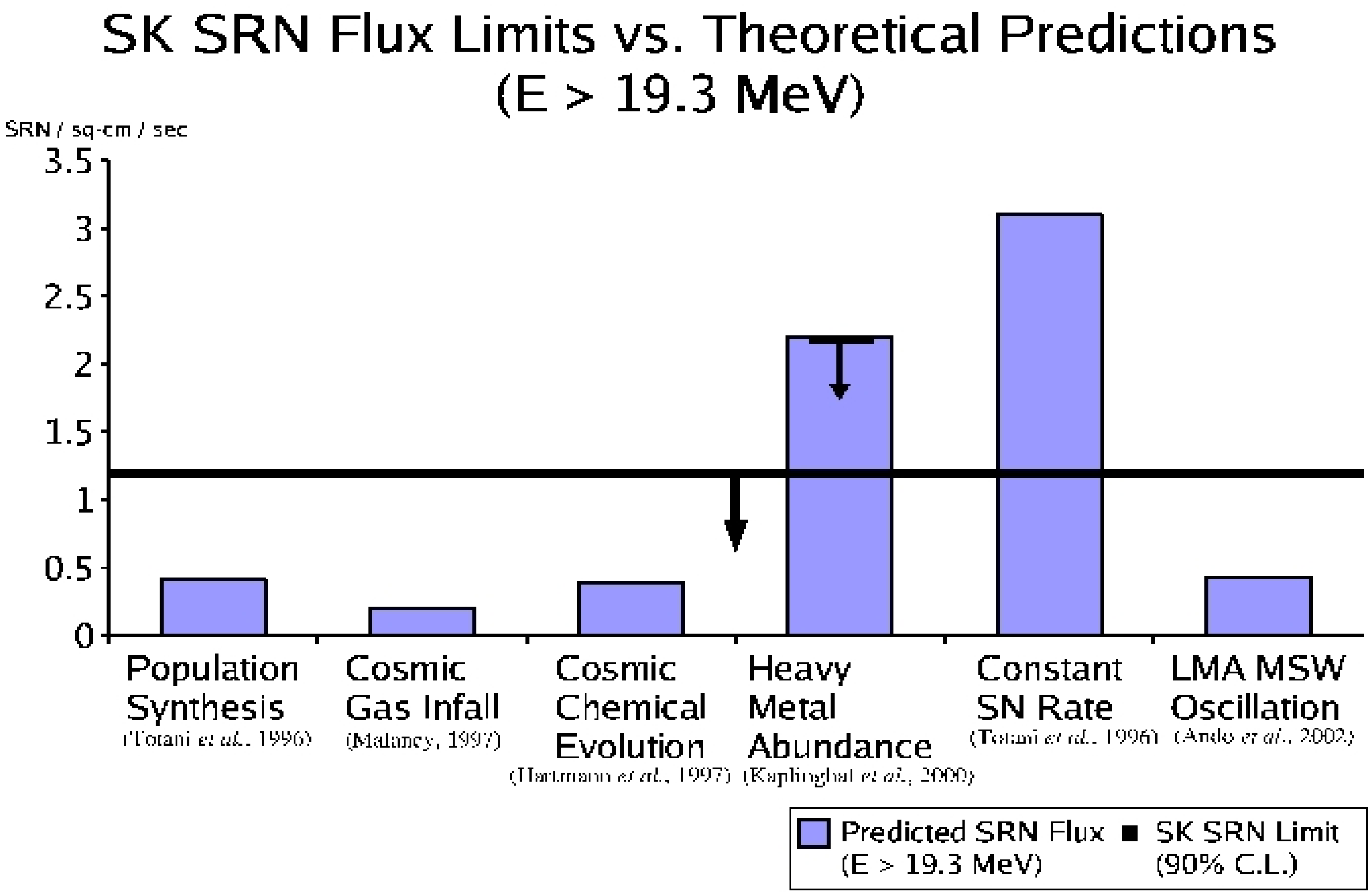
In 2003, Super-Kamiokande published the world's best limits on this so-far unseen flux [M.Malek et al., Phys. Rev. Lett. 90 061101 (2003)].





Unfortunately, the search was strongly limited by backgrounds, and no clear event excess was seen.

Here's how the SK result constrained the existing models:

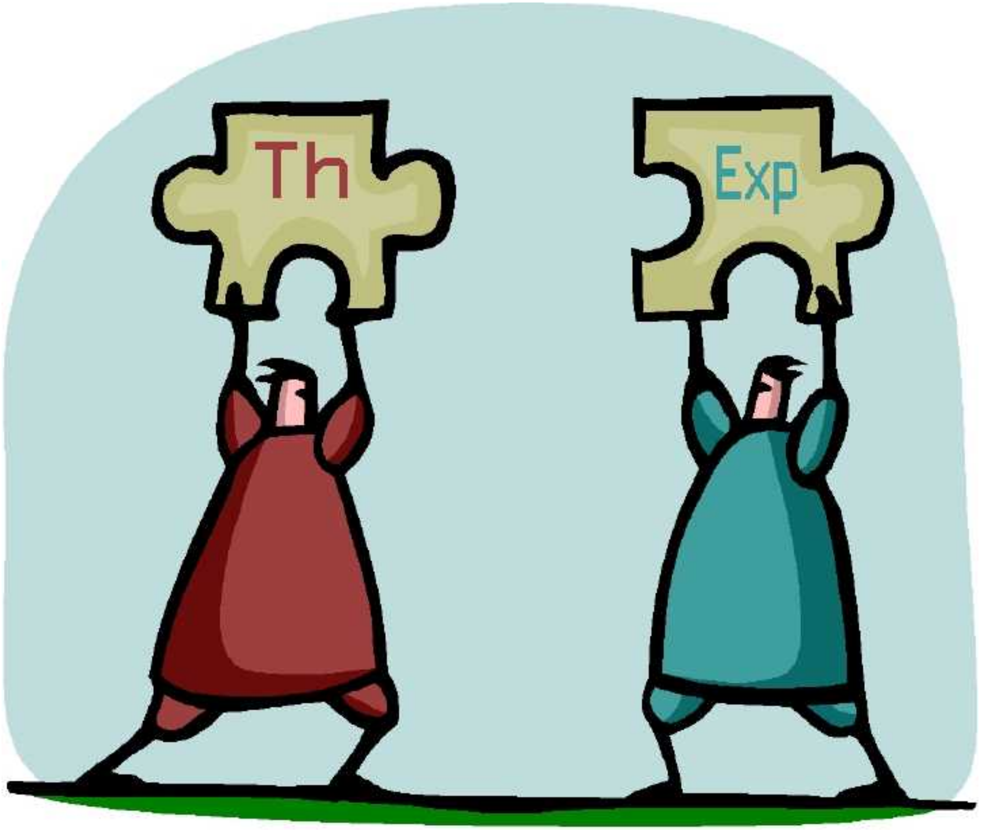


So, experimental DSNB limits are approaching theoretical predictions. Clearly, reducing the remaining backgrounds and going lower in energy would extremely valuable. But how?

Well, all of the events in the present SK analysis are <u>singles</u> in time and space.

And this rate is actually very low… just <u>three events per cubic meter per year.</u>

With this in mind, John Beacom and I undertook to tackle the DSNB problem once and for all, with the ambitious goal of detecting a clear, positive signal within the <u>next four years.</u>



This partnership of theory and experiment has proven quite productive.

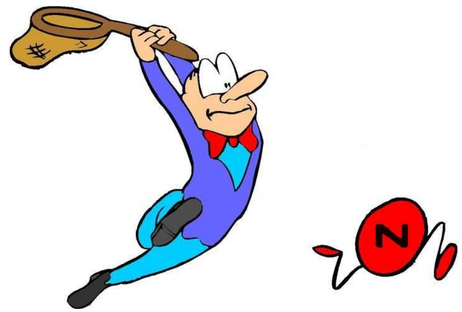
"Wouldn't it be great," we thought, "if there was a way to tag <u>every</u> DSNB event in Super-K?"

