Water-based Antineutrino Detection

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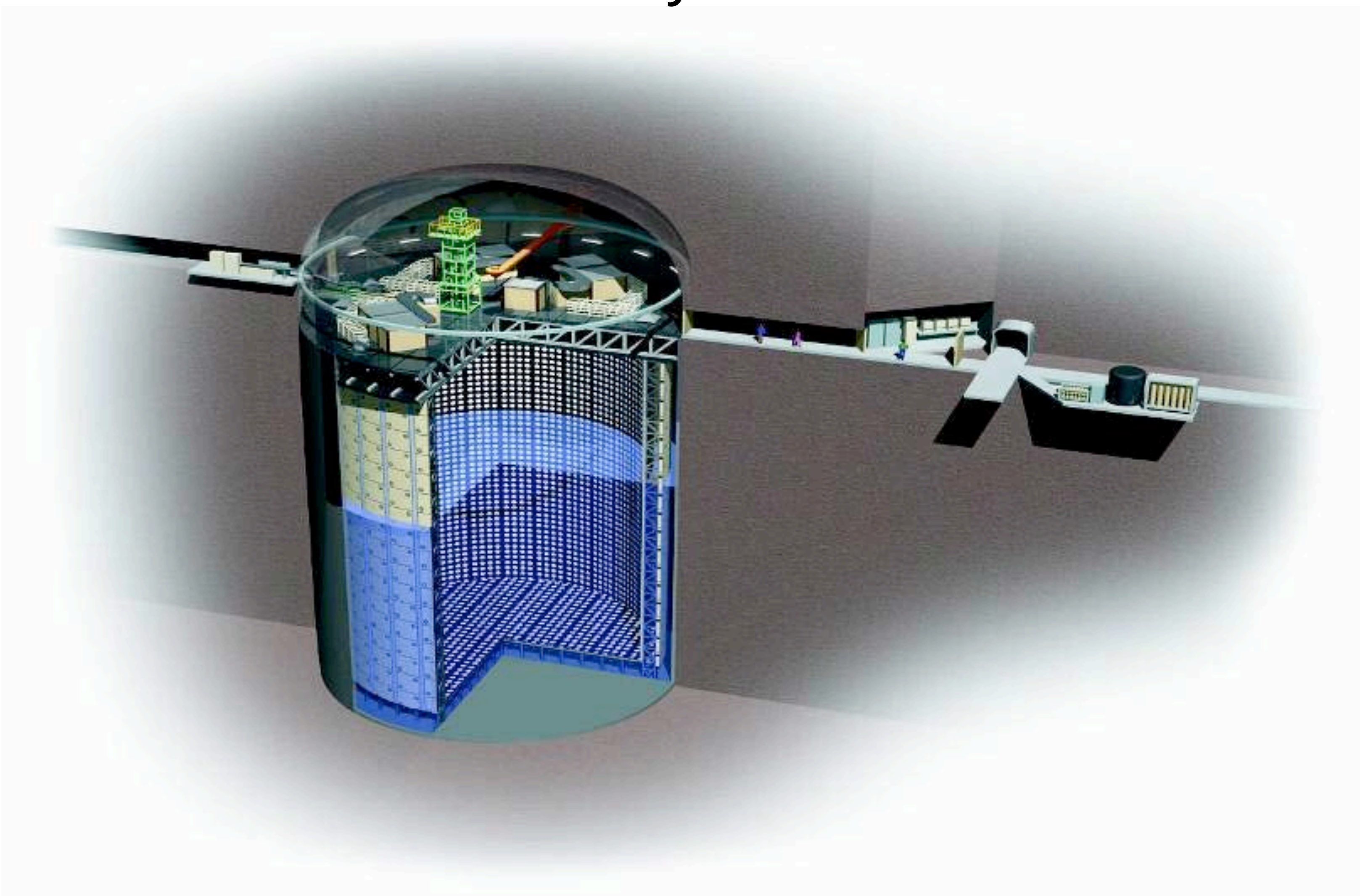
My beloved Super-Kamiokande has been taking data, with an occasional interruption, for over ten years now…



