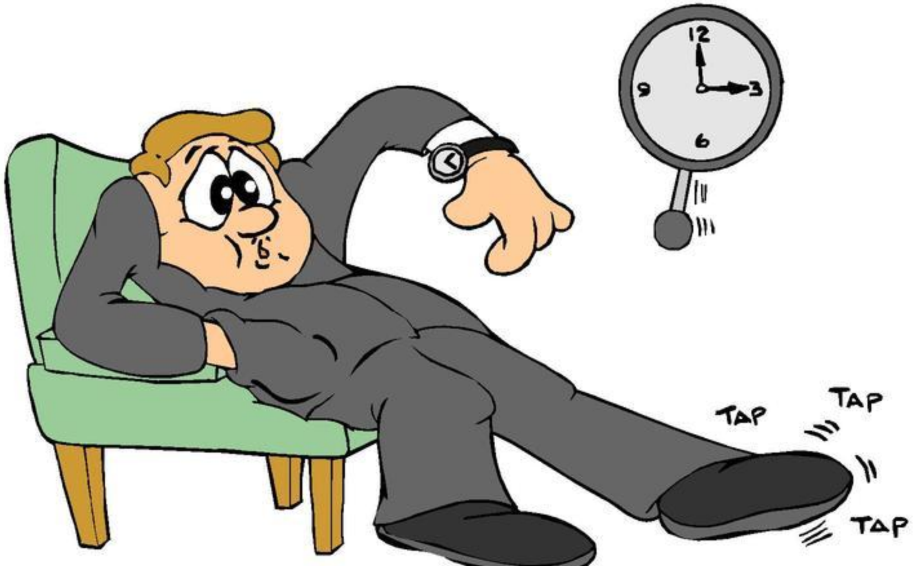
GADZOOKS!

Supernova Neutrinos Without The Annoying Wait



Mark Vagins

IPMU, University of Tokyo

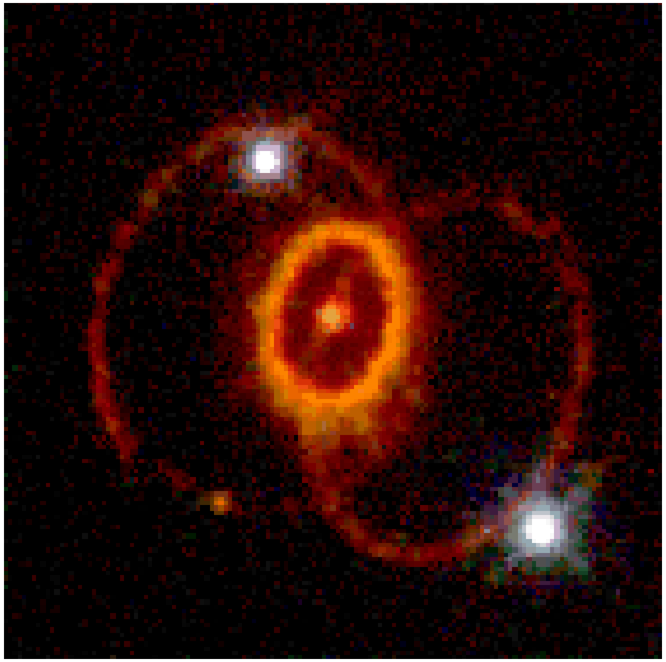
JIGSAW10, Mumbai, India

February 25, 2010

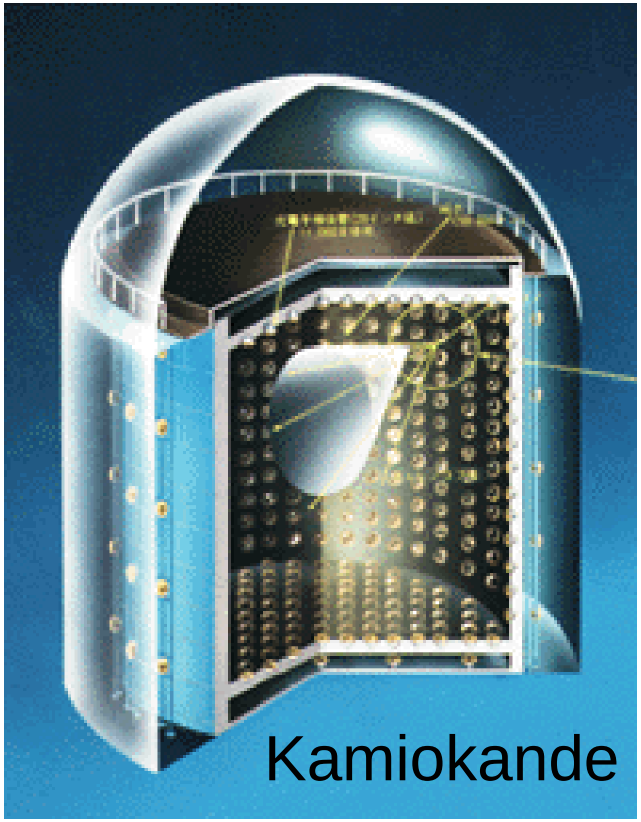
A long time ago, in a (neighbor) galaxy far, far away…

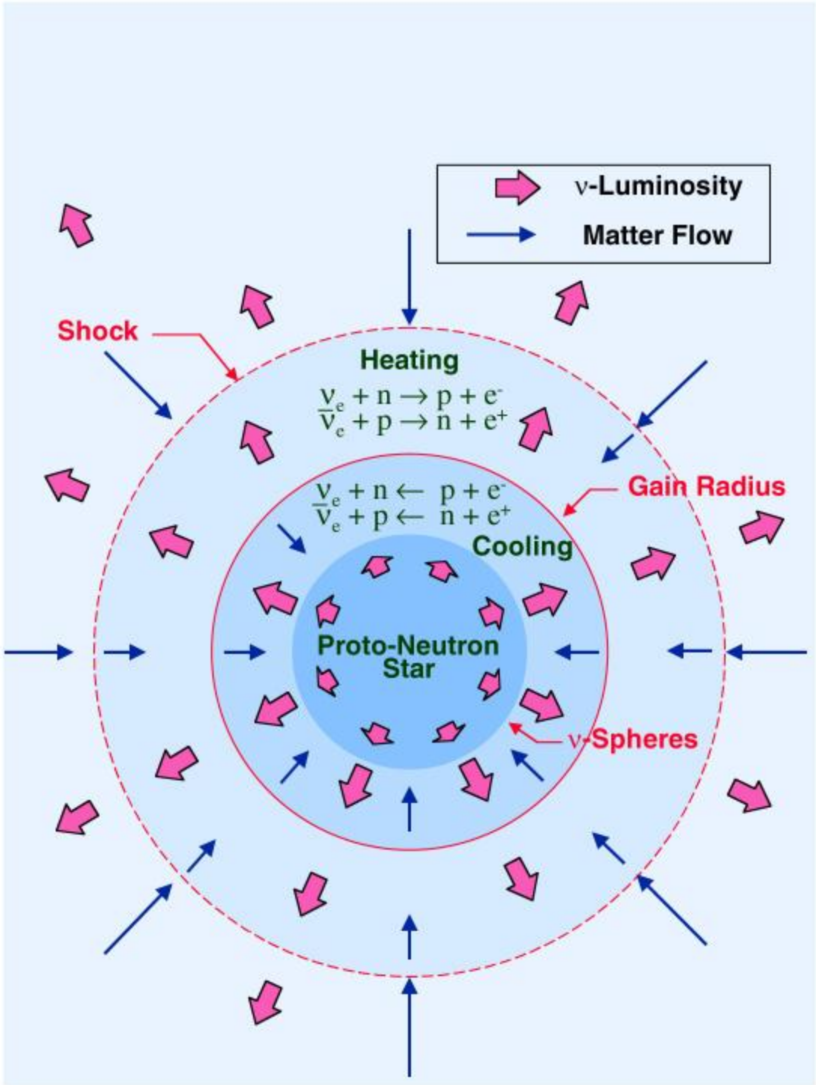
A long time ago, in a (neighbor) galaxy far, far away…

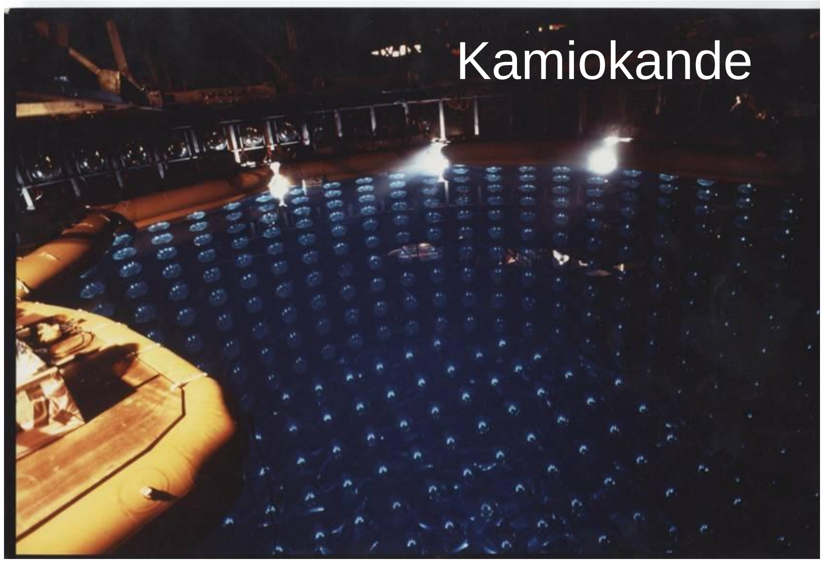
Sanduleak -69^{o} 202 was gone, but not forgotten.