Well, the reaction we are looking for is

$$\bar{\nu}_e + p \longrightarrow e^+ + n$$

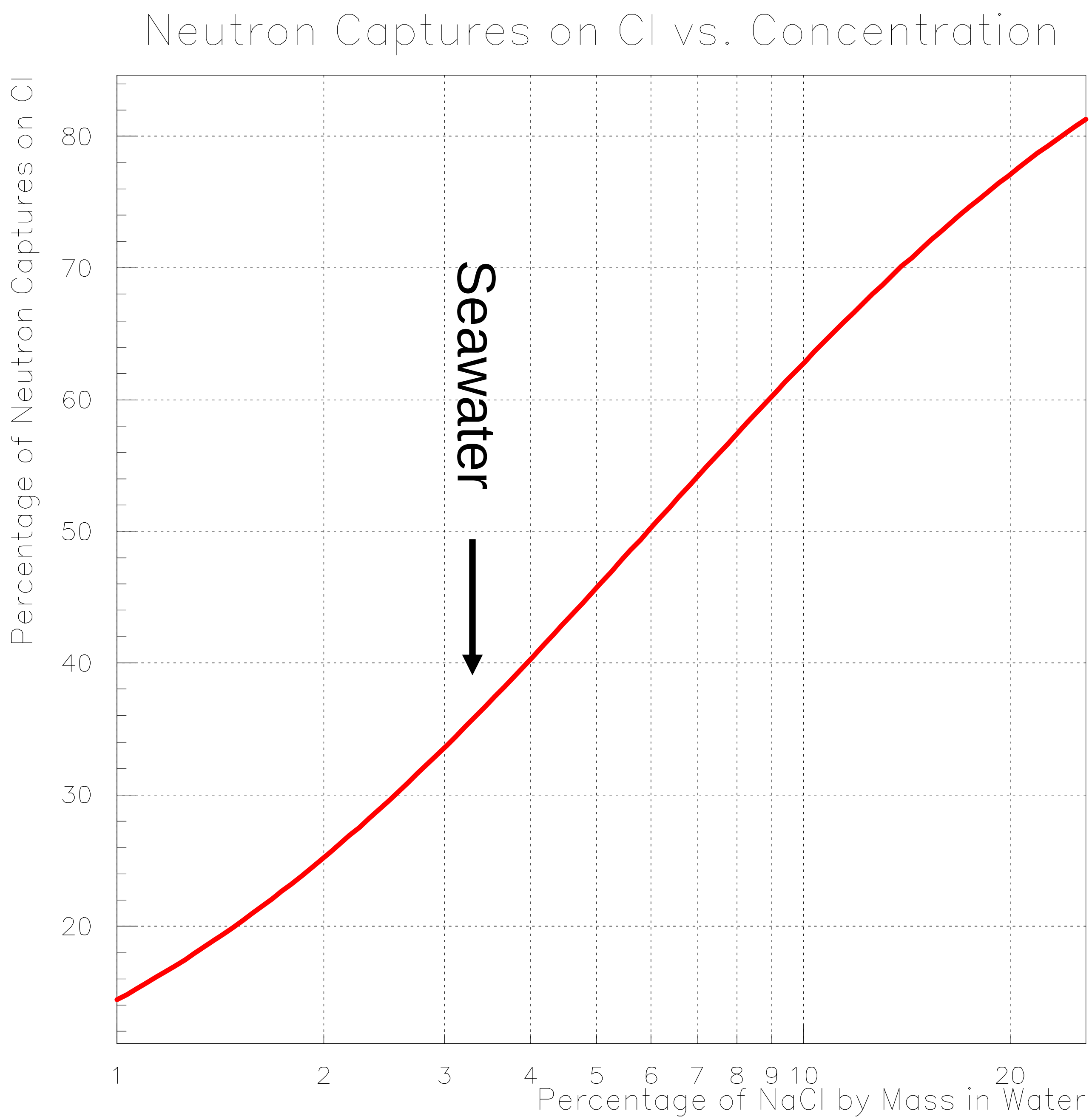
What if we could reliably identify the neutron and look for coincident signals?

But we’re going to have to compete with
hydrogen in capturing the neutrons!

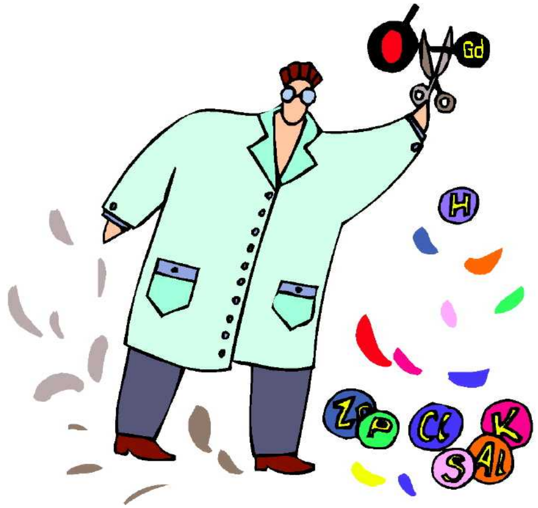


Also, plain old NaCl simply won’t work…

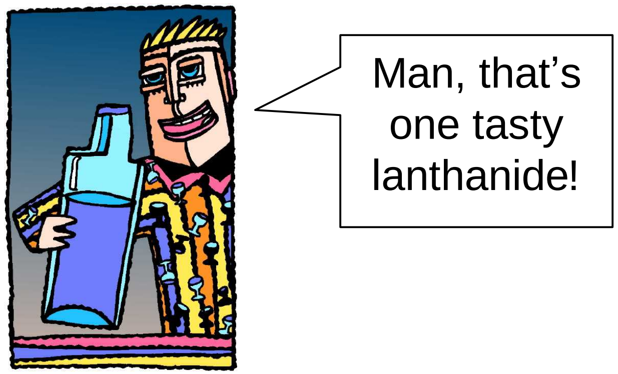
We’d need to add 3 kilotons of salt to SK just to get 50% of the neutrons to capture on the chlorine!