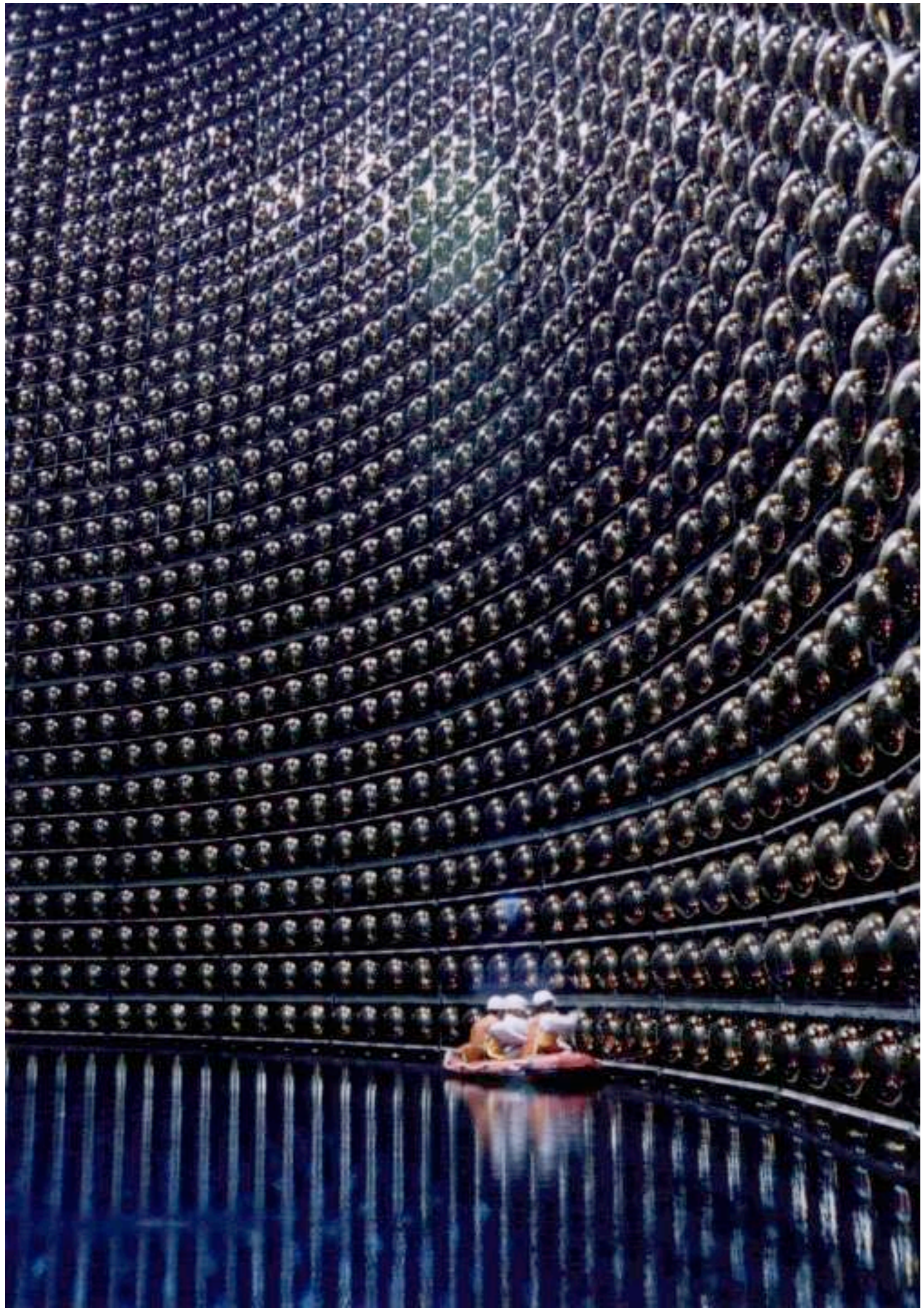
The Location

Super-Kamiokande

50,000 tons of ultra-pure H_2O

13,000 light detectors

One kilometer underground



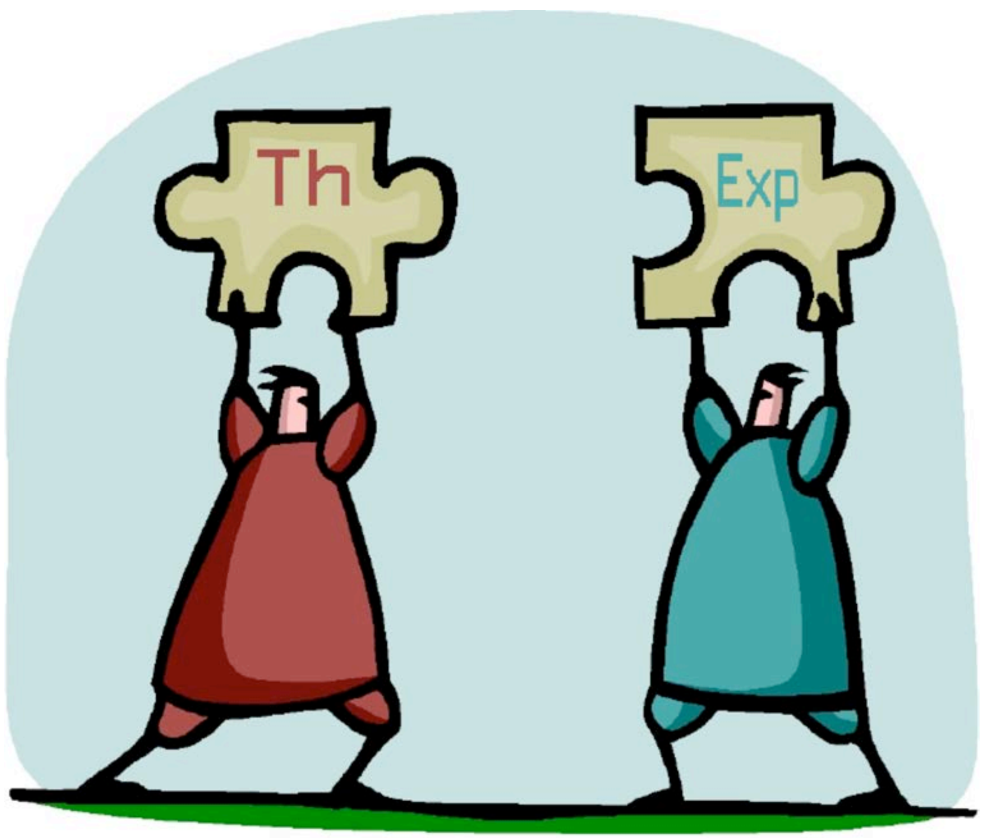
Observes neutrinos from the Sun, supernovas, and cosmic rays

But what does the future hold?

On July 30th, 2002, at ICHEP2002 in Amsterdam, Yoichiro Suzuki, then the newly appointed head of SK, said to me,

"We <u>must</u> find a way to get the new physics."

Taking this as our mandate, theorist John Beacom and I focused on finding some way to get new physics out of Super-Kamiokande.



This partnership of theory and experiment has proven quite productive.

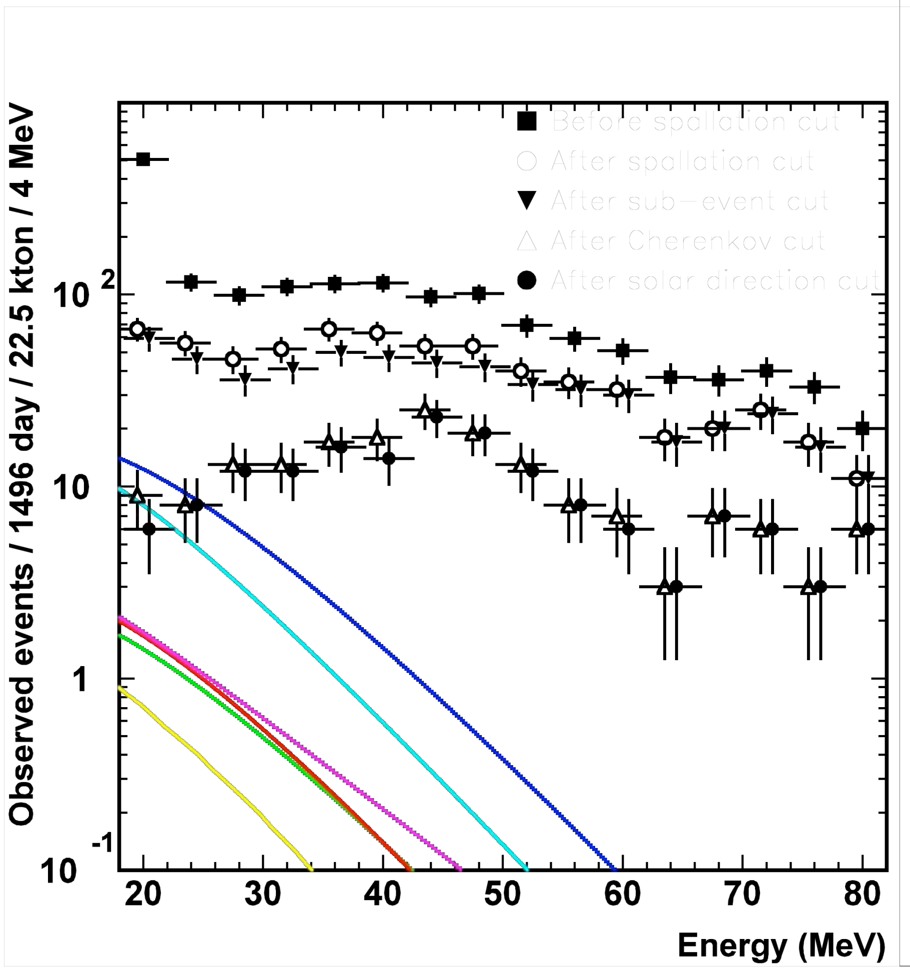
For example, supernova neutrinos are certainly interesting…
but how could we be sure of seeing some in SK?