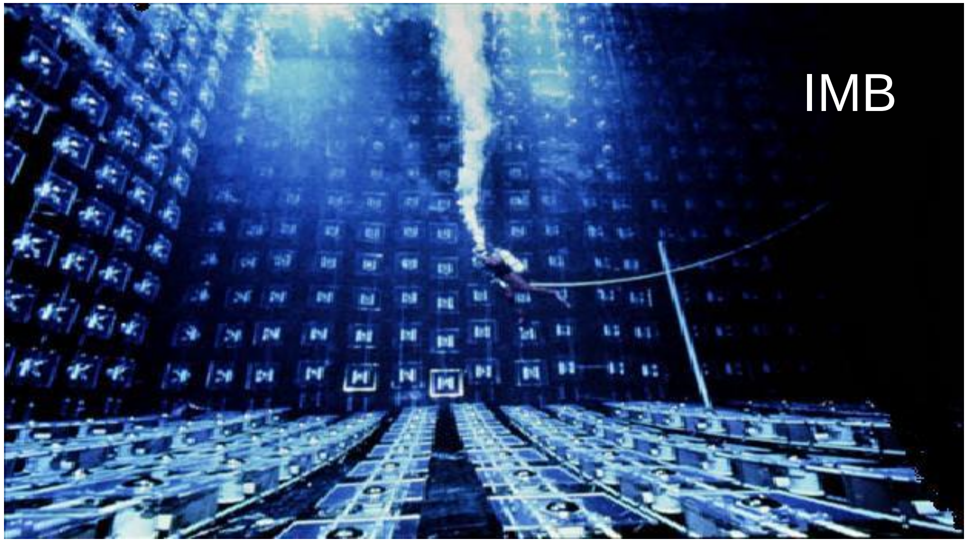


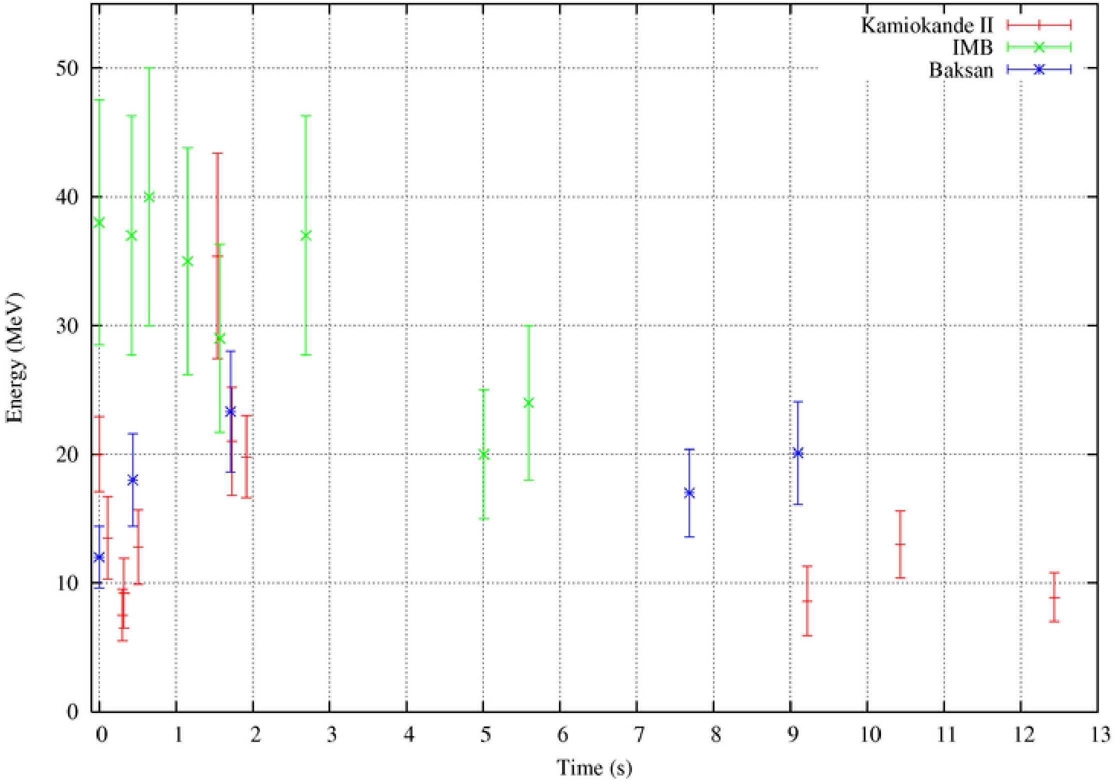
A core-collapse supernova releases >98% of its energy as neutrinos.
In 1987, we saw the evidence firsthand...






Kamiokande


IMB


Kamiokande II
IMB
Baksan
Energy (MeV)
Time (s)
0
10
20
30
40
50
0
1
2
3
4
5
6
7
8
9
10
11
12
13


Baksan

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

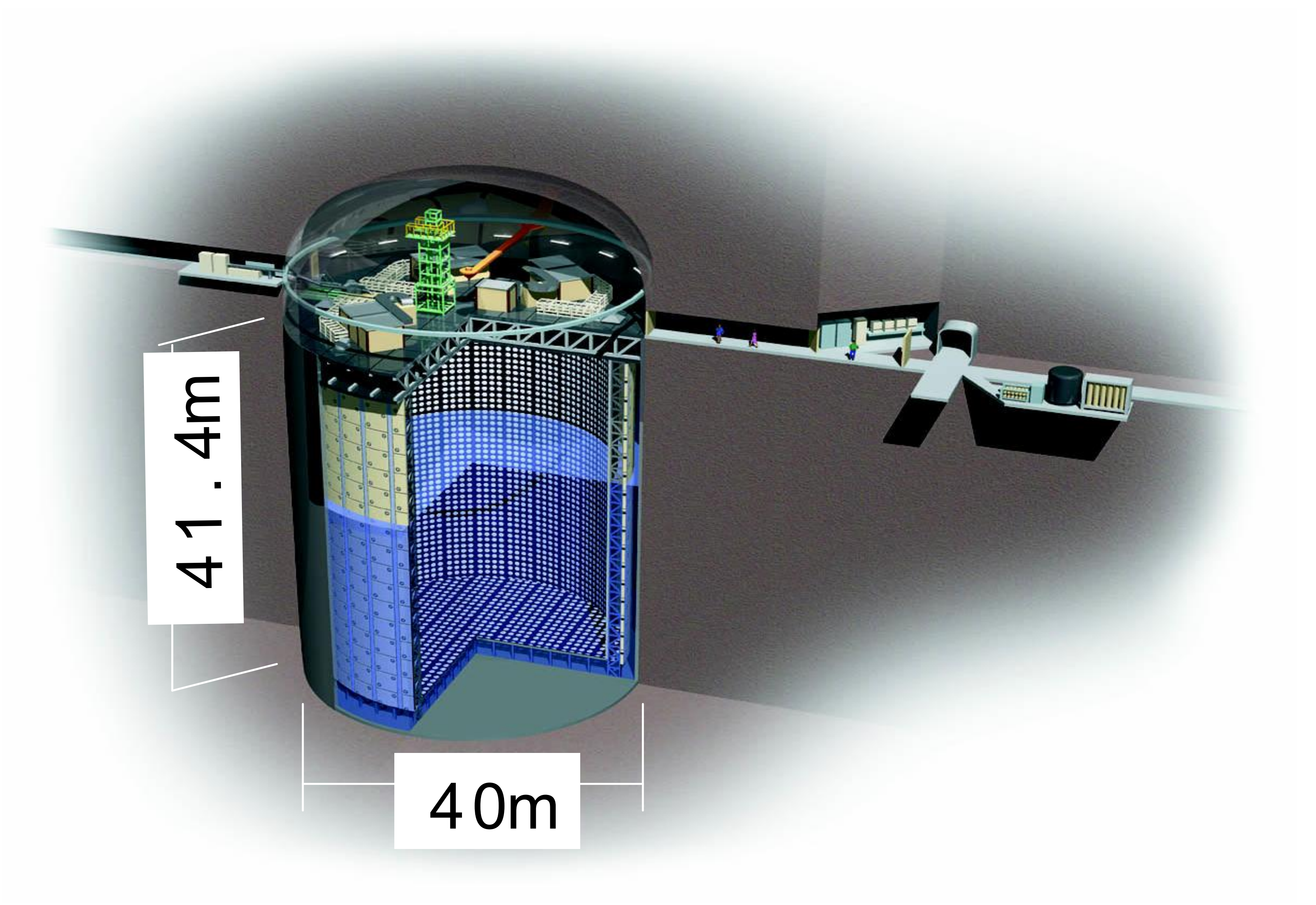
….for the last <u>twenty-three years!</u>

Now, most of the physicists and astronomers in this crowd probably already feel that 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.

Can we expect to see more supernova neutrinos sometime soon?