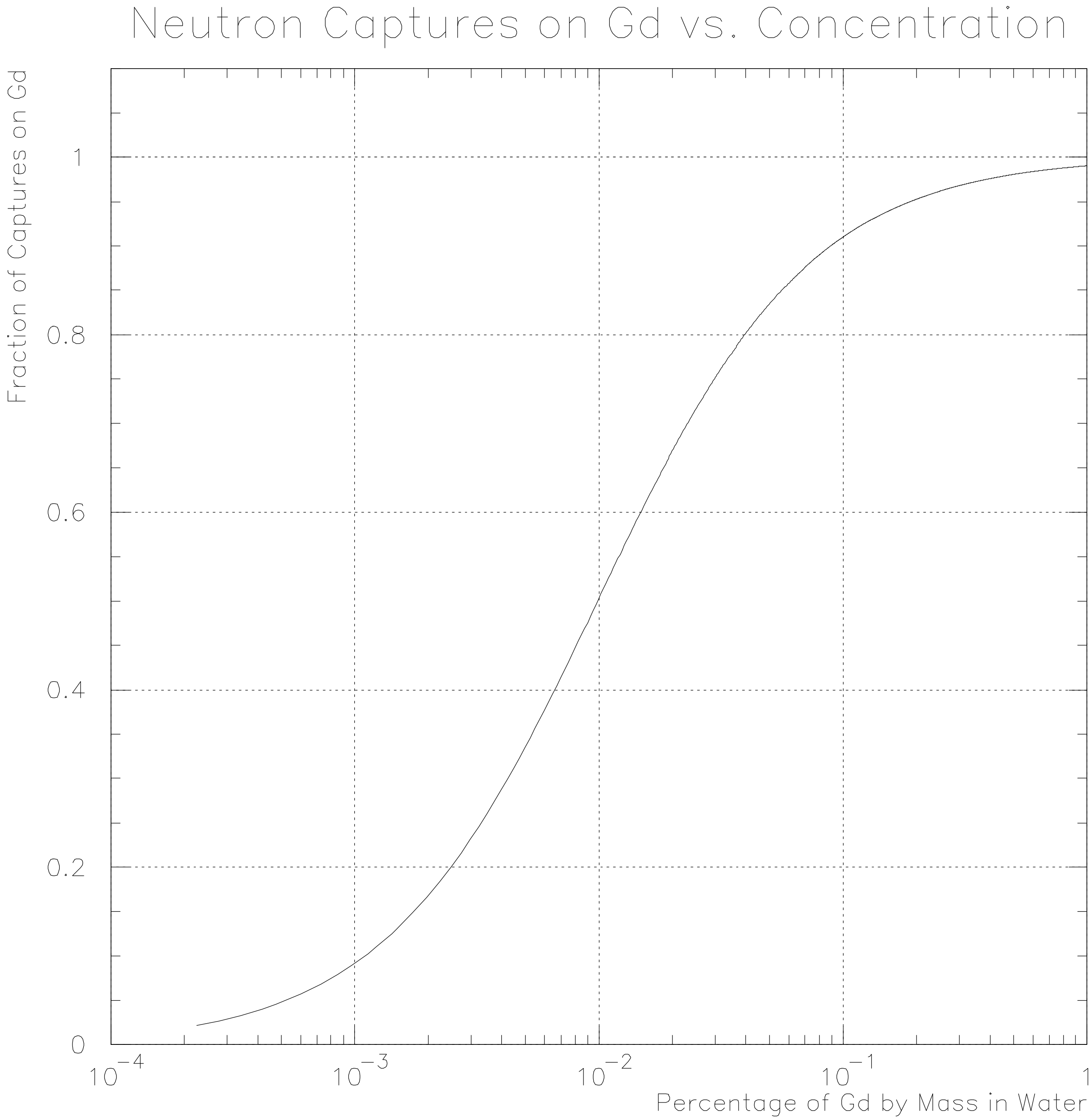

Neutron Captures on Cl vs. Concentration
Percentage of Neutron Captures on Cl
80
70
60
50
40
30
20
Seawater
1
2
3
4
5
6
7
8
9
10
20
Percentage of NaCl by Mass in Water

So, we eventually turned to the best neutron capture nucleus known – gadolinium.



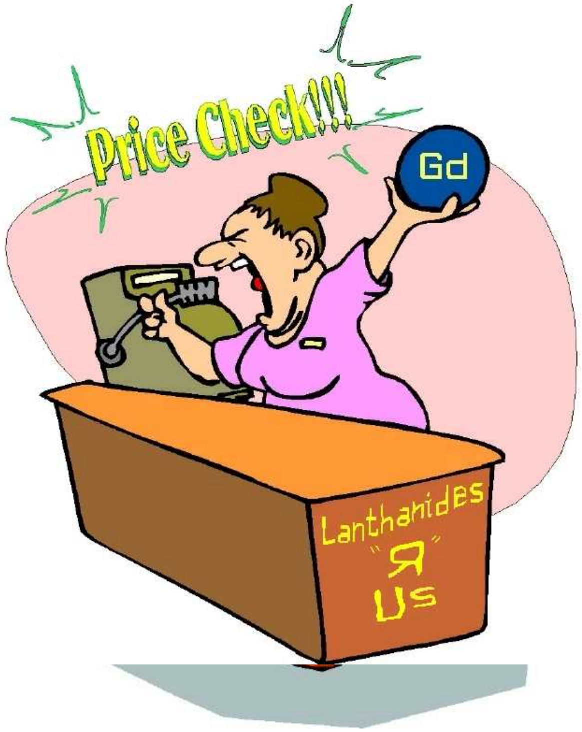
- $GdCl_3$, unlike metallic Gd, is highly water soluble
- Neutron capture on Gd emits a 8.0 MeV γ cascade
- 100 tons of $GdCl_3$ in SK (0.2% by mass) would yield >90% neutron captures on Gd
- Plus, it's not even toxic!





Neutron Captures on Gd vs. Concentration
Fraction of Captures on Gd
1
0.8
0.6
0.4
0.2
0
10^-4
10^-3
10^-2
10^-1
1
Percentage of Gd by Mass in Water

But, um, didn't you just say 100 tons?
What's <u>that</u> going to cost?



In 1984: $4000/kg –> $400,000,000

In 1993: $485/kg –> $48,500,000

In 1999: $115/kg –> $11,500,000

In 2005: $4/kg –> $400,000

So, perhaps Super-K can be turned into a great big antineutrino detector… it would then steadily collect a handful of DSNB events every year with greatly reduced backgrounds and threshold.

Also, imagine a next generation, megaton-scale water Cherenkov detector collecting 100+ per year!

This is the only neutron detection technique which is extensible to such scales, and at minimal expense, too: ~1% of the detector construction costs

If we can do relics, we can do a great job with a galactic supernova:

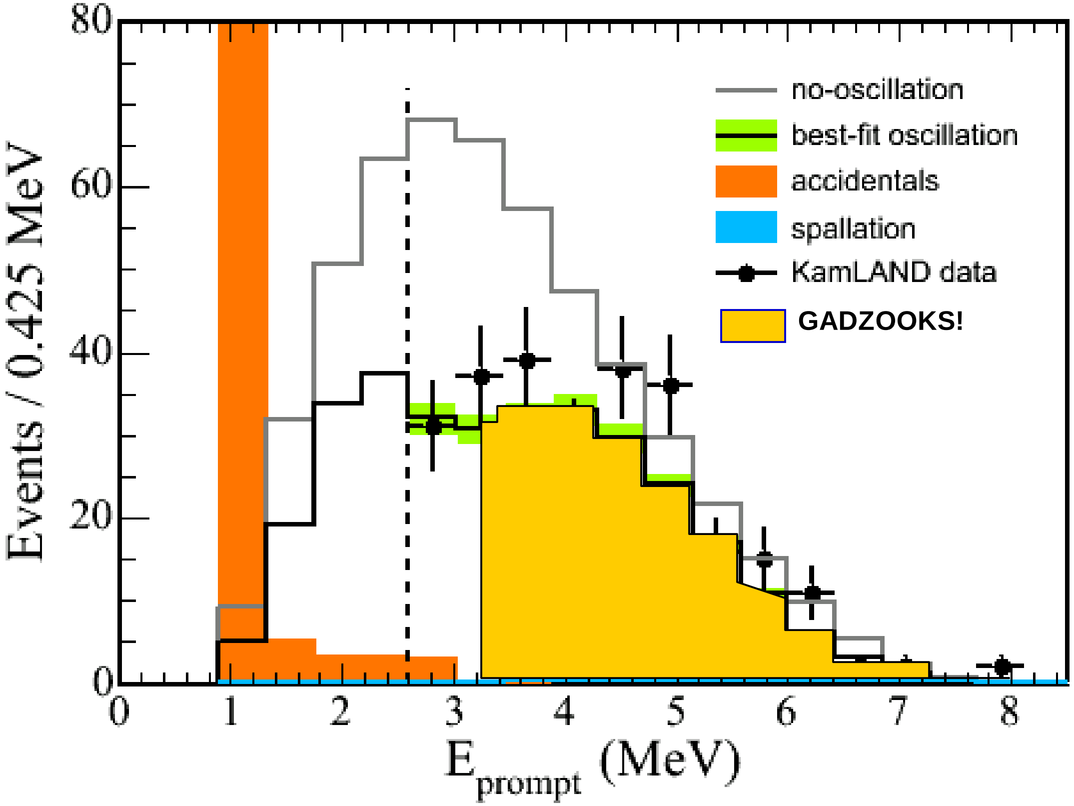
- The copious inverse betas get individually tagged and can be subtracted away from
- the directional elastic scatter events, doubling SK's SN pointing accuracy.
- The ^{16}O NC events no longer sit on a large background and are hence individually identifiable, as are
- the backwards-peaked ^{16}O CC events.