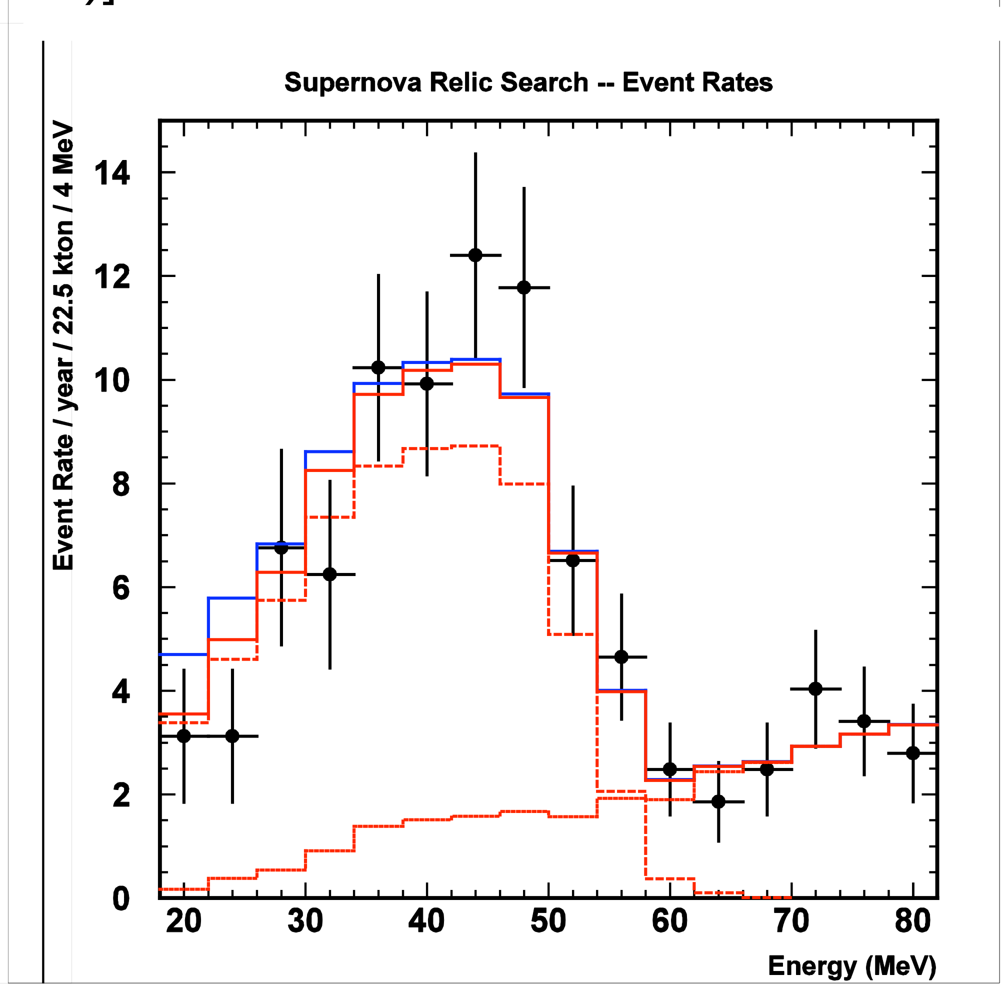
Well, *galactic* supernovas may be somewhat rare on a human timescale, but supernovas are not.

On average, there is one supernova explosion somewhere in our universe every second!

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

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





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

So, experimental DSNB limits are approaching theoretical predictions. Clearly, reducing the remaining backgrounds and going lower in energy would be 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>

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

Since the reaction we are looking for is

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

what if we could reliably identify the neutron (currently invisible in Super-K) and look for <u>coincident</u> signals?

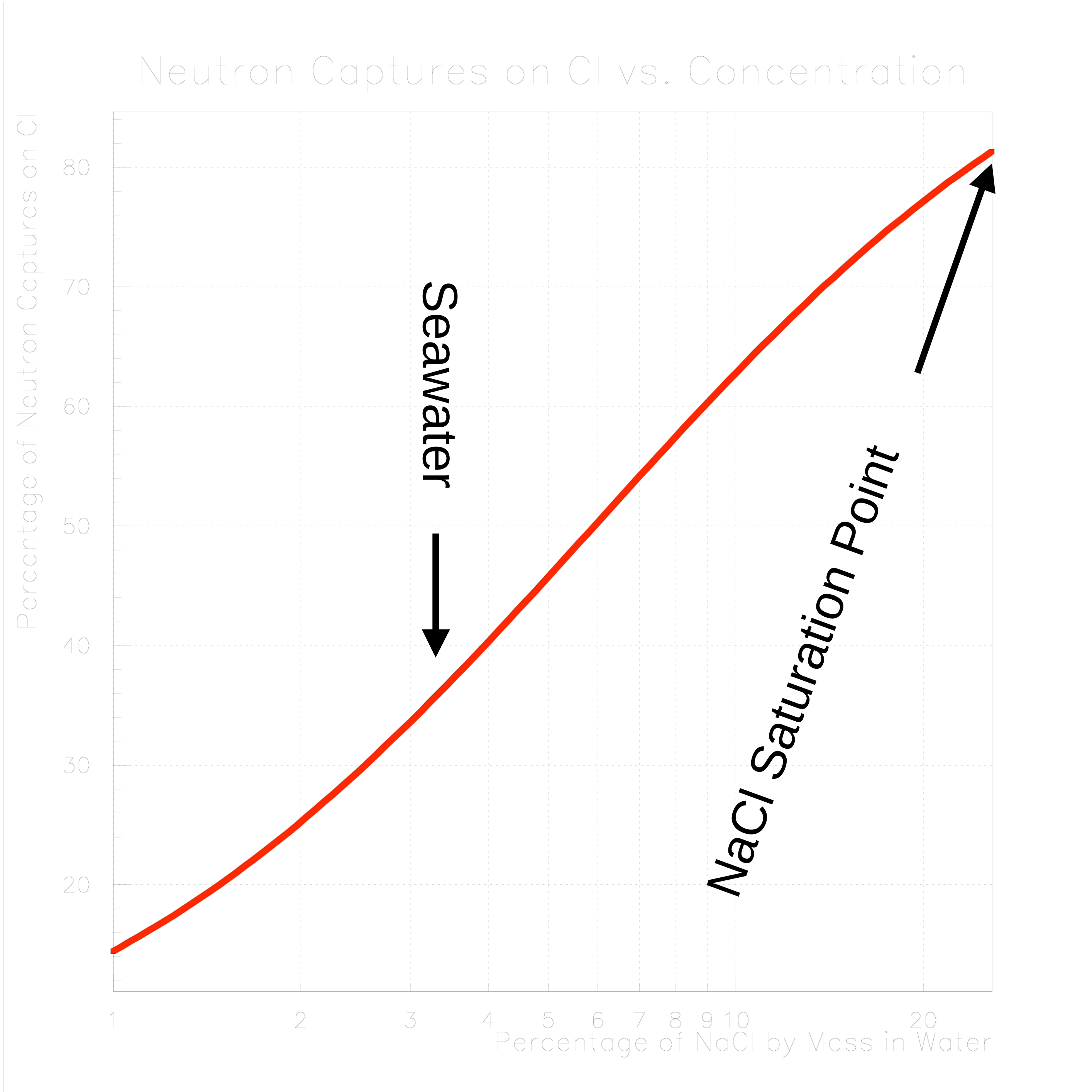
But we're going to have to compete with hydrogen

($p + n \rightarrow d + 2.2$ MeV γ)

in capturing the neutrons!