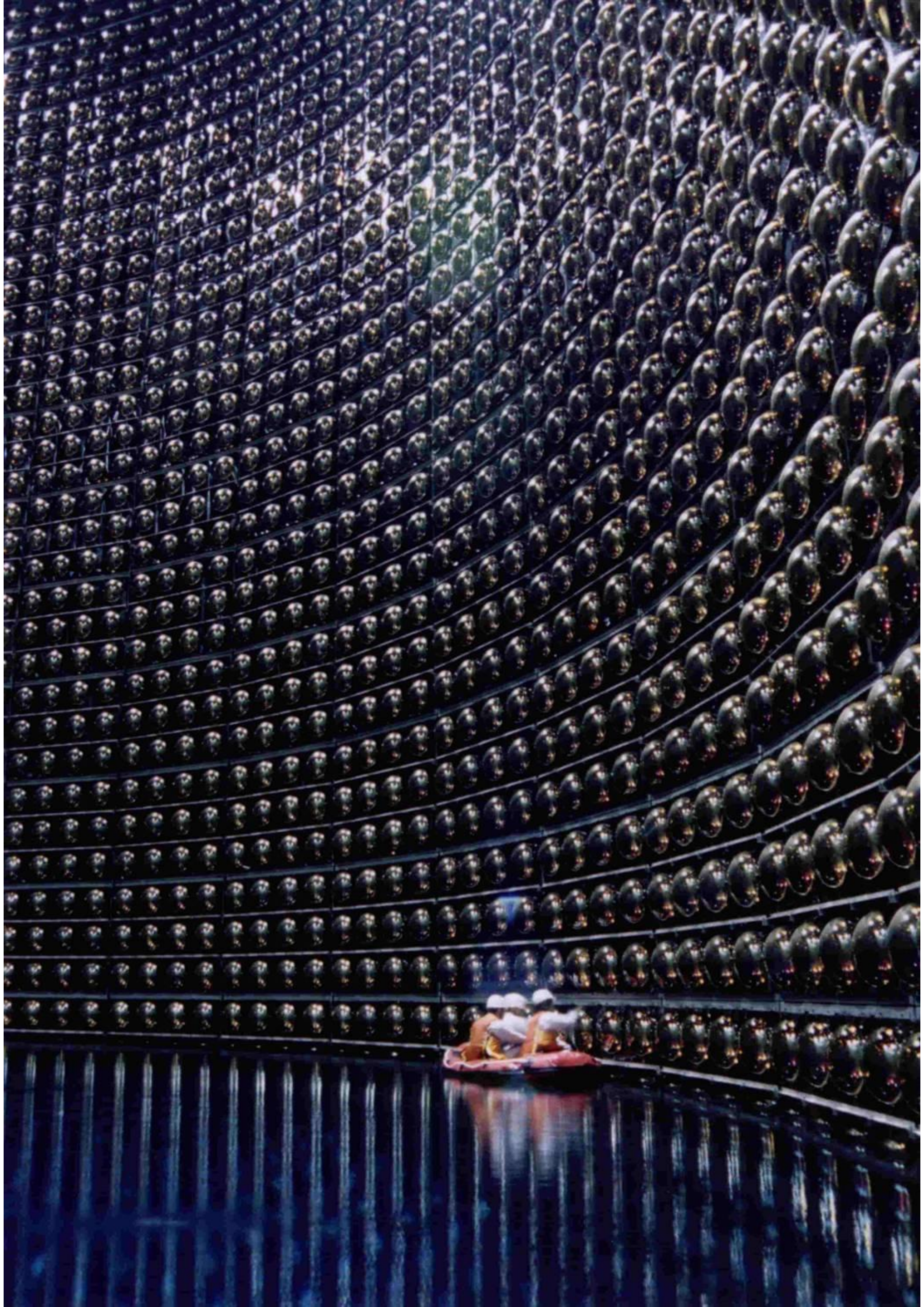


The Super-Kamiokande neutrino detector, in Mozumi, Japan.

50,000 tons of ultra-pure H_2O

13,000 light detectors

One kilometer underground



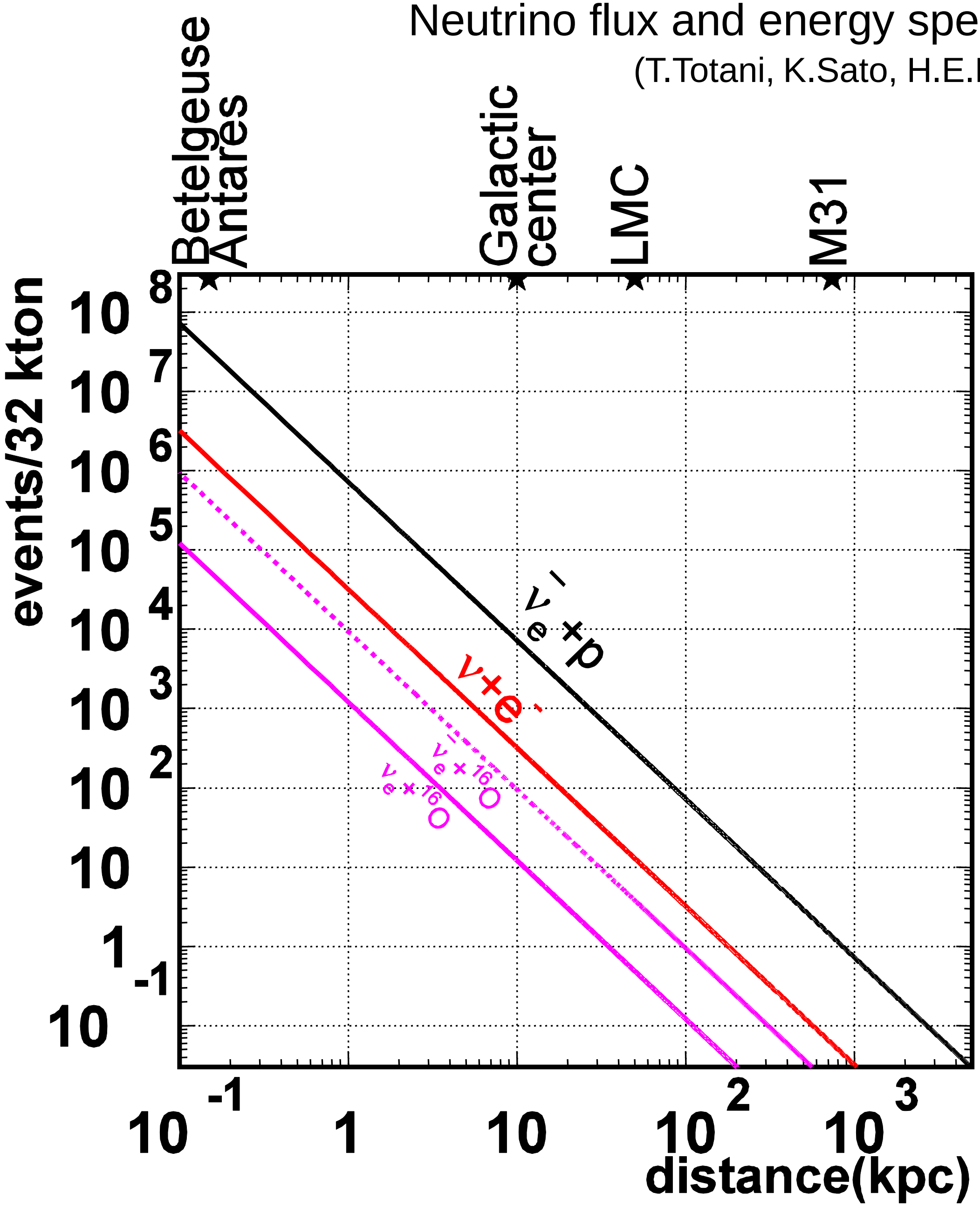
Observes solar neutrinos from the Sun and atmospheric neutrinos from cosmic rays.

This is by far the world's most capable supernova neutrino detector.

Expected number of events from a supernova at SK

Neutrino flux and energy spectrum from Livermore simulation

(T.Totani, K.Sato, H.E.Dalhed and J.R.Wilson, ApJ.496,216(1998))



5MeV threshold

~7,300 $\overline{\nu}_e$+p events

~300 ν+e events

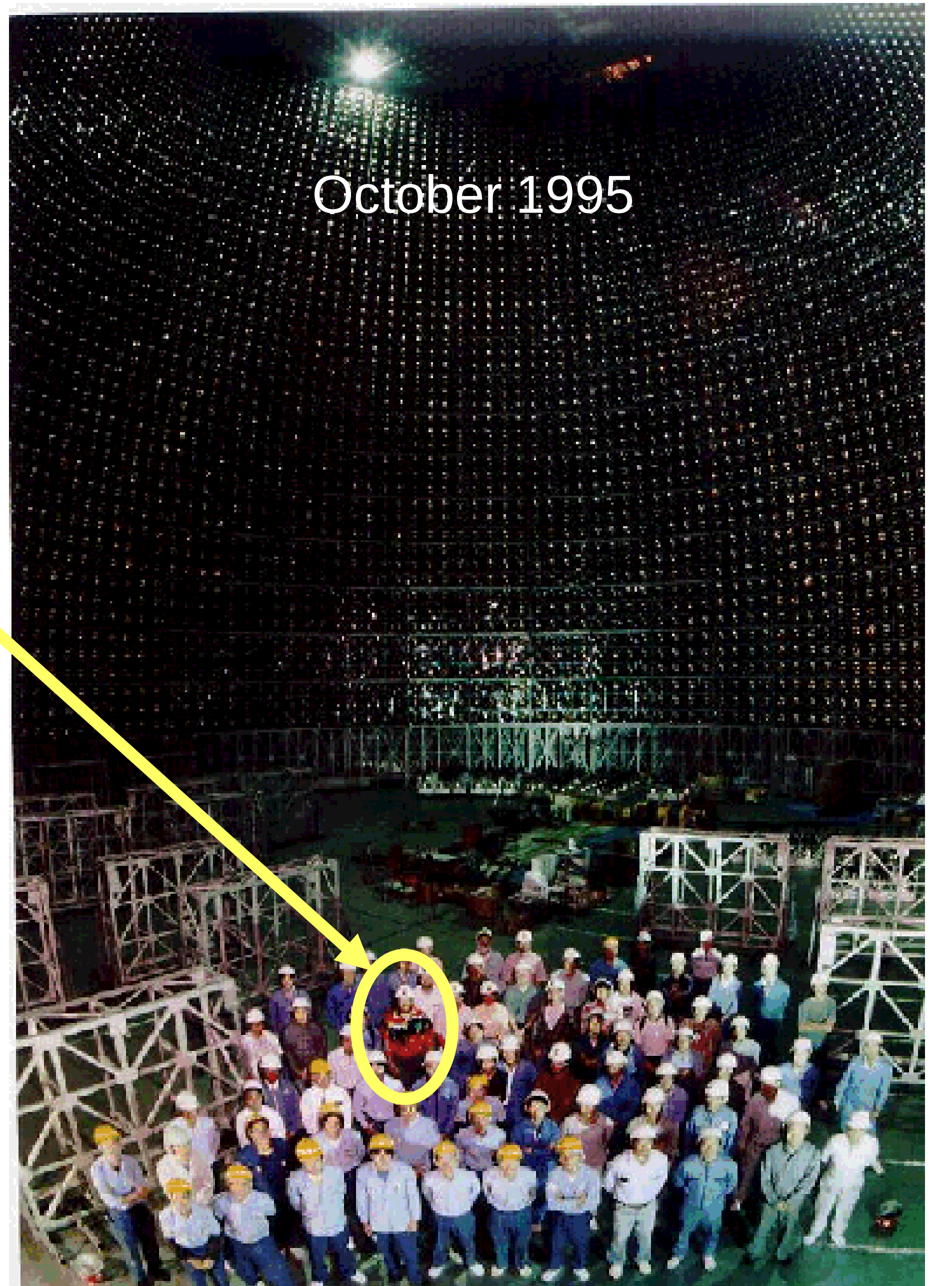
~100 $\overset{(-)}{\nu}_e + {}^{16}O$ events

for 10 kpc supernova

[M. Nakahata]