Here's our proposed name for this water Cherenkov upgrade:

Gadolinium
Antineutrino
Detector
Zealously
Outperforming
Old
Kamiokande,
Super!

Oh, and as long as we're collecting $\bar{\nu}_e$'s...

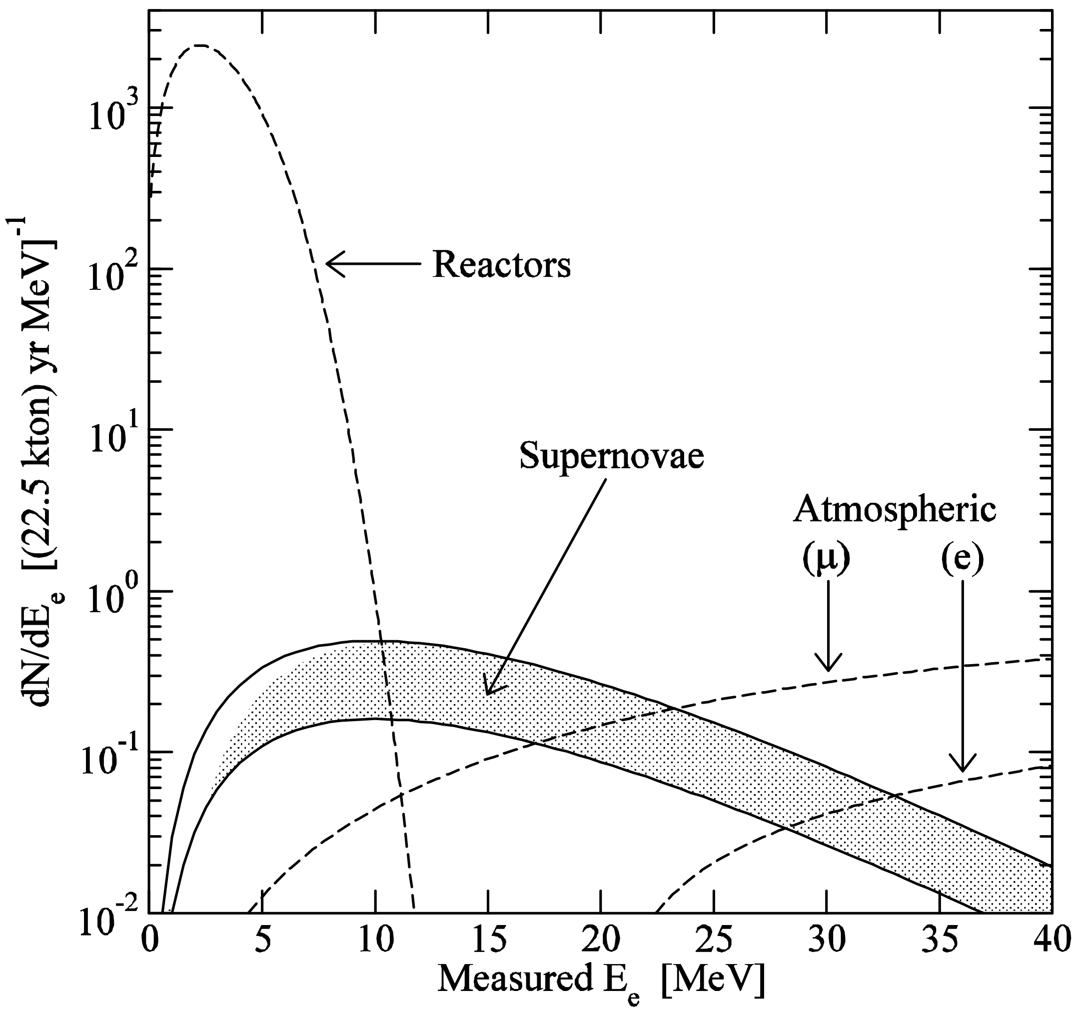
KamLAND's first 22 months of data



GADZOOKS! will collect this much reactor neutrino data in <u>two weeks.</u>

Hyper-K with $GdCl_3$ will collect <u>six KamLAND years of data in one day!</u>

Here's what the coincident signals in Super-K with $GdCl_3$ will look like (energy resolution is applied):



As I mentioned earlier, for the last three years John Beacom and I have been working on this issue with an eye towards enhancing the (soon to be) existing Super-Kamiokande-III detector.

We finally got our first GADZOOKS! (Gadolinium Antineutrino Detector Zealously Outperforming Old Kamiokande, Super!) paper written up as hep-ph/0309300 and sent it off to Physical Review Letters.

After a long wait due largely to one of the world's slowest referees,

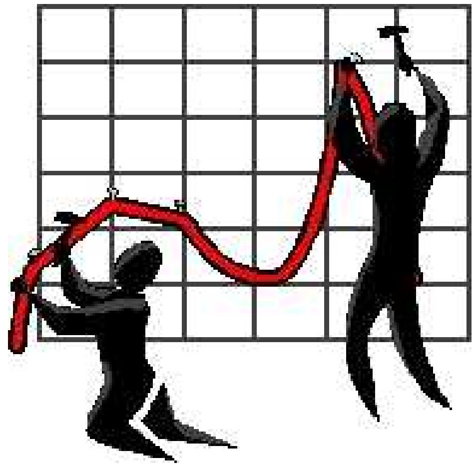
our paper was finally published in Physical Review Letters as

Phys. Rev. Lett., 93:171101, 2004

While waiting for PRL, we have been quite pleased by the many excellent phenomenological papers which have been in some way inspired by (and cite) our preprint.
Here’s a brief selection ordered by topic:

- Relic supernova neutrinos –
  - Strigari, Kaplinghat, Steigman, and Walker, JCAP 0403:007, 2004
  - S. Ando, Astrophys.J 607, 20-31, 2004
  - Fogli, Lisi, Mirizzi, and Montanino, hep-ph/0401227
- Galactic supernova neutrinos –
  - Tomas, Semikoz, Raffelt, Kachelriess, and Dighe, Phys.Rev. D68:093013, 2003
  - Odrzywodek, Misiaszek, and Kutschera, Astropart.Phys. 21:303-313, 2004
- Reactor antineutrinos -
  - Choubey and Petcov, hep-ph/0404103

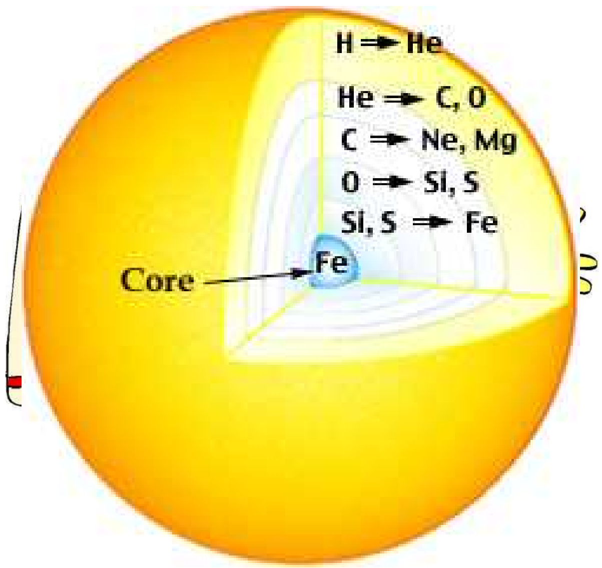
Relics, Now With More Flavor:



Inspired by GADZOOKS! and the current SK relic limit, Strigari et al. have updated their calculations using the latest Sloan Digital Sky Survey data and solar oscillation results…

They conclude that the present SK limit is just above their best fit prediction of the DSNB rate!

Odrzywodek et al. note that late-stage Si burning in very large, very close stars could provide a two day early warning of a core collapse supernova if neutron detection is possible.



In SK with $GdCl_3$ this would mean an increase in the low energy singles rate… a factor of 10 increase in the case of Betelgeuse.