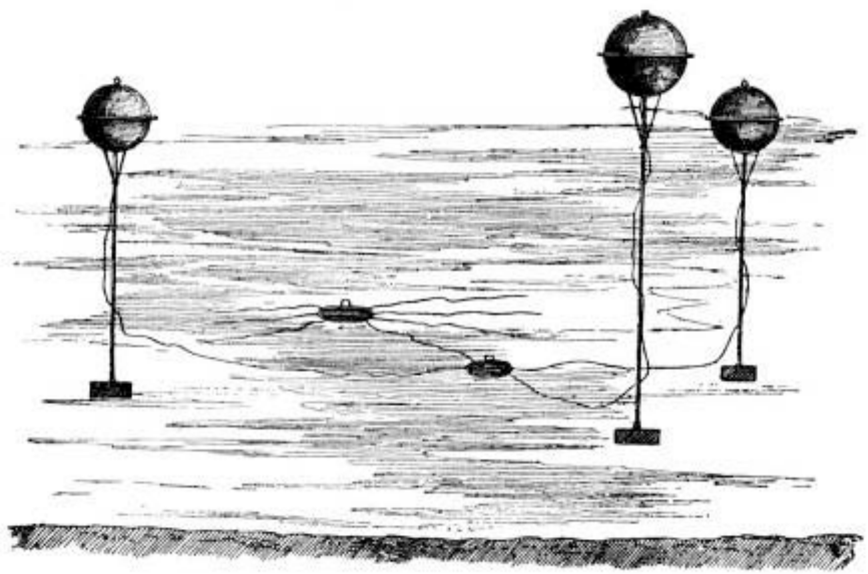
Plus, plain old NaCl isn't going to work…

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
1
2
3
4
5
6
7
8
9
10
20
Percentage of NaCl by Mass in Water
Seawater
NaCl Saturation Point

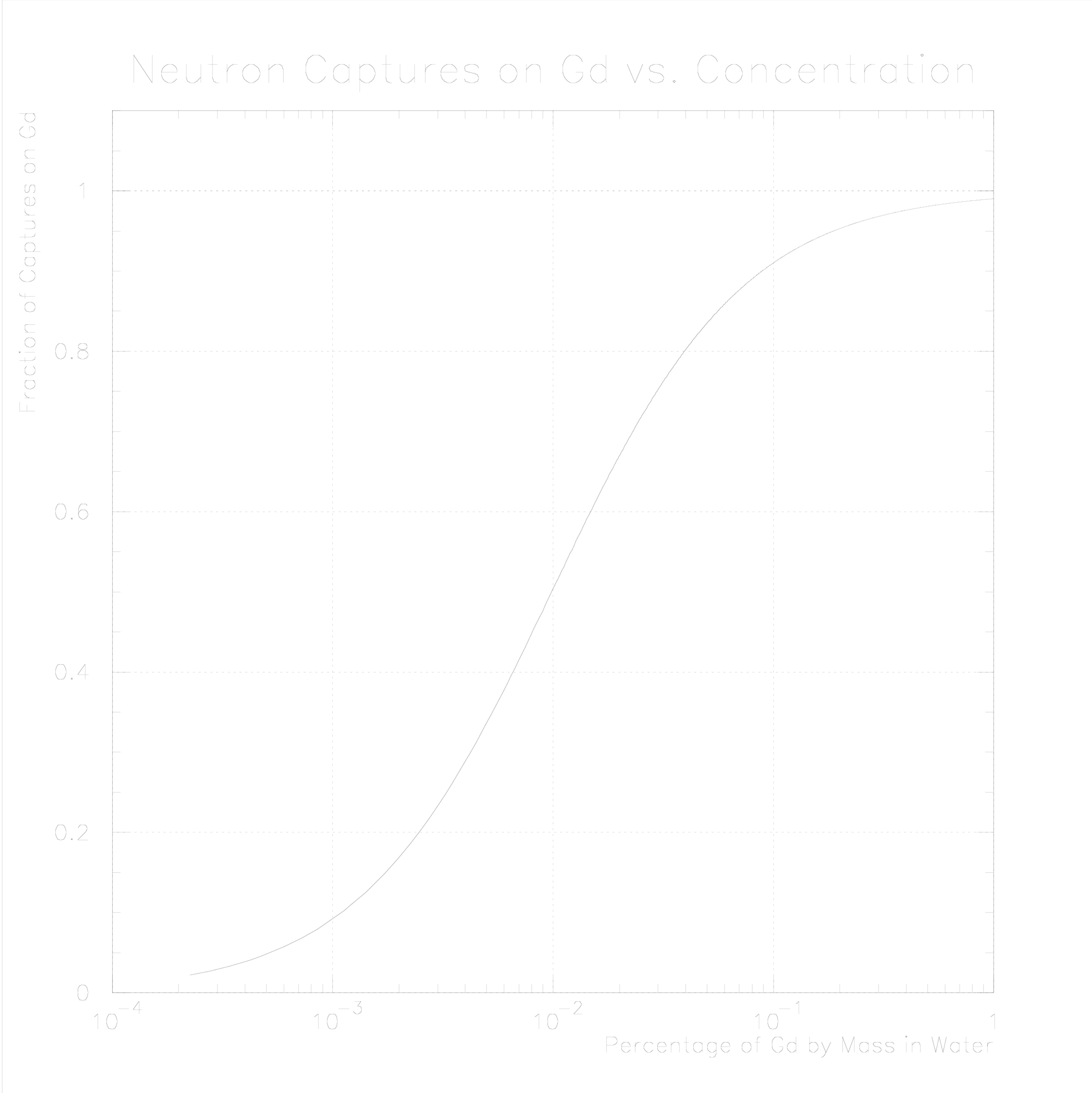
However, regular NaCl might be just the right thing to use in giant undersea water Cherenkov detectors as proposed by John Learned a few years ago:



Locally produced, low ^{40}K salt would enhance antineutrino detection while maintaining proper buoyancy.

But, for SK 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 particularly toxic!


Neutron Captures on Gd vs. Concentration
Fraction of Captures on Gd
0
0.2
0.4
0.6
0.8
1
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 2006: $5/kg –> $500,000

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!

Doped water is the only neutron detection technique which is extensible to Mton scales, and at minimal expense, too:

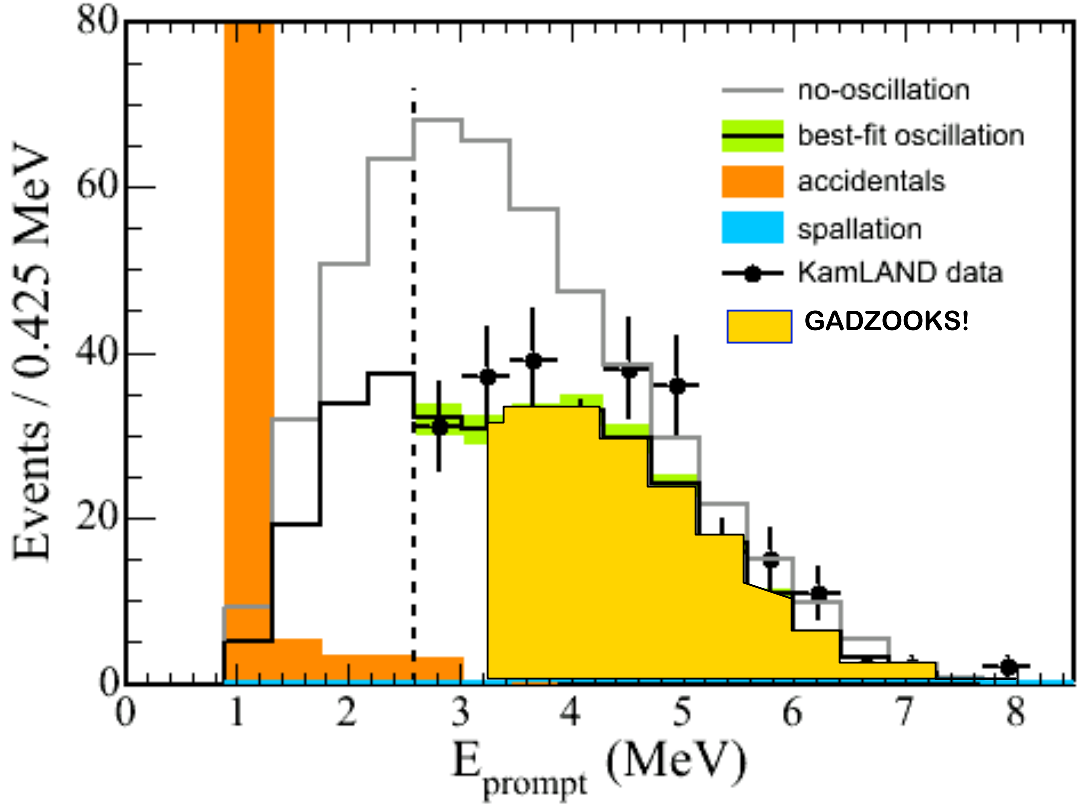
~1% of the detector construction costs

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...

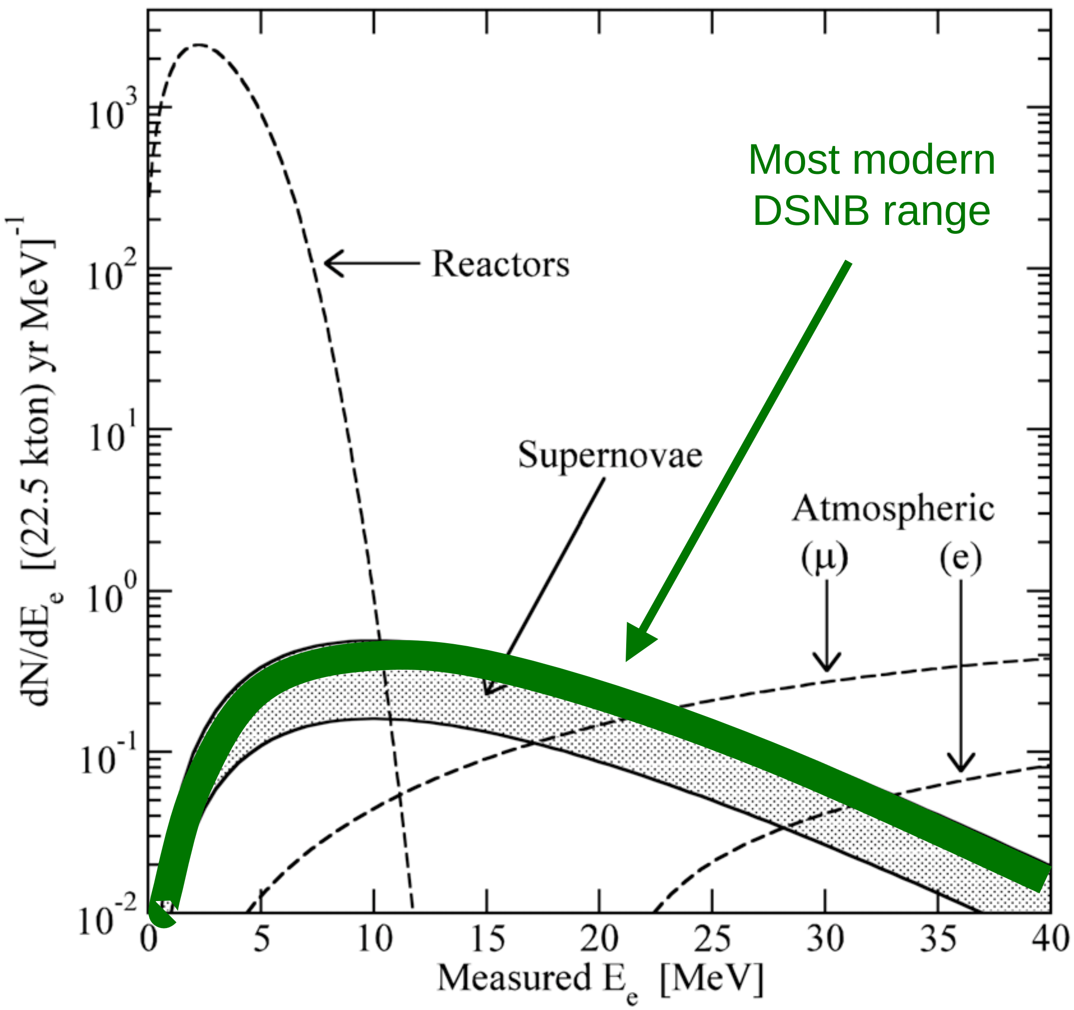
KamLAND's first 22 months of data



GADZOOKS! will collect this much reactor neutrino data in *two weeks.*

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

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



Our paper proposing all of this was published as

Beacom and Vagins, *Phys. Rev. Lett.*, **93**:171101, 2004.

Others quickly took notice…

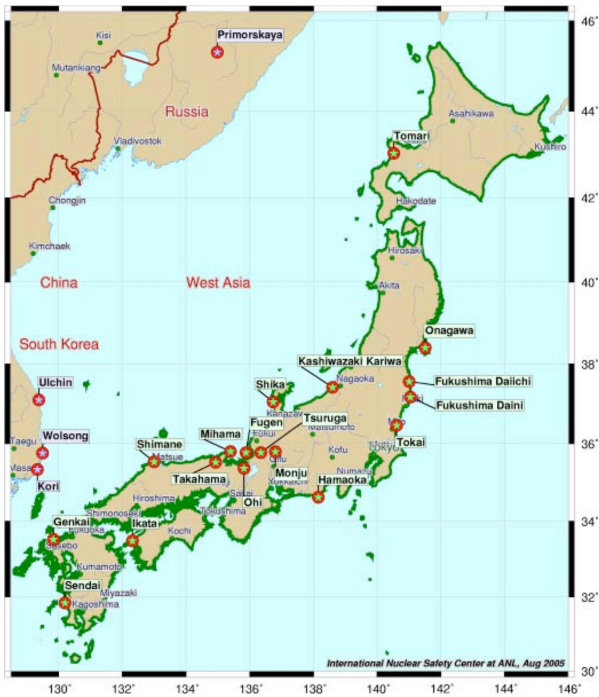
Choubey and Petcov consider the reactor signal of GADZOOKS!

Phys. Lett. **B594**: 333, 2004

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.