I've been a part of
Super-K (and wearing
brightly-colored shirts)
from its very early days…

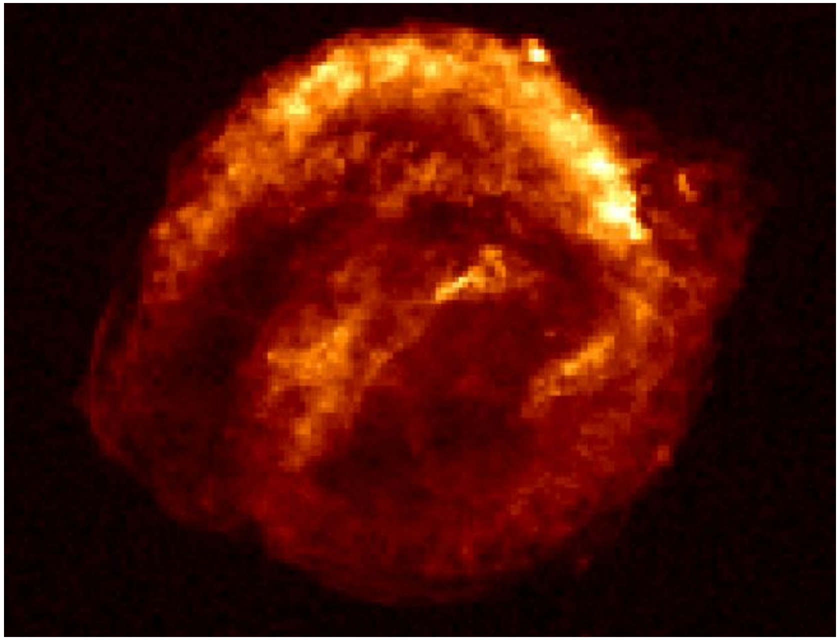
January 1996

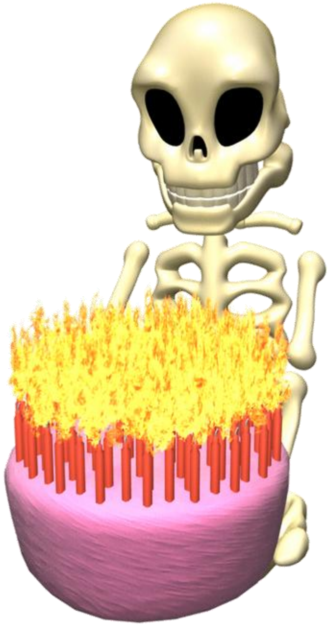


Super-K has now been taking data for over a decade.
But what does the future hold?

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."





Unfortunately, it has been a couple of decades since SN1987A, and 405 years and 139 days since a supernova was last definitely observed within our own galaxy!

Of course, no neutrinos were recorded that mid-October day in 1604…

but it was probably a type Ia, anyway!

So, how could we see some supernova neutrinos without having to wait too long?

With this goal in mind, John Beacom and I wrote the original GADZOOKS!

(Gadolinium Antineutrino Detector Zealously Outperforming Old Kamiokande, Super!)

paper in late 2003. It was published the following year:

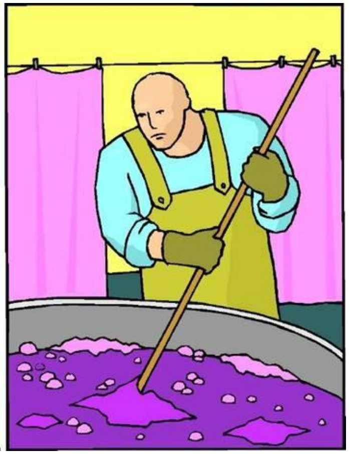
[Beacom and Vagins, *Phys. Rev. Lett.*, **93**:171101, 2004]

How can we identify neutrons produced by the inverse beta process (from supernovae, reactors, etc.) in really big water Cherenkov detectors?

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

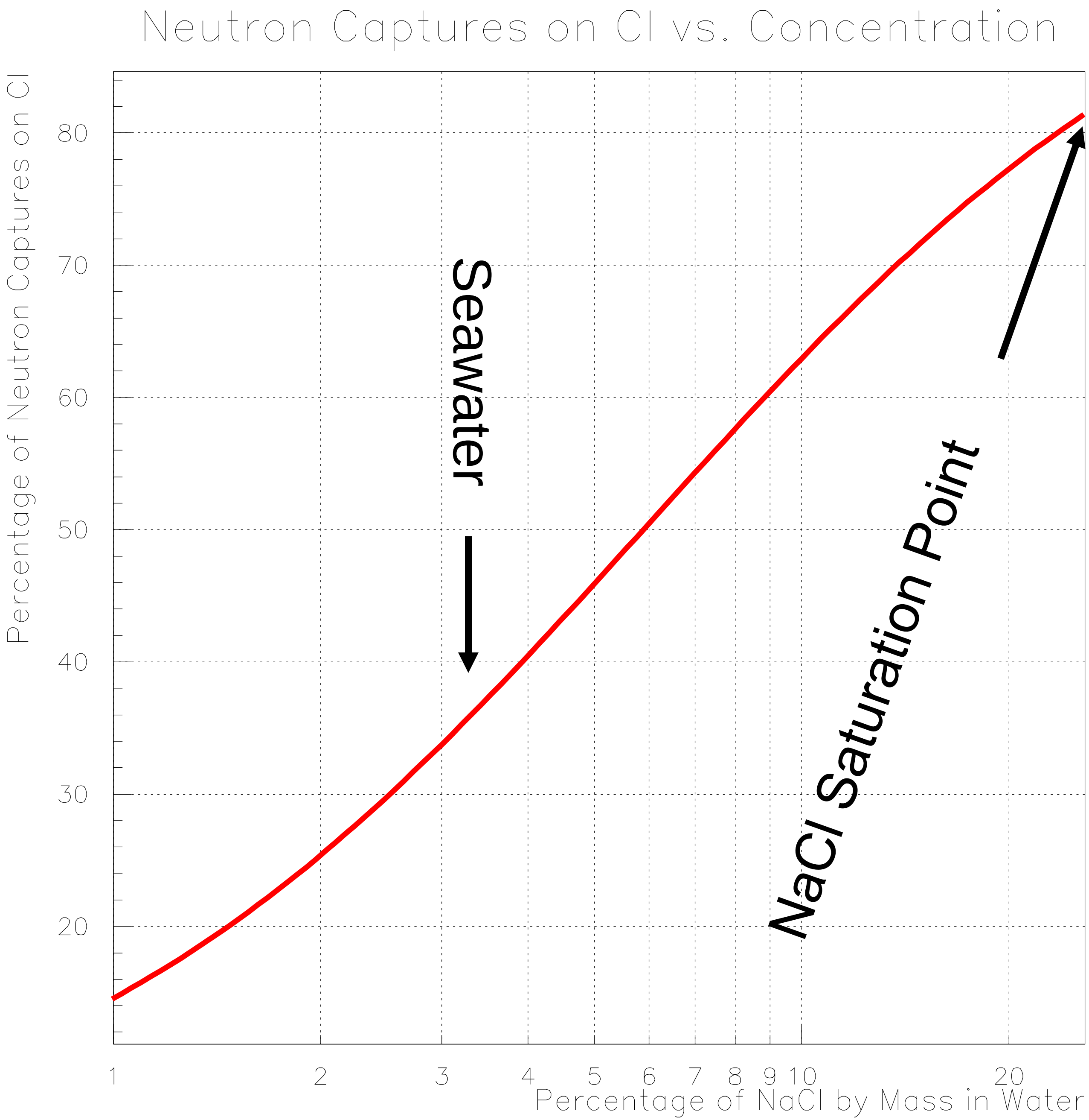
Beyond the kiloton scale, you can forget about using liquid scintillator, ^{3}He counters, or heavy water!

Without a doubt, at the 50 kton+ scale the only way to go is a solute mixed into the light water...



One thing's for sure: plain old NaCl isn't going to work!