[SK with Gd is the only detector which can do this]

Choubey and Petcov consider the reactor signal of GADZOOKS!

From hep-ph/0404103:

- “SK-Gd can rule out the ‘wrong’ [LMA] solution with about 0.4 to 0.5 years of data. This is in sharp contrast to what we have obtained for KamLAND, where it is hard to resolve the low-LMA – high-LMA ambiguity even with 2.6 kTy of data once the Shika-2 reactor is switched on.”
- “The upper limit on Δm^2_{21} is determined solely by the SK-Gd data.”
- “The lower limit on $\sin^2\theta_{12}$ is determined by the SK-Gd data.”
- “The results of our analysis show that the SK-Gd experiment has a remarkable potential in reducing the uncertainties in the values of Δm^2_{21} and $\sin^2\theta_{12}$.”
- “We find that the SK-Gd experiment could provide one of the most precise (if not the most precise) determinations of the solar neutrino oscillation parameters Δm^2_{21} and $\sin^2\theta_{12}$.”

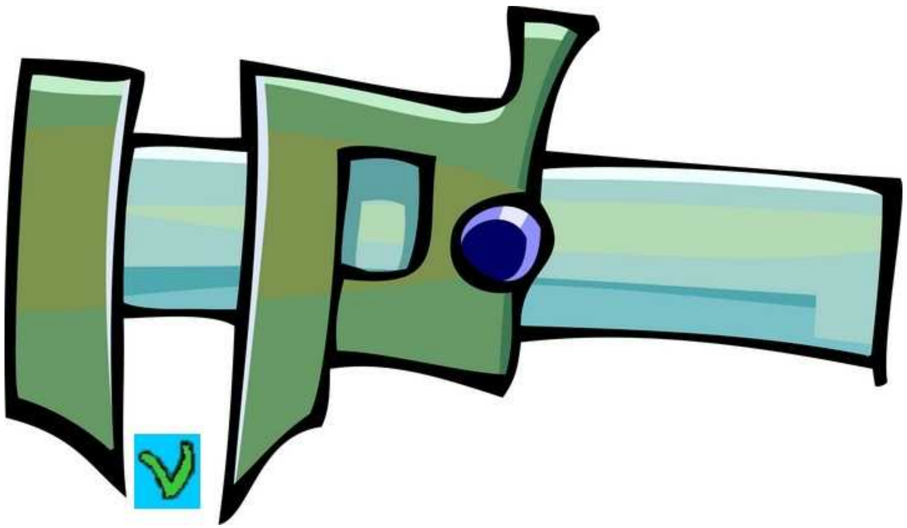
Here are their main results…

Choubey and Petcov consider the reactor signal of GADZOOKS!

Data set used	99% CL range of $\Delta m^2_{21} \times 10^{-5}\text{eV}^2$	99% CL spread of Δm^2_{21}	99% CL range of $\sin^2\theta_{12}$	99% CL spread in $\sin^2\theta_{12}$
only solar	3.2 - 14.9	65%	$0.22 - 0.37$	25%
solar+162 Ty KL	5.2 - 9.8	31%	$0.22 - 0.37$	25%
solar with future SNO	$3.3 - 11.9$	57%	$0.22 - 0.34$	21%
solar+1 kTy KL(low-LMA)	6.5 - 8.0	10%	$0.23 - 0.37$	23%
solar+2.6 kTy KL(low-LMA)	$6.7 - 7.7$	7%	$0.23 - 0.36$	22%
solar with future SNO+1.3 kTy KL(low-LMA)	$6.7 - 7.8$	8%	$0.24 - 0.34$	17%
3 yrs SK-Gd	7.2 - 7.4	1.4%	$0.25 - 0.37$	19%
5 yrs SK-Gd	$7.0 - 7.3$	$< 1\%$	$0.26 - 0.35$	15%
solar+3 yrs SK-Gd(low-LMA)	$7.0 - 7.4$	3%	$0.25 - 0.34$	15%
solar+3 yrs SK-Gd(high-LMA)	$14.5 - 15.4$	3%	$0.24 - 0.37$	21%
solar with future SNO+3 yrs SK-Gd(low-LMA)	$7.0 - 7.4$	3%	$0.25 - 0.335$	14%
solar with future SNO+3 yrs SK-Gd(high-LMA)	$14.5 - 15.4$	3%	$0.24 - 0.35$	19%
3 yrs SK-Gd with Kashiwazaki "down"	$6.8 - 7.6$	6%	$0.23 - 0.40$	27%
7 yrs SK-Gd with *only* Shika-2 "up"	$7.0 - 7.3$	$< 1\%$	$0.28 - 0.32$	6.7%

Table 1: The range of parameter values allowed at 99% C.L. and their corresponding spread.

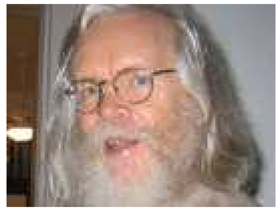
Therefore, we could very well be just a few years away from the world's first true precision measurement (<1 % uncertainty) of a fundamental neutrino parameter!

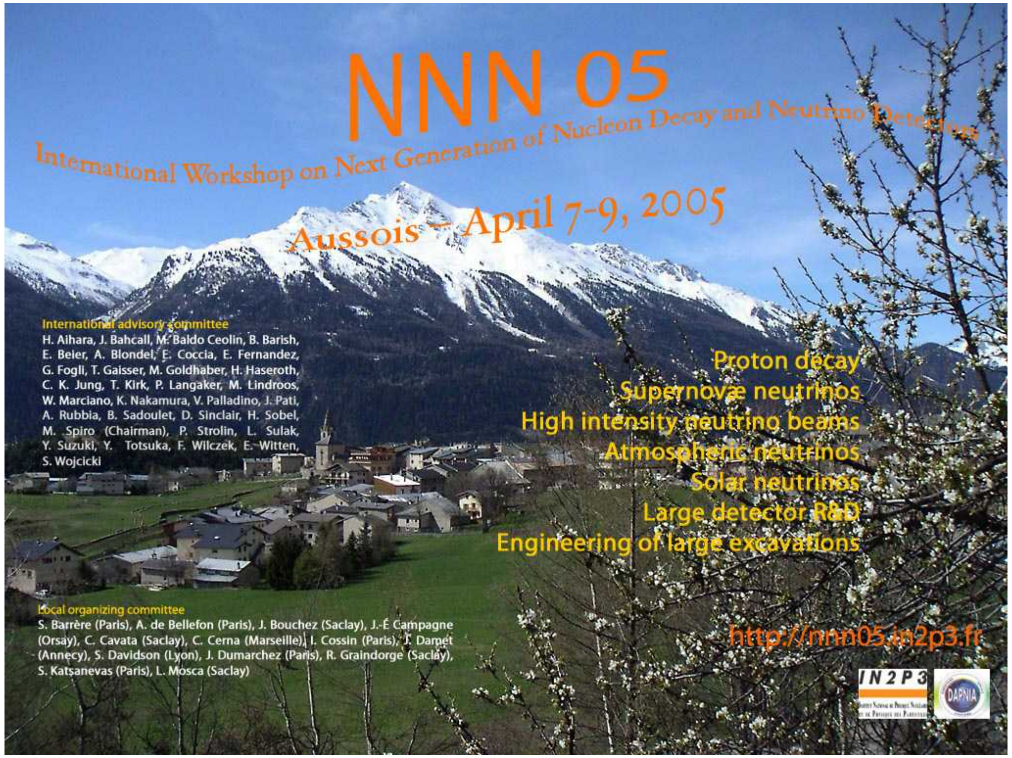


So, our GADZOOKS! proposal has definitely been getting a lot of attention recently:

At NNN05, <u>before I had even given my talk</u>, John Ellis suddenly stood up and demanded of the SK people in attendance:

Why haven't you guys put gadolinium in Super-K yet?