So, adding 100 tons of $GdCl_3$ to Super-K would provide us with at least two brand-new, <u>guaranteed</u> signals:



1) Precision measurements of the neutrinos from all of Japan's power reactors
(~5,000 events per year)

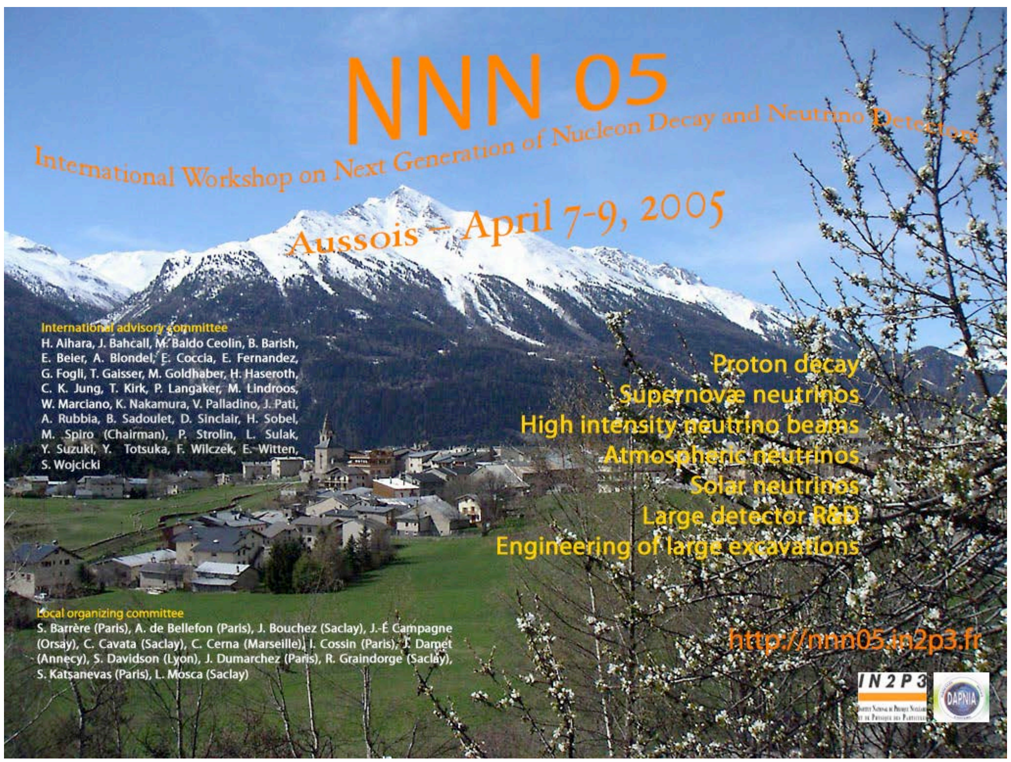
2) Discovery of the diffuse supernova neutrino background [DSNB], also known as the "relic" supernova neutrinos
(~5 events per year)

In addition to our two guaranteed new signals, it is likely that adding $GdCl_3$ to SK-III will provide a variety of other interesting (and not yet fully explored) possibilities:

- Solar antineutrino flux limit improvements (X100)
- Full de-convolution of a galactic supernova's ν signals
- Early warning of an approaching SN ν burst
- (Free) proton decay background reduction
- New long-baseline flux normalization for T2K
- Matter- vs. antimatter-enhanced atmospheric ν samples(?)

Our GADZOOKS! proposal has definitely been getting a lot of attention recently:

At NNN05, before I had even given my talk, 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…

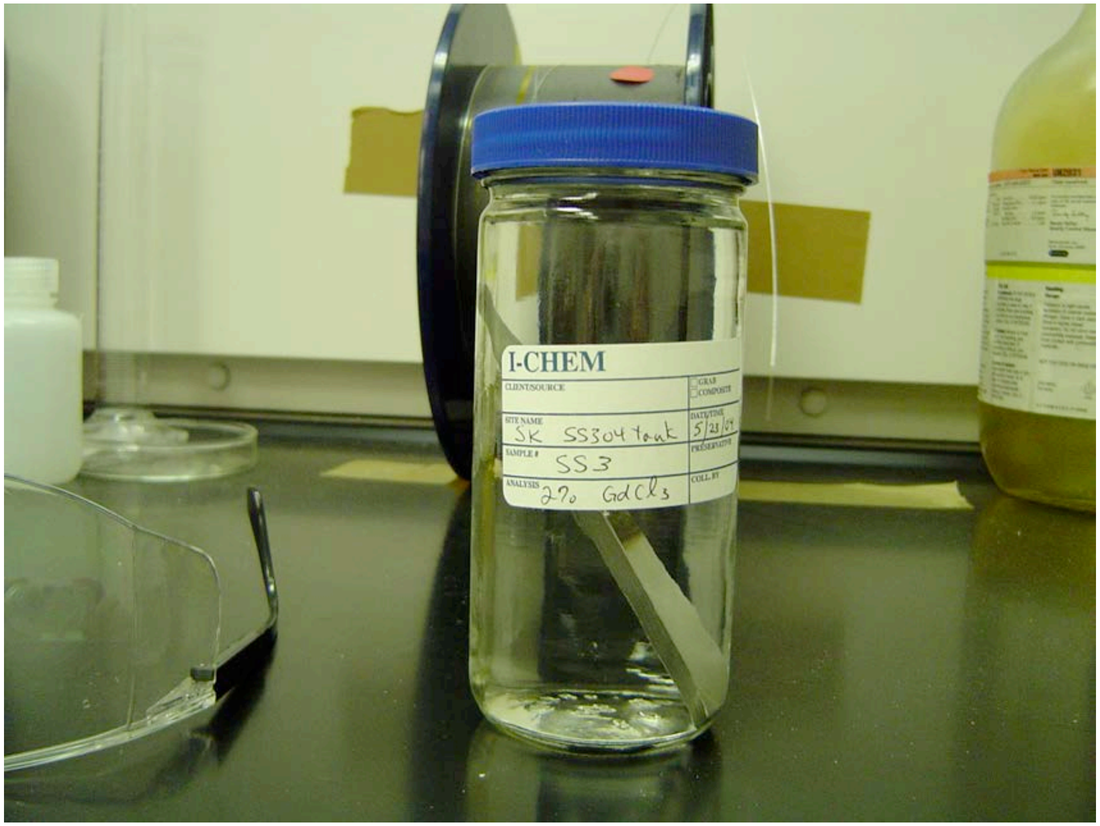
…since we need to know the answers to the following questions:

- 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 $GdCl_3$?

Since 2003, the U.S. DoE's Advanced Detector Research Program has been supporting our study of these key gadolinium R&D issues.