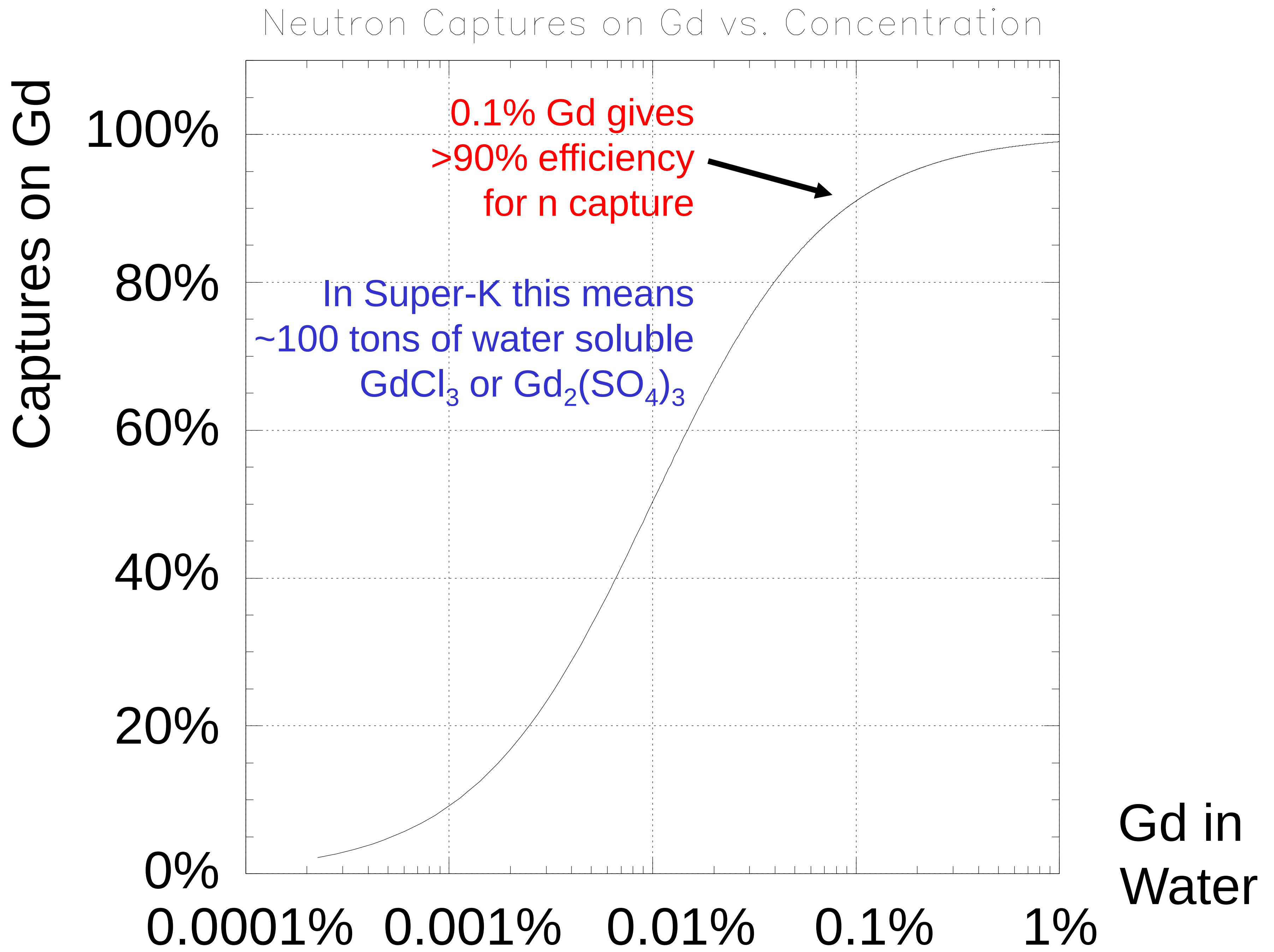
To get 50% neutron capture on Cl
(the other 50% will be on the hydrogen
in the water and essentially invisible)
you'll need to use 6% NaCl by mass:
→ *3 <u>kilotons</u> of salt for a 50 kton detector!* ←



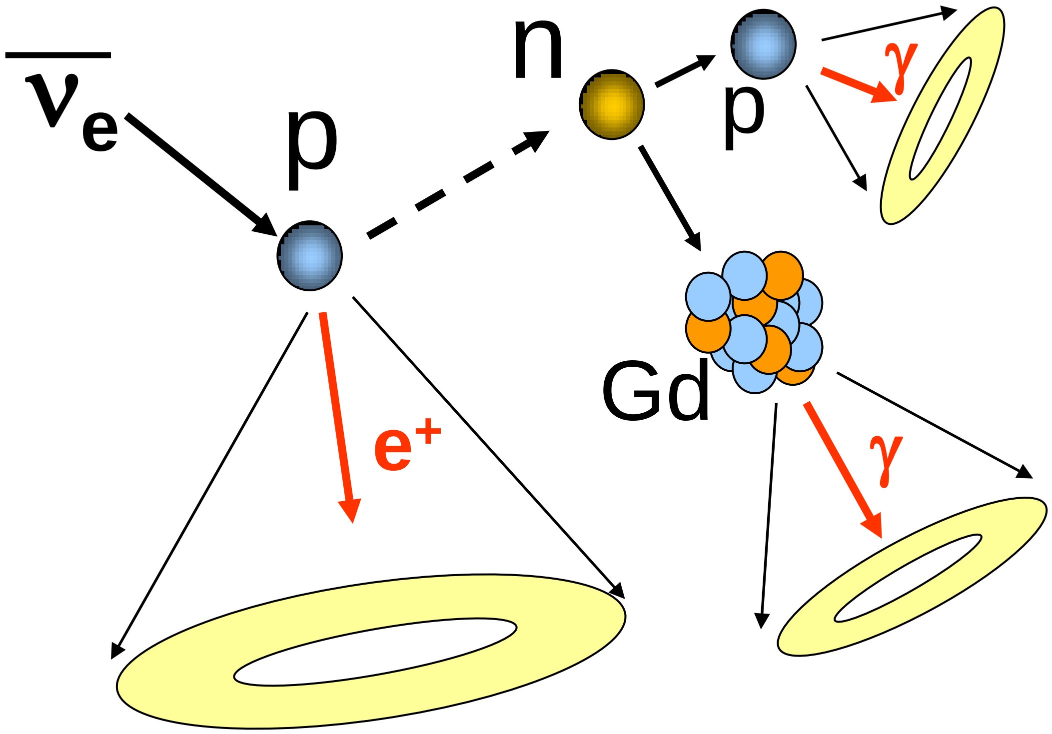
Neutron Captures on Cl vs. Concentration
Percentage of Neutron Captures on Cl
80
70
60
50
40
30
20
Seawater
NaCl Saturation Point
1
2
3
4
5
6
7
8
9
10
20
Percentage of NaCl by Mass in Water

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

- $GdCl_3$ and $Gd_2(SO_4)_3$, unlike metallic Gd, are highly water soluble
- Neutron capture on Gd emits a 8.0 MeV γ cascade
- 100 tons of $GdCl_3$ or $Gd_2(SO_4)_3$ in SK (0.2% by mass) would yield >90% neutron captures on Gd
- Plus, they are easy to handle and store.


Neutron Captures on Gd vs. Concentration
Captures on Gd
100%
80%
60%
40%
20%
0%
0.0001%
0.001%
0.01%
0.1%
1%
Gd in Water
0.1% Gd gives
>90% efficiency
for n capture
In Super-K this means
~100 tons of water soluble
$GdCl_3$ or $Gd_2(SO_4)_3$

Neutron tagging in Gd-enriched Super-Kamiokande



Possibility 1: 10% or less

$n+p \rightarrow d + \gamma$

2.2MeV γ-ray

Possibility 2: 90% or more

$n+Gd \rightarrow \sim 8MeV\ \gamma$

$\Delta T = \sim 30\ \mu sec$

Positron and gamma ray vertices are within ~50cm.

$\bar{\nu}_e$ can be identified by delayed coincidence.

[reaction schematic by M. Nakahata]

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 2010: $5/kg –> $500,000

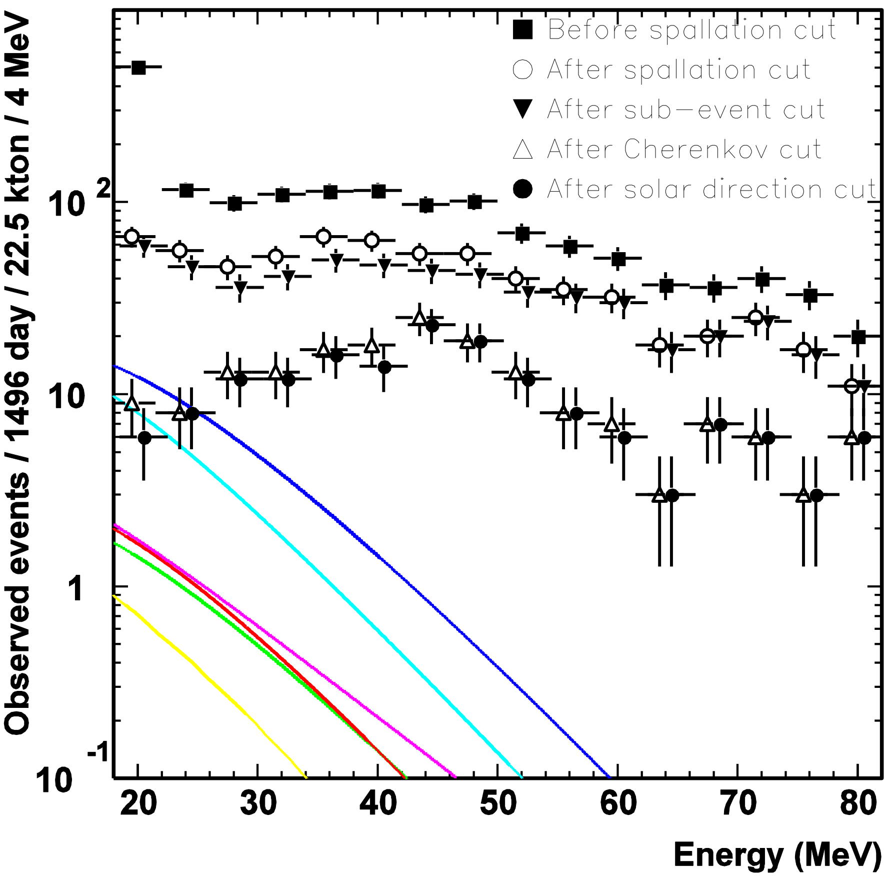
Diffuse Supernova Neutrino Background [DSNB] Signal