As I told him, studies are under way…

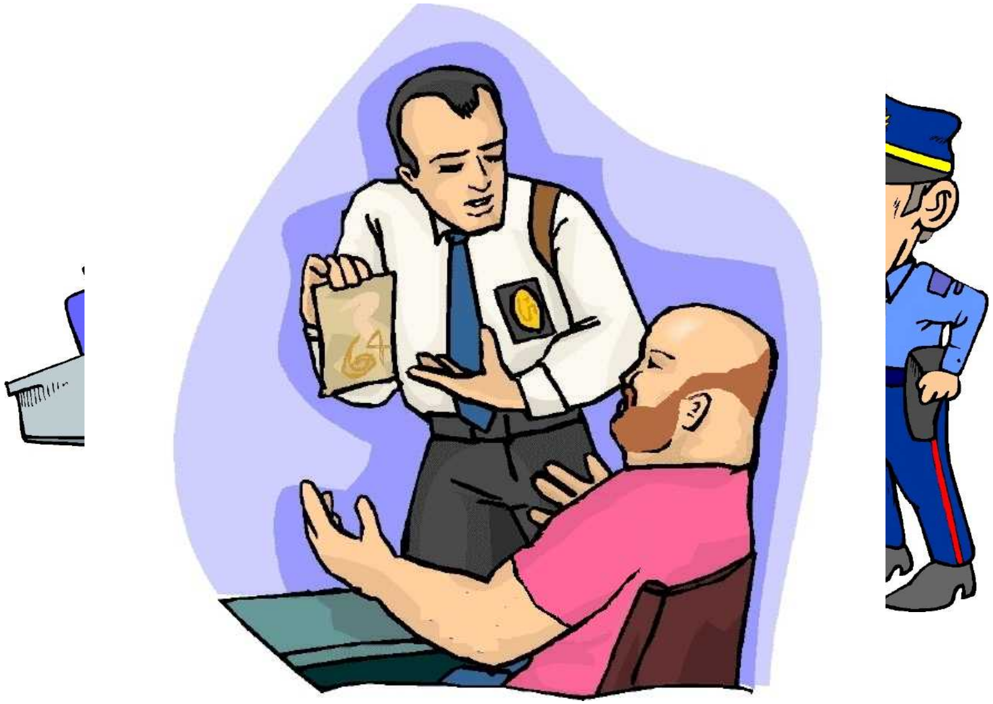
You see, Beacom and I never wanted to merely propose a new technique – we wanted to make it work!

Now, suggesting a major modification of one of the world's leading neutrino detectors may not be the easiest route…

…and so to avoid wiping out, some careful hardware studies would be needed.

- What does $GdCl_3$ do the Super-K tank materials?
- Will the resulting water transparency be acceptable?
- Any strange Gd chemistry we need to know about?
- How will we filter the SK water but retain $GdCl_3$?

As a matter of fact, I very rapidly made two discoveries regarding $GdCl_3$ while carrying a sample from Los Angeles to Tokyo:

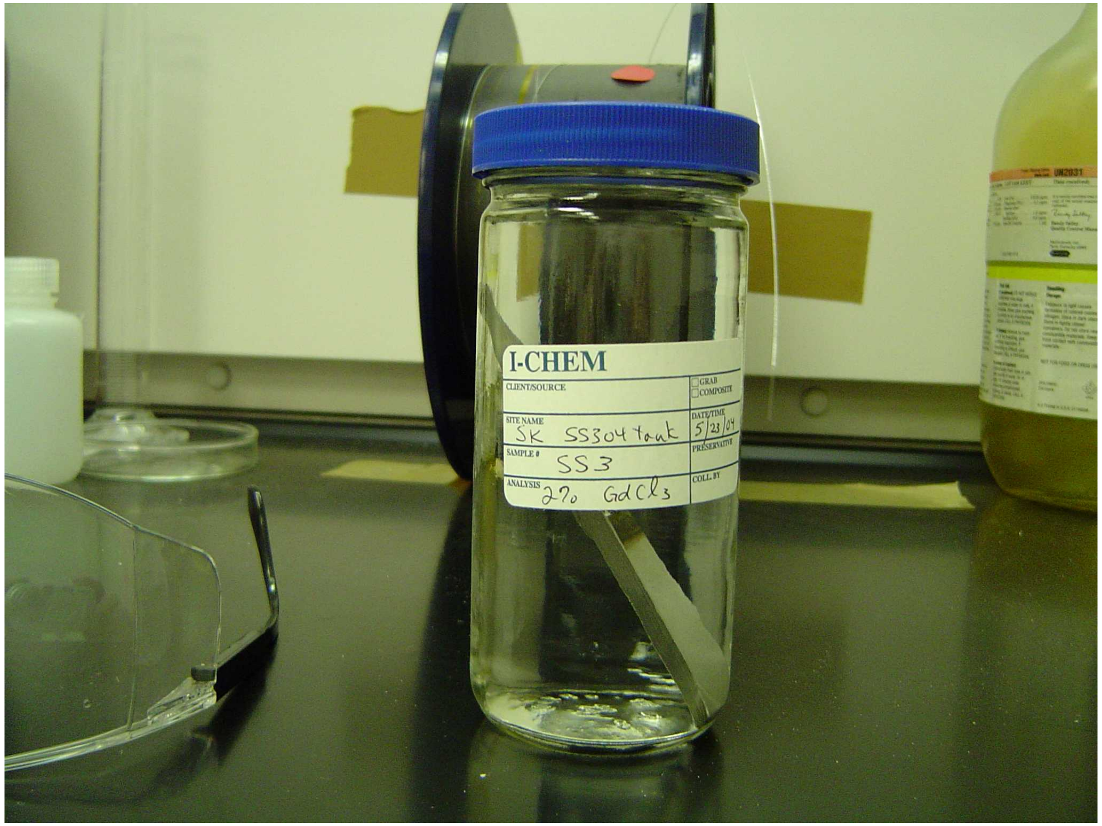


1) $GdCl_3$ is quite opaque to X-rays
2) Airport personnel get very upset when they find a kilogram of white powder in your luggage

While hep-ph/0309300 was being assembled, I was awarded a U.S. DoE Advanced Detector Research Program grant to support the study of key gadolinium R&D issues.

Work immediately got under way at UC Irvine building a small version of the SK water filtration system, while at Louisiana State University a materials aging study was put together under the supervision of Bob Svoboda.

Example of Soak Sample



Tank Weld Joint:

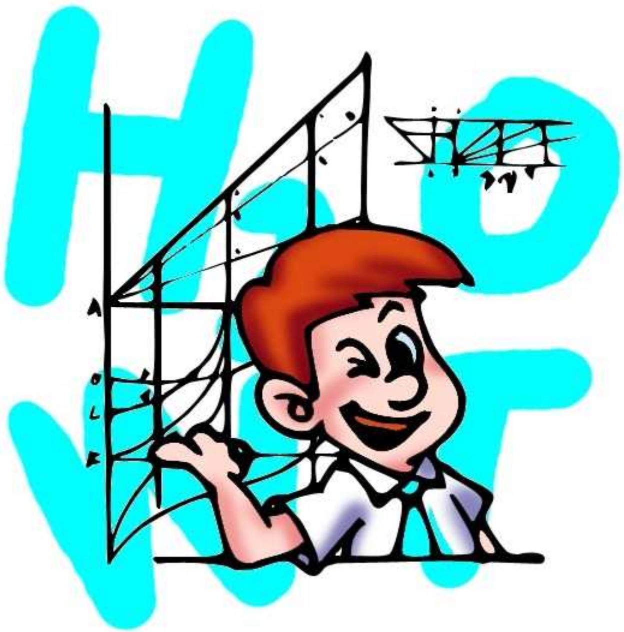
Room temperature soak in 2% $GdCl_3$

We will inspect surface every three months via SEM, optical, and XRD

Now at 20 years of equivalent exposure!