[Tabletop version of the SK water filtration system at UC Irvine]

Example of Soak Sample



Tank Weld Joint:

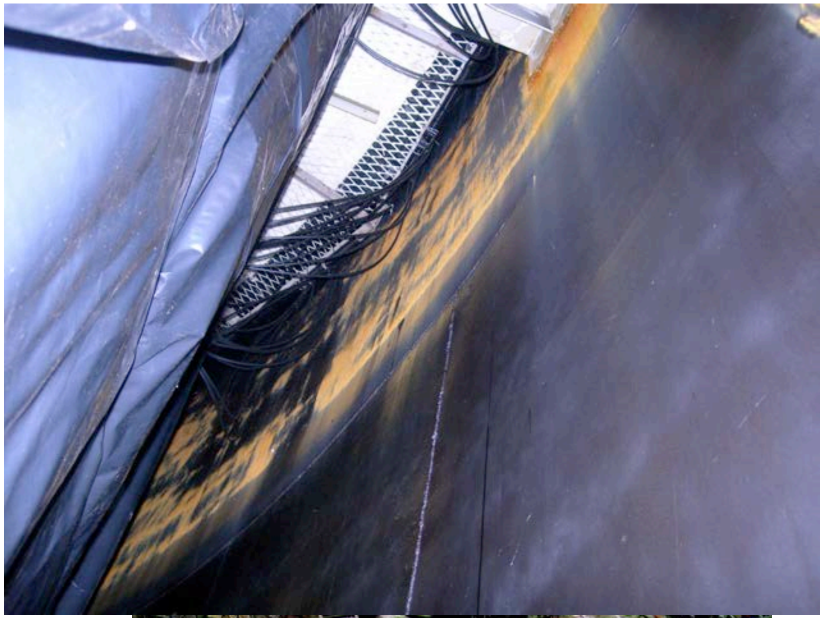
Room temperature soak in 2% $GdCl_3$

Inspect surface via SEM, optical, and XRD

Now at 35 years of equivalent exposure!

In order to study the $GdCl_3$ concept in a "real world" setting, over the past year we have used the old one kiloton [1KT] detector from the K2K experiment, injecting some 200 kg of $GdCl_3$ and removing it from the water a few months later.

This 2% model of Super-K and Super-K itself *are* quite similar, but they are not completely identical…

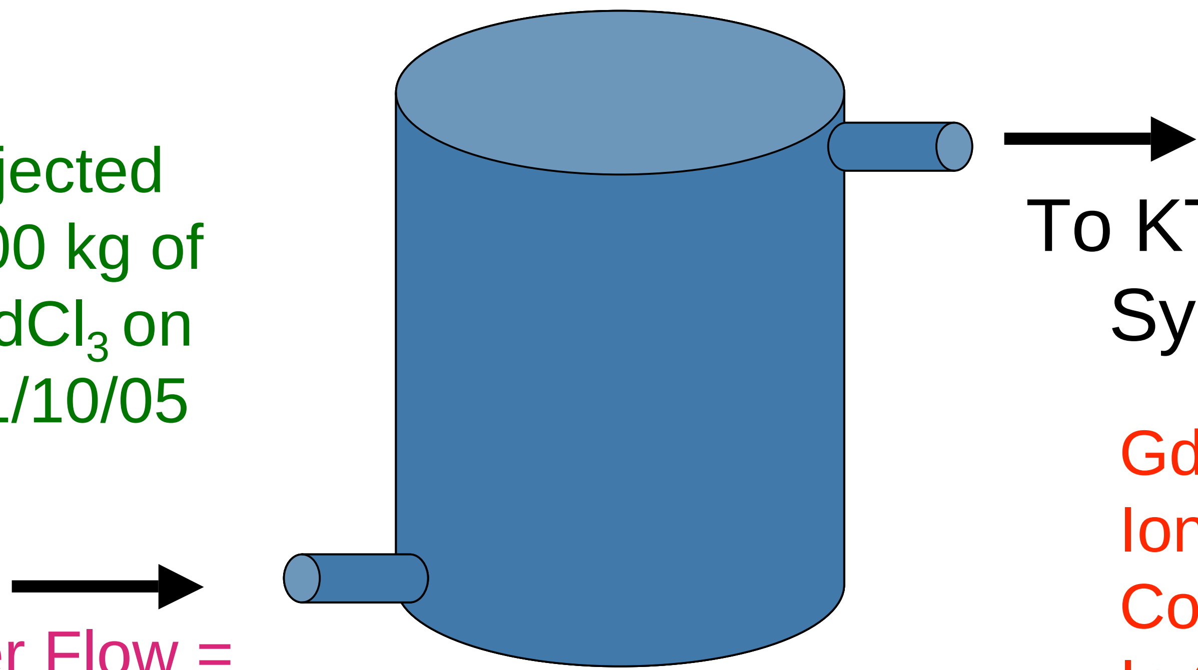


The most important difference:

- the SK tank is high grade stainless steel while the 1KT tank is painted iron with large (~20%) areas of pre-existing rust

Adding $GdCl_3$ to KT Detector

Injected 200 kg of $GdCl_3$ on 11/10/05



To KT Water System

Water Flow = 21 tons/hr

Gd^{3+} and Cl^{-} Ions At Full Concentration In Clear Water On 11/12/05

November 12th, 2005

A few days later, rust started to appear in our filters...

So, what have we learned so far?

We have now demonstrated:

- Choice of high-quality detector materials is important
- That $GdCl_3$ itself does not ruin water transparency
- Our PMT’s work properly in conductive water
- $GdCl_3$ is easy to dissolve and pre-treat, but lifts rust
- Gd filtering works well at large scales and flows
- We can remove the $GdCl_3$ quickly if need be ($)

So, now what?

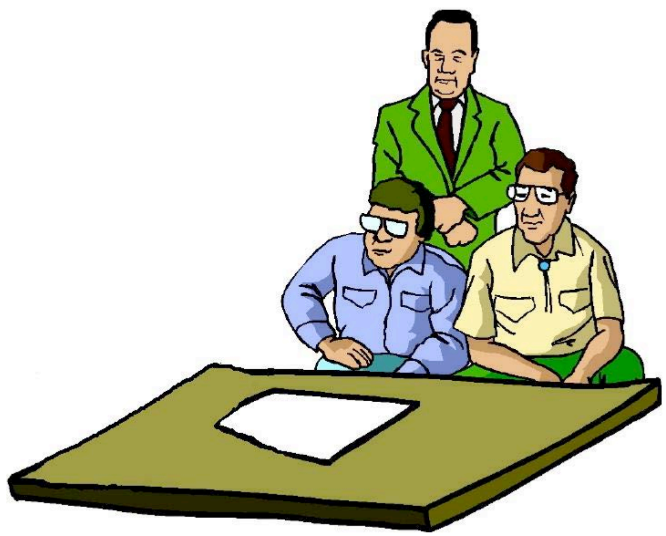
Well, if we want to put this stuff into Super-K
it is certain, after our work with the 1KT,
that we now must do a test which simulates the
physical conditions in SK as closely as possible…

We'll need to use a <u>stainless steel tank filled with degasified water.</u>

A new SS tank is currently under construction by Bob Svoboda at LLNL for this purpose.