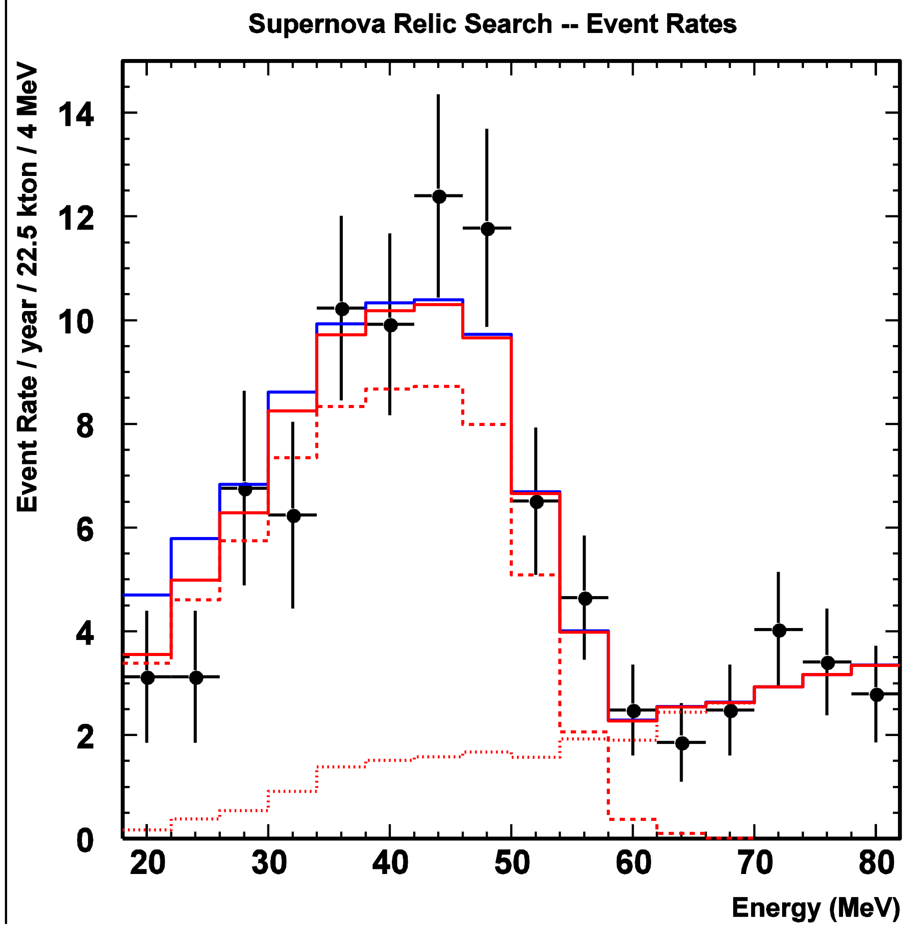
On average there is <u>one supernova explosion each second</u> somewhere in the universe.These produce a diffuse supernova neutrino background [DSNB], also known as the “relic” supernova neutrinos.

After traveling an average distance of

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

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)].

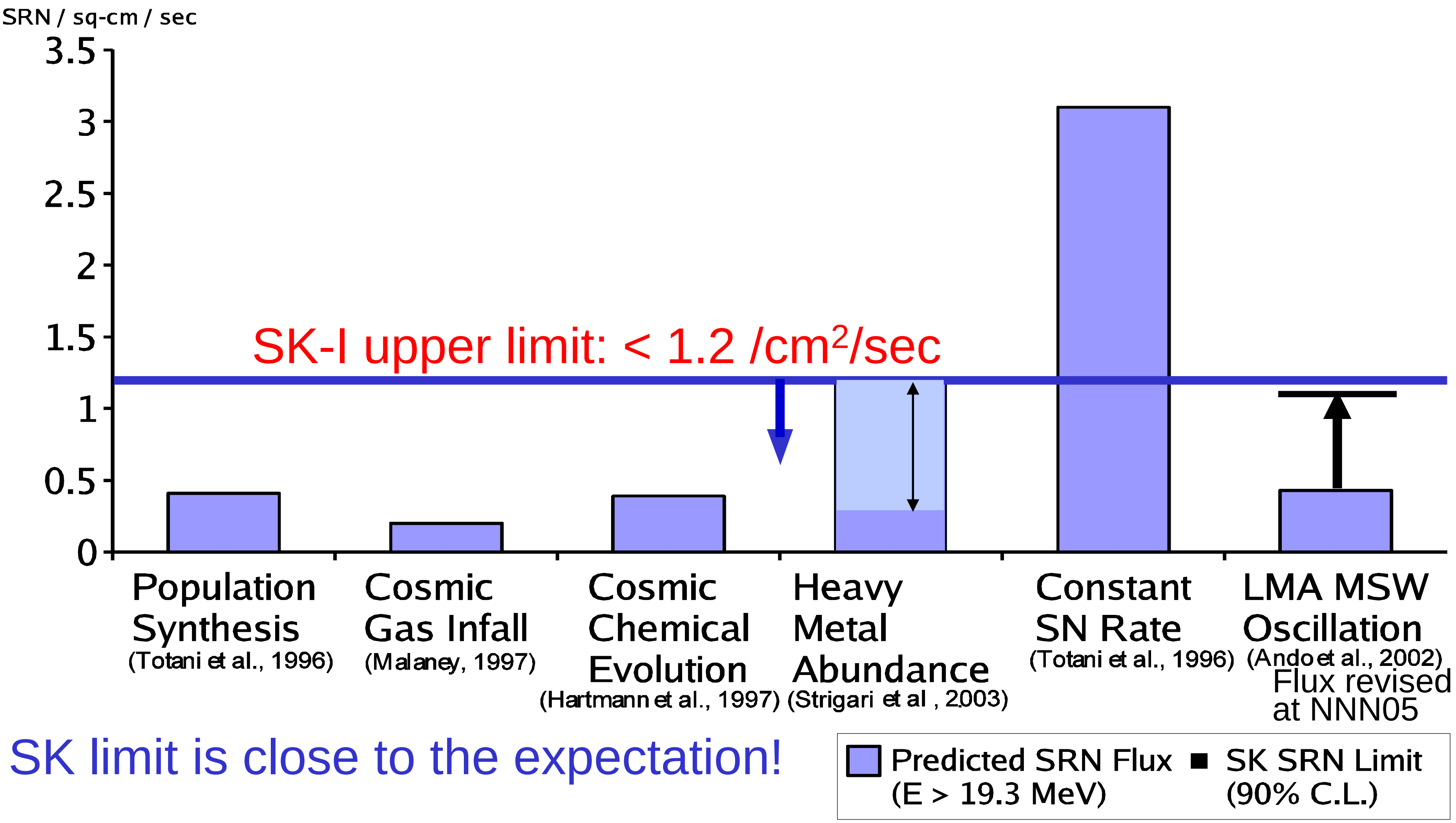




Unfortunately, the search was strongly limited by backgrounds, and no clear event excess was seen.

Flux limit and theoretical prediction

E_e>18 MeV (E_ν>19.3 MeV)



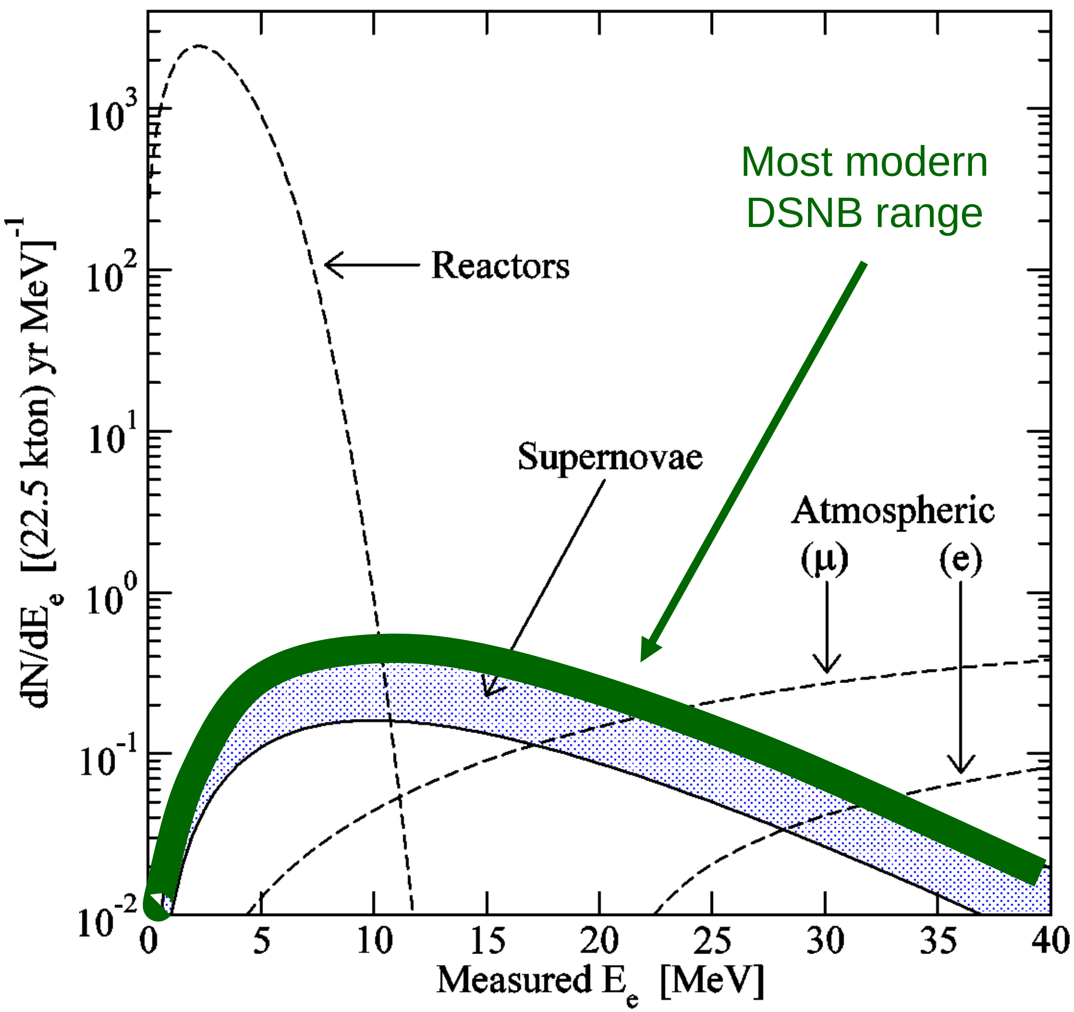
SK limit is close to the expectation!