With the help of a crew and equipment from the University of Hawaii, very preliminary measurements which we made in Japan last March indicate an absolute lower bound on the attenuation of 0.2% $GdCl_3$ (plus contaminants) which is

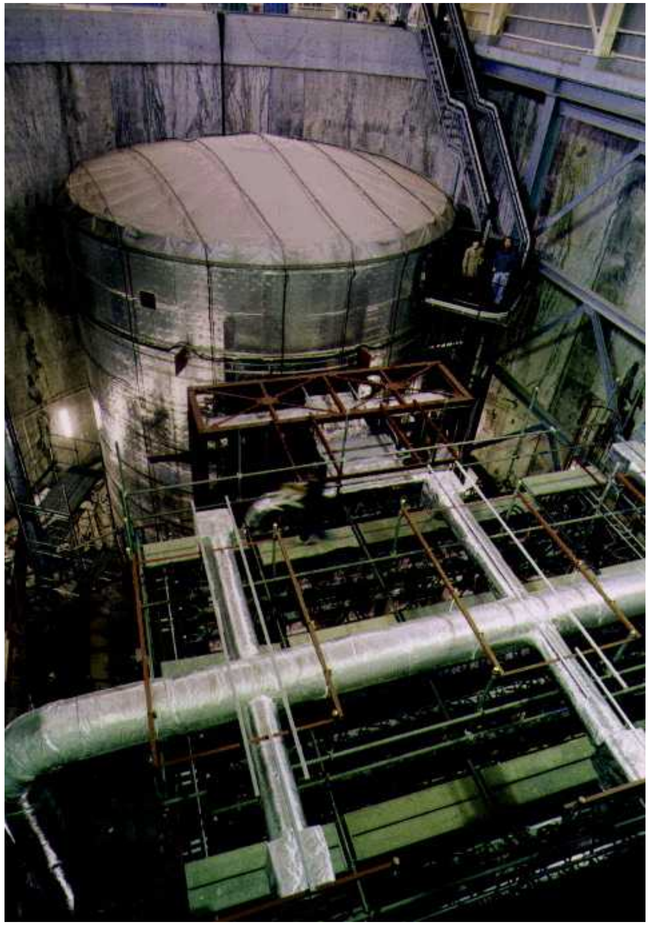
> 58 +/- 1 meters.



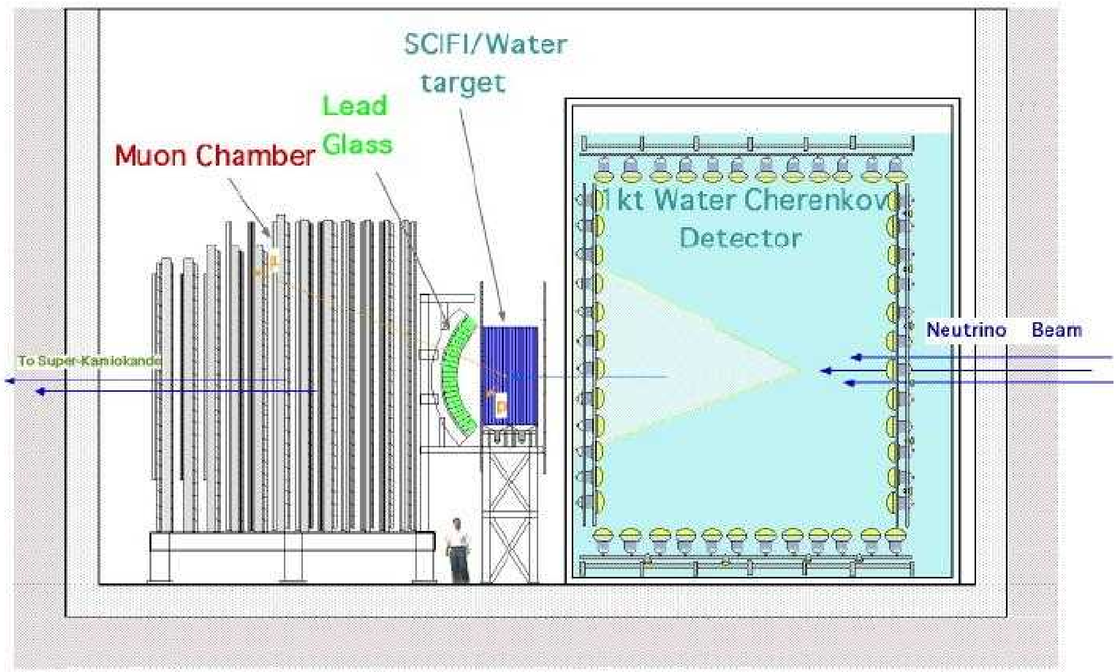
These bench tests have been very encouraging.
In a single pass through our UCI water filtering system we can remove ~99.99% of the Gd and return it to our 500 liter holding tank.

But can this be scaled up to kilotons of Gd-enriched water?

With the help of this big detector at KEK we are about to find out!



This summer I'll employ some excellent large-scale hardware to find out if the $GdCl_3$ technique will work:

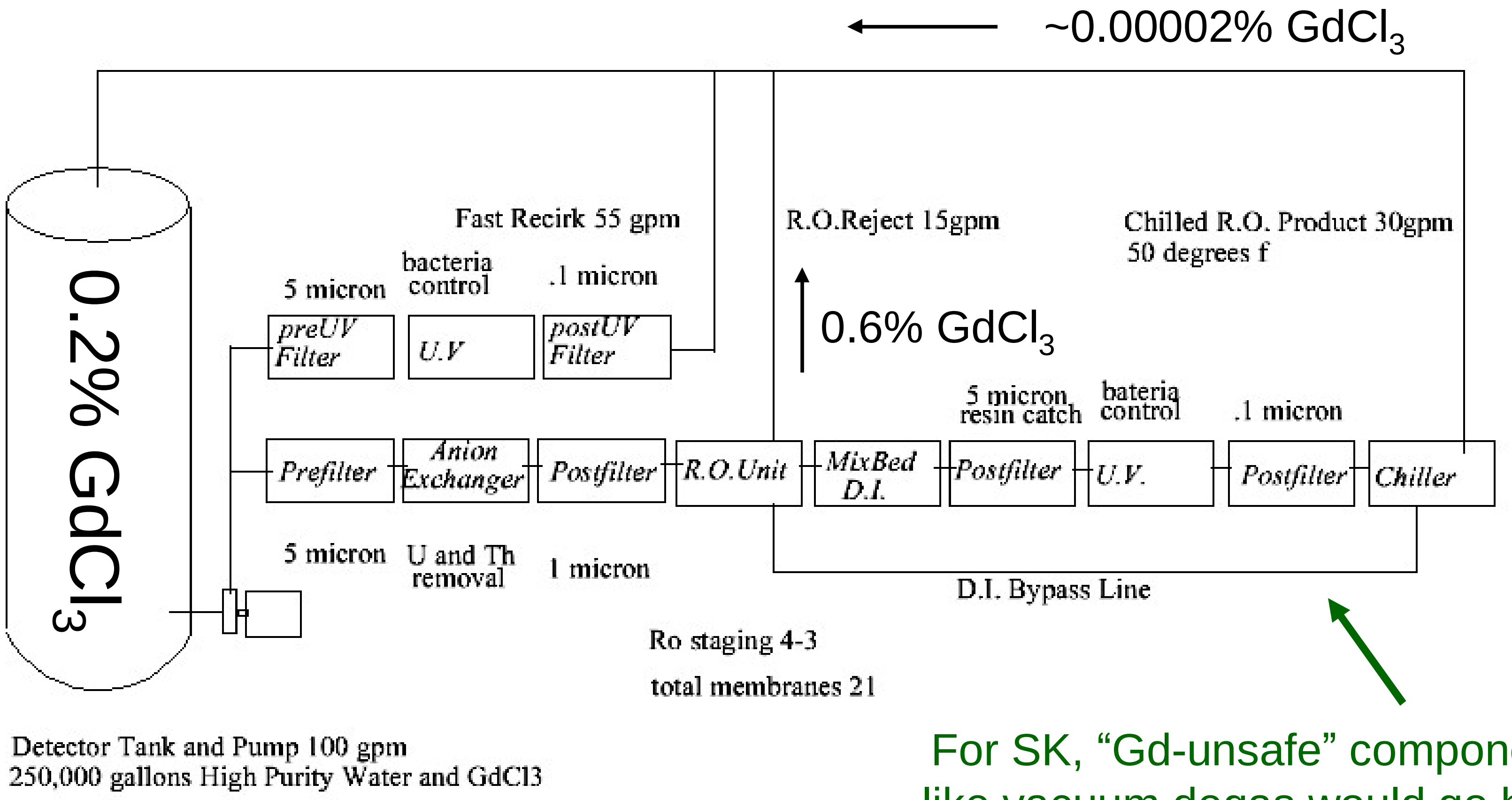


<u>K2K's 1 kiloton tank will be used for "real world" studies of</u>

- Gd Water Filtering – UCI built and maintains this water system
- Gd Light Attenuation – using real 20" PMTs
- Gd Materials Effects – many similar detector elements as in Super-K