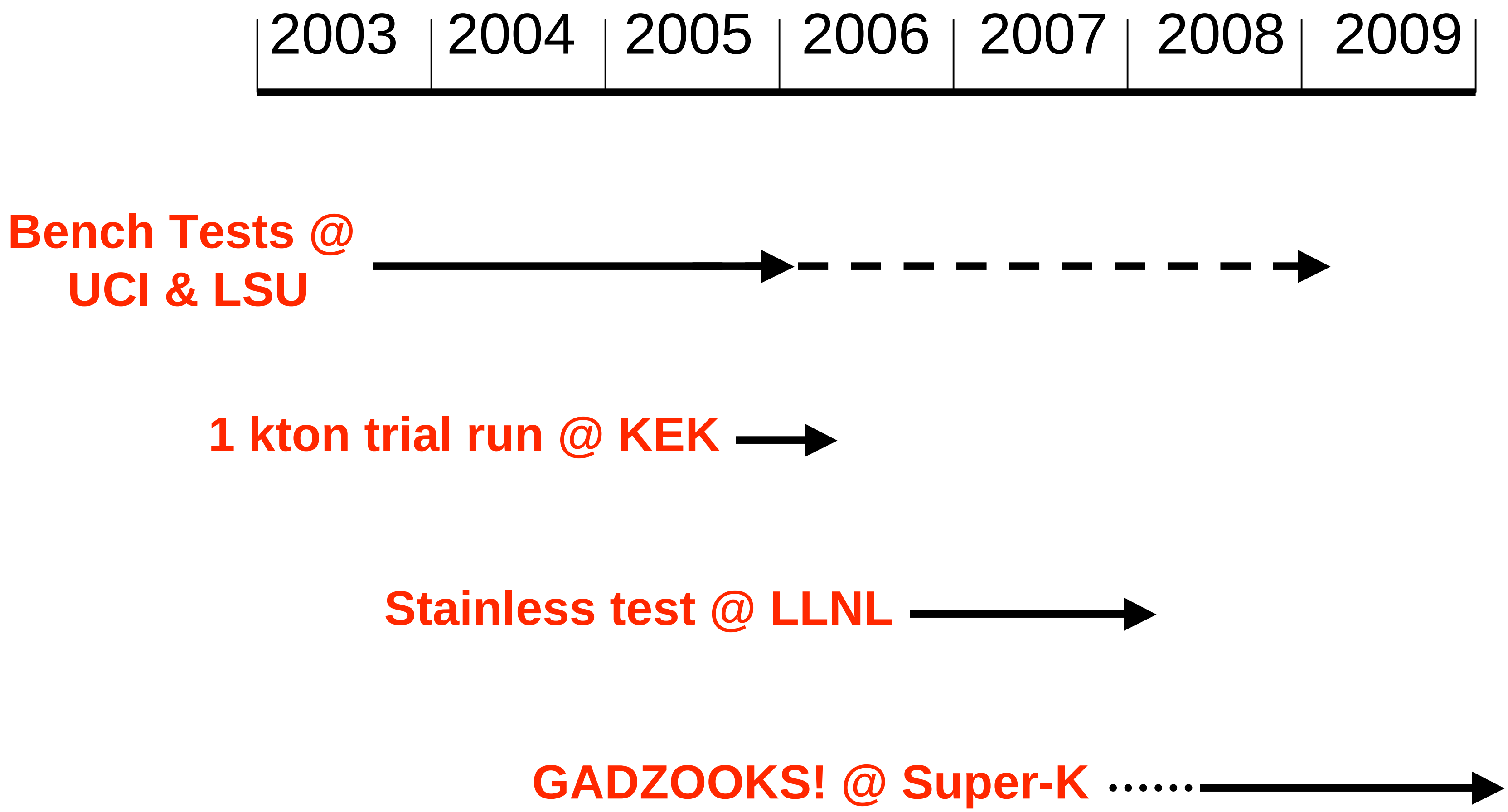
Following all of the R&D which has already been done, during the May 2006 SK Collaboration meeting an official "SK Gadolinium Committee" was formed.

Their task is to evaluate the results of the various $GdCl_3$ studies (and possibly suggest new ones), ultimately making a "go/no go" recommendation to the SK leadership sometime in 2008.

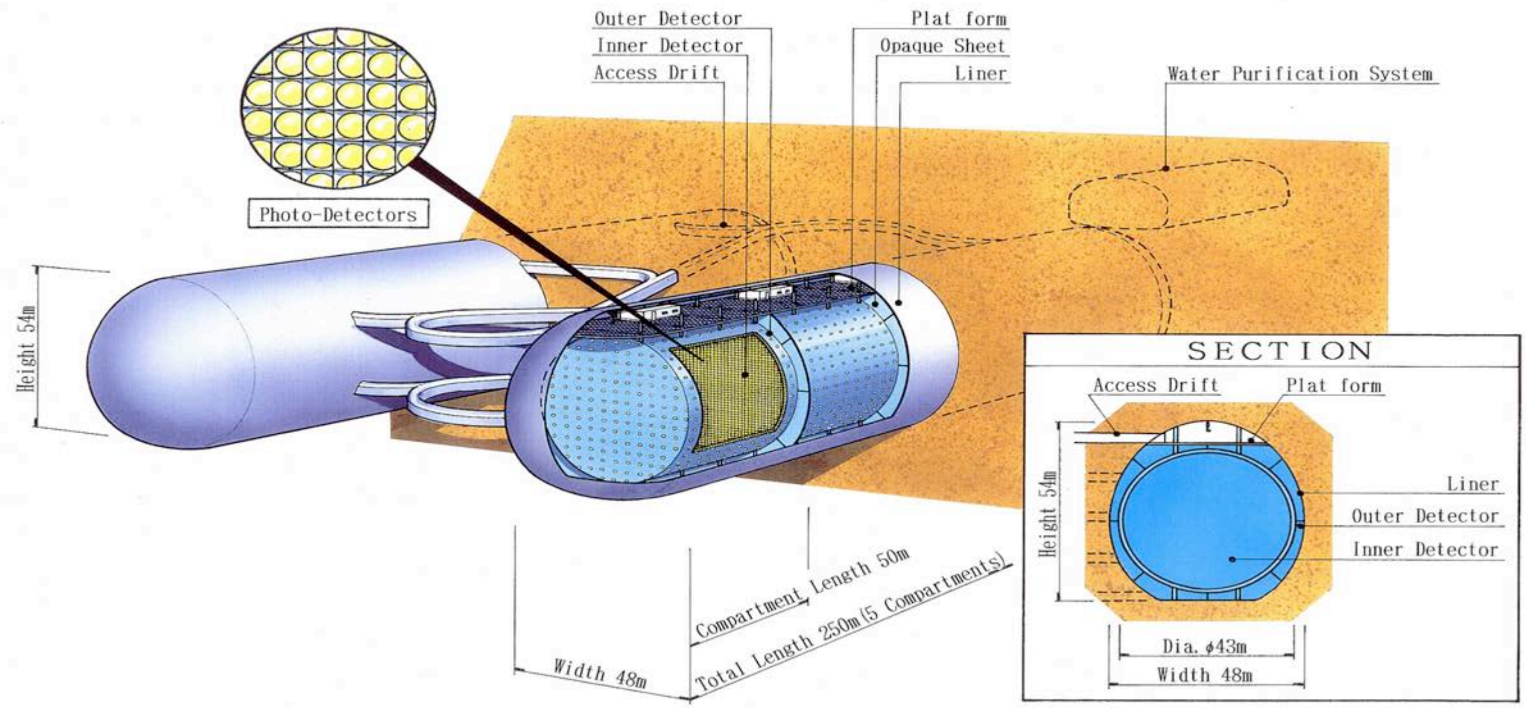


My initial TDR will be submitted to them next month!

A Gadolinium Timeline:



Last year at NuInt05 in Okayama, Japan, Kenzo Nakamura suggested that (at least) one "tube" of Hyper-Kamiokande should be designed, from the beginning, for $GdCl_3$-enriched water.



We clearly have our colleagues' attention and interest. Now we simply have to make it all work!