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

Note that 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>

Here's what the coincident signals in Super-K with $GdCl_3$ or $Gd_2(SO_4)_3$ will look like (energy resolution is applied):



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

spatial and temporal separation between prompt e^+ Cherenkov light and delayed Gd neutron capture gamma cascade:

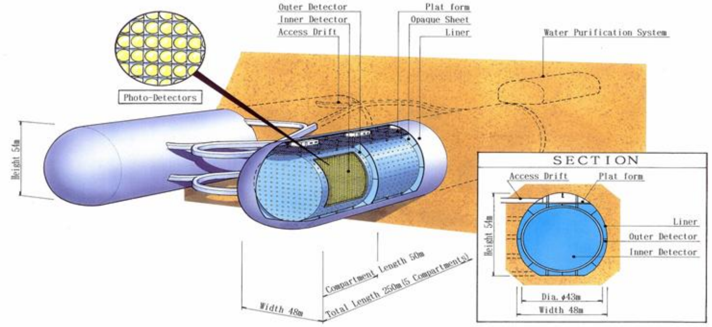
λ=~4cm, τ=~30μs

→ A few clean events/yr in Super-K with Gd

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!

Hyper-K



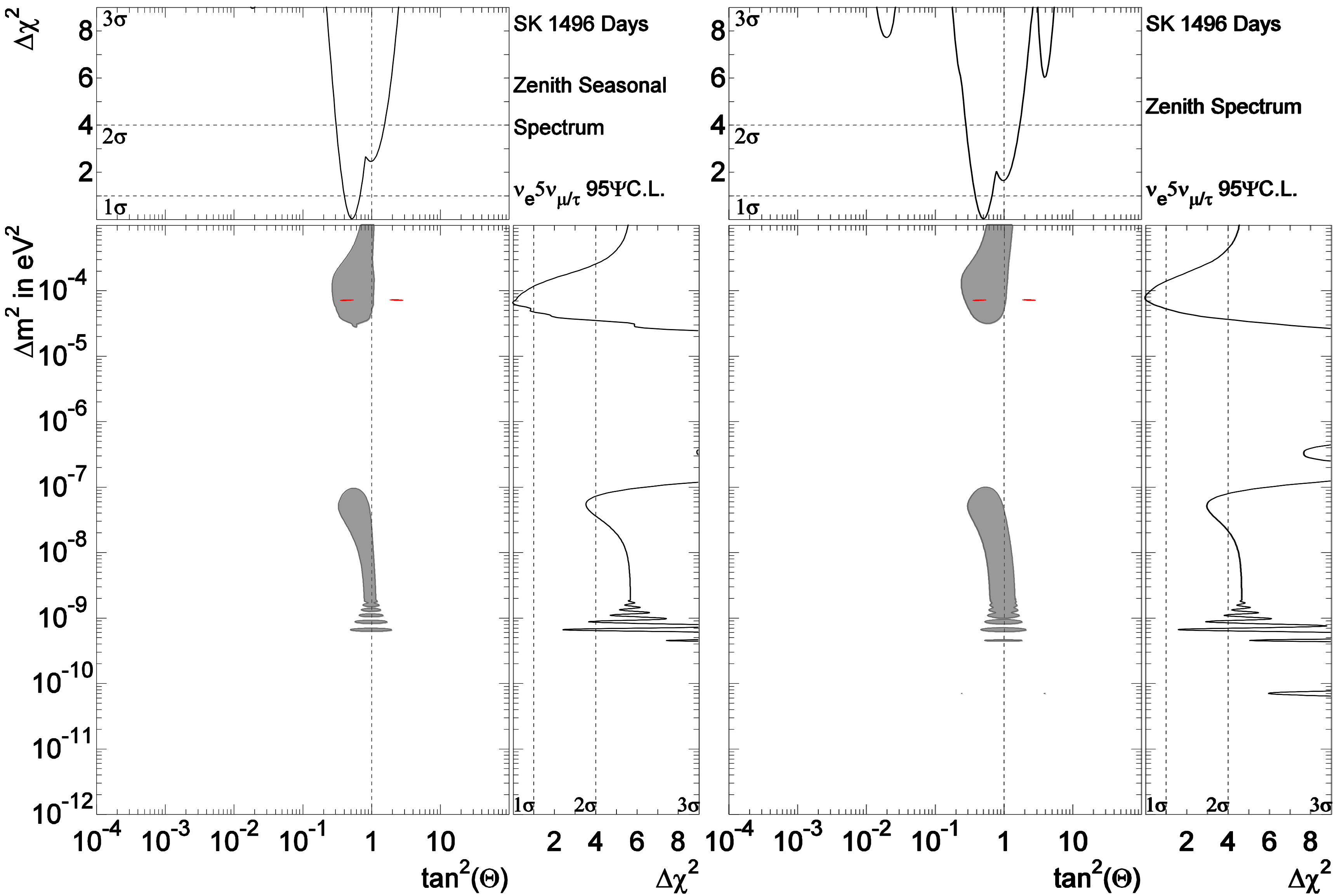
N.B.: This is the only neutron detection technique which is extensible to Mton scales, and at minimal expense, too: ~1% of the detector construction costs

Reactor Antineutrino Signal and the Solar Neutrino Parameters

How good a job can Super-K do - by itself - on the solar neutrino parameters?

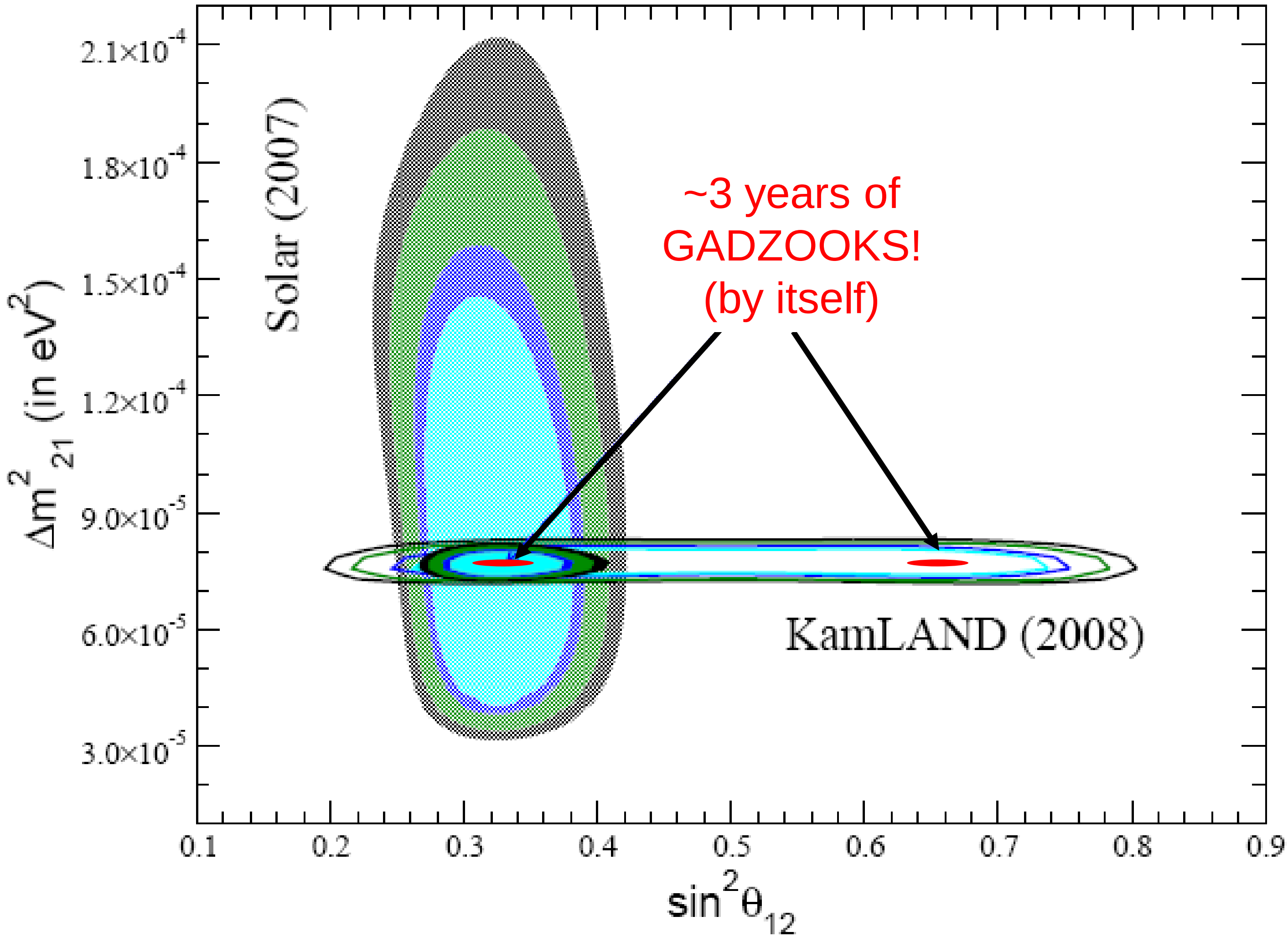
Without gadolinium

With gadolinium



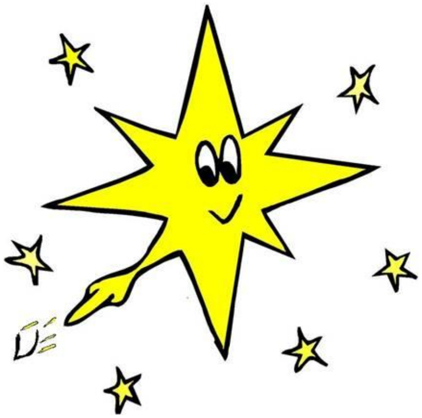
[plots by Michael Smy, red reactor antineutrino contours by Choubey & Petcov (confirmed by Kirk Bays)]

How does this compare with the rest of the world's data?