We are nearly ready for this effort…

Here's our design for the rebuilt 1 kton water system:



For SK, "Gd-unsafe" components like vacuum degas would go here.

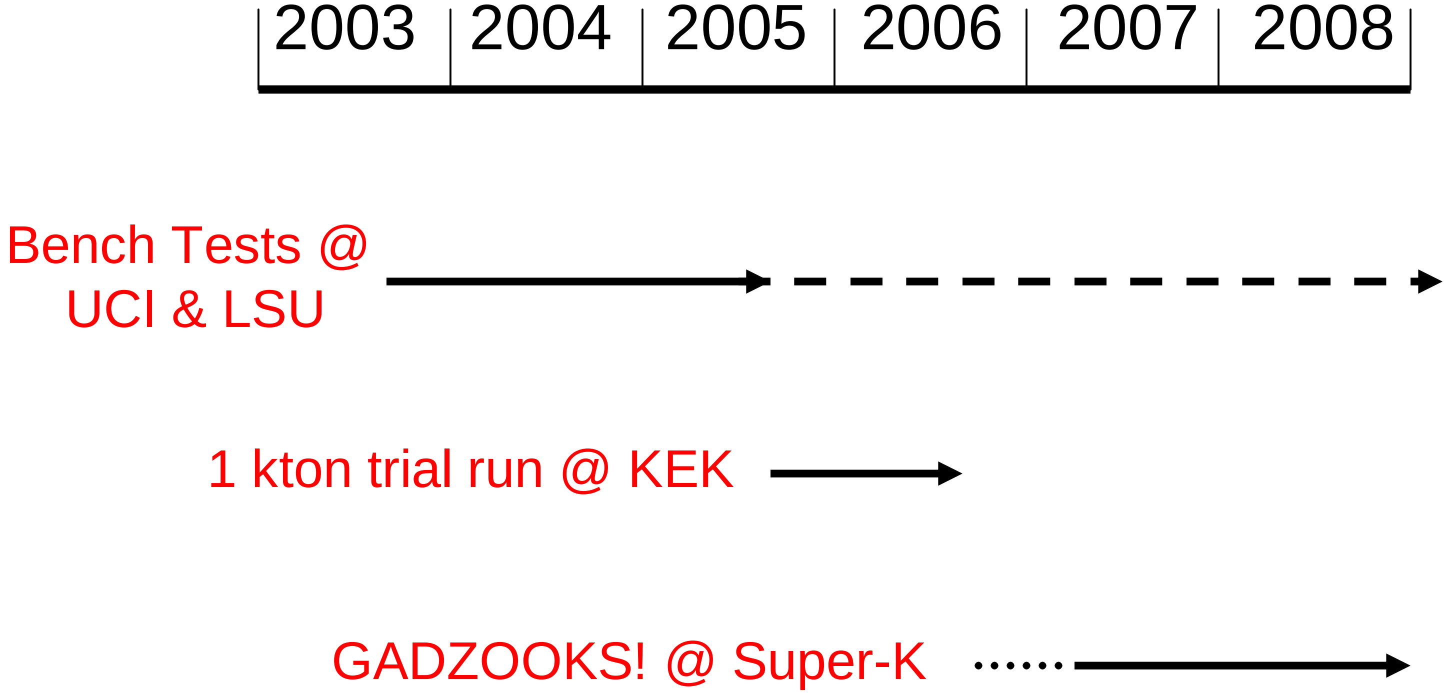
The entire one kiloton volume is recirculated every two days.

A Busy Summer

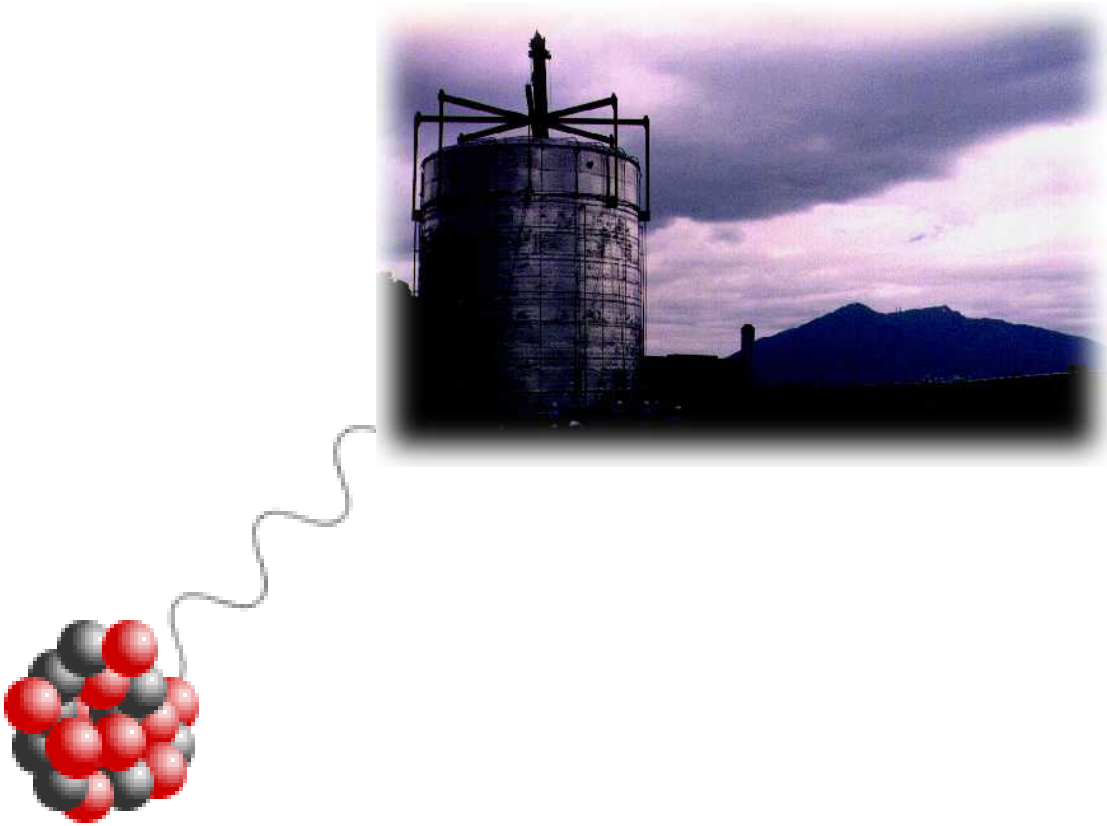
In August/September we will rebuild the one kiloton's water system at KEK.

We expect to introduce 2,000 kg of $GdCl_3$ into the tank sometime in September!

A $GdCl_3$ Timeline:



Soon we will be taking our <u>GADZOOKS!</u> studies to Tsukuba…



Gd

Let’s go put the γ in gama oil!

That’s it for now…

time for me to get back to seeing if this beautiful dream can be made a reality!