[Global/KamLAND plot from A. Bandyopadhyay, S. Choubey, S. Goswami, S.T. Petcov, and D.P. Roy; arXiv:0804.4857]

In a nutshell: adding 100 tons of soluble Gd to Super-K would provide at least two brand-new signals:



1) Discovery of the diffuse supernova neutrino background [DSNB], also known as the “relic” supernova neutrinos (up to 5 events per year)

2) Precision measurements of the neutrinos from all of Japan’s power reactors (a few thousand events per year) Will improve world average precision of Δm^2_{12}

In addition to our two guaranteed new signals, it is likely that adding gadolinium to SK will provide a variety of other interesting possibilities:

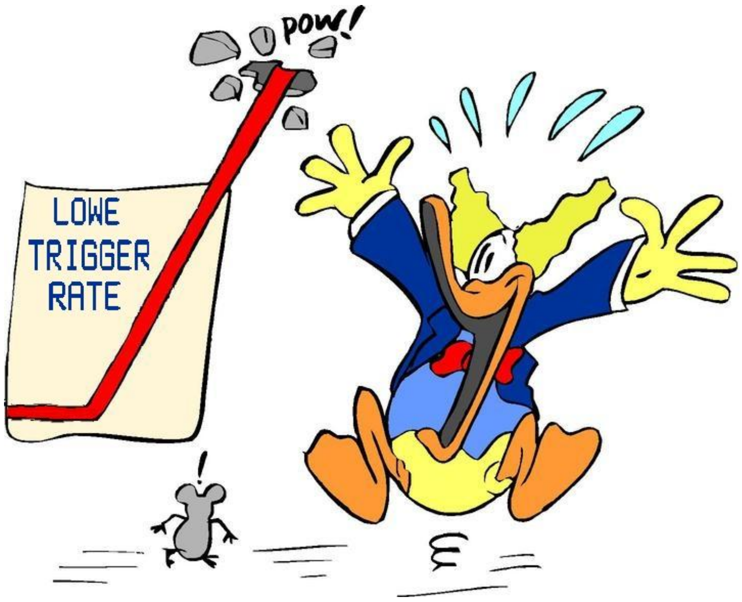
- Sensitivity to very late-time black hole formation
- Full de-convolution of a galactic supernova's ν signals
- Early warning of an approaching SN ν burst
- (Free) proton decay background reduction
- New long-baseline flux normalization for T2K
- Matter- vs. antimatter-enhanced atmospheric ν samples(?)

All of this could work even better in an much larger detector.

Indeed, such a massive new project will *need* to have some new physics topics to study!

Supernova Early Warning Signal

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

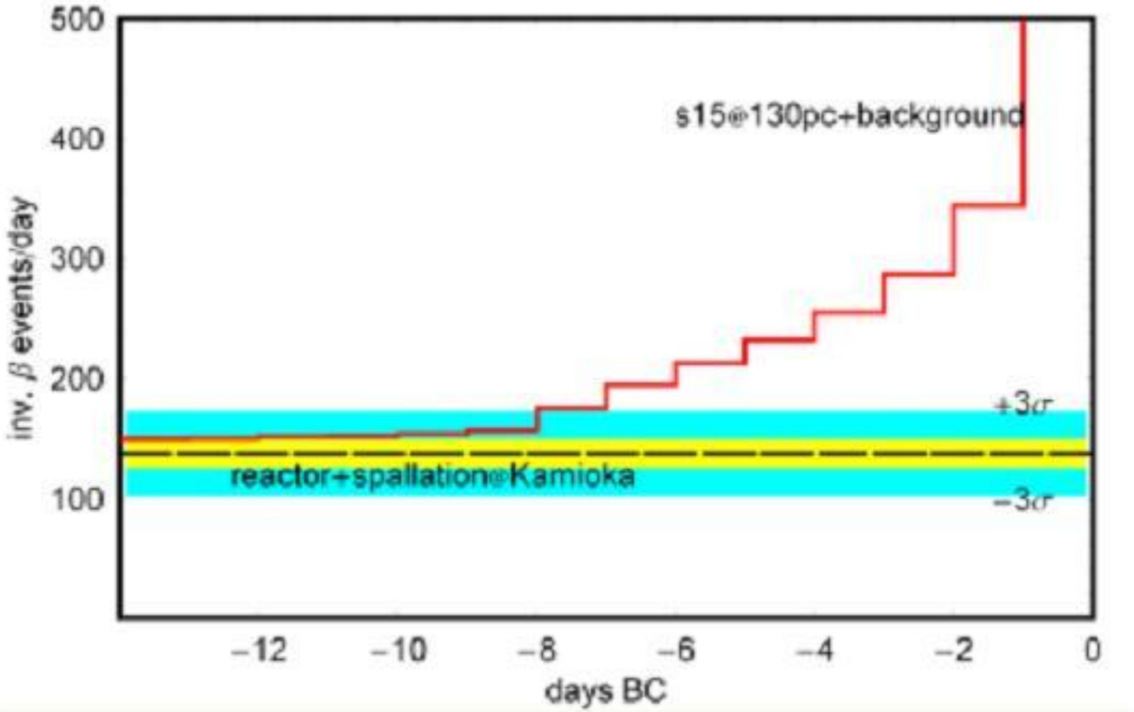


$e^+ + e^- \rightarrow \bar{\nu}_e + \nu_e$ (just above inverse beta threshold)

$\bar{\nu}_e + p \rightarrow e^+ + n$ (e^+ non-relativistic)

[Odrzywodek, Misiaszek, and Kutschera, *Astropart.Phys.* 21:303-313, 2004]

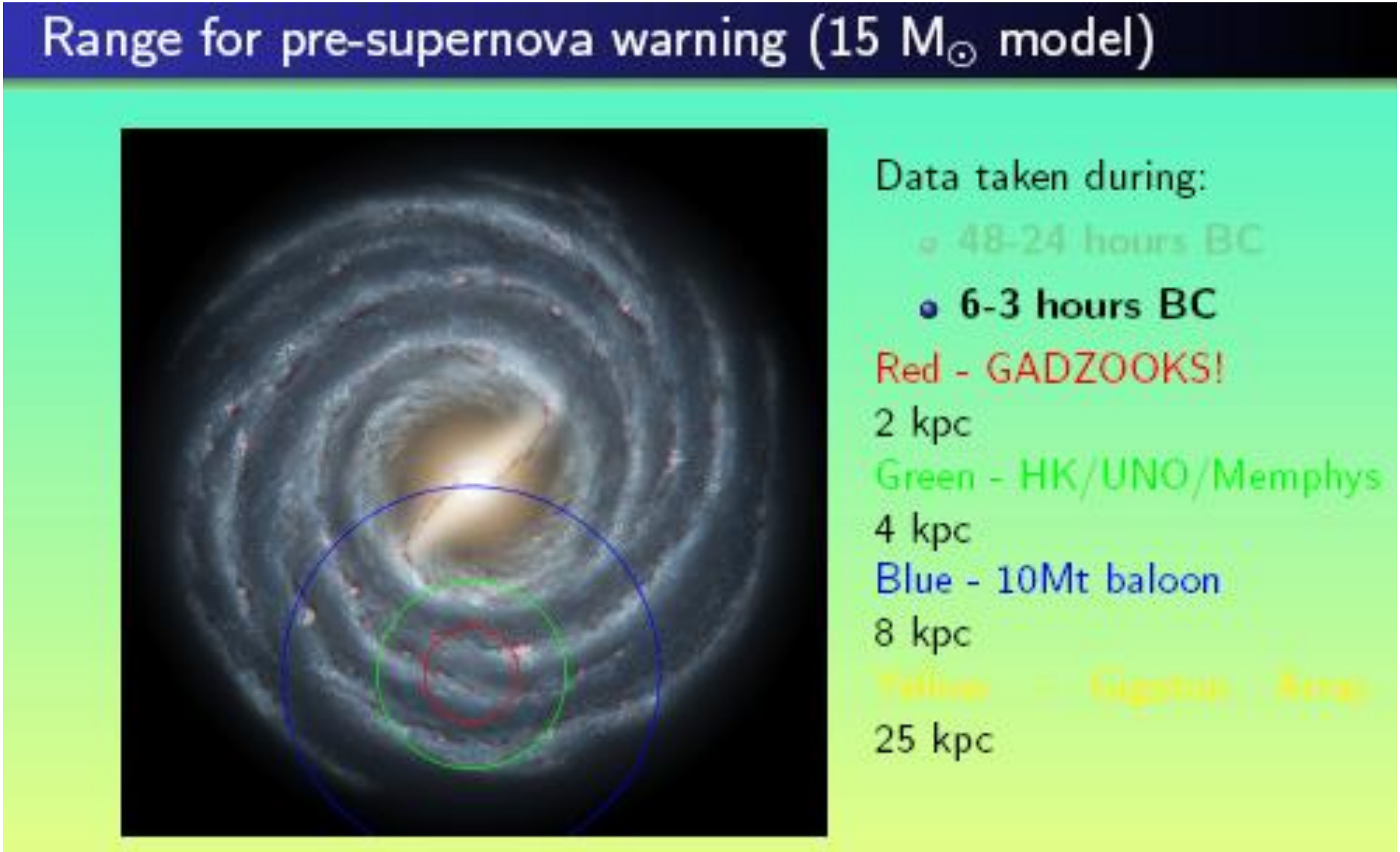
(Nearby) Galactic Supernova Early Warning



The latest calculations of Si burning now say that Gd in SK could provide early warning of a supernova out to two kiloparsecs. In the case of nearby Betelgeuse (shown above) we would observe a 5-σ excursion in our SLE singles rate <u>one week</u> before explosion. It would continue to increase monotonically until the burst – impossible to miss!

[plot by A. Odrzywolek, "Twenty Years After SN1987A" meeting, Feb. 2007]

Here’s how very large water Cherenkov detectors enhanced with dissolved Gd could do…



[plot by A. Odrzywolek, “Twenty Years After SN1987A” meeting, Feb. 2007]

GADZOOKS! R&D

Okay, so the physics sounds good.
But can we make it work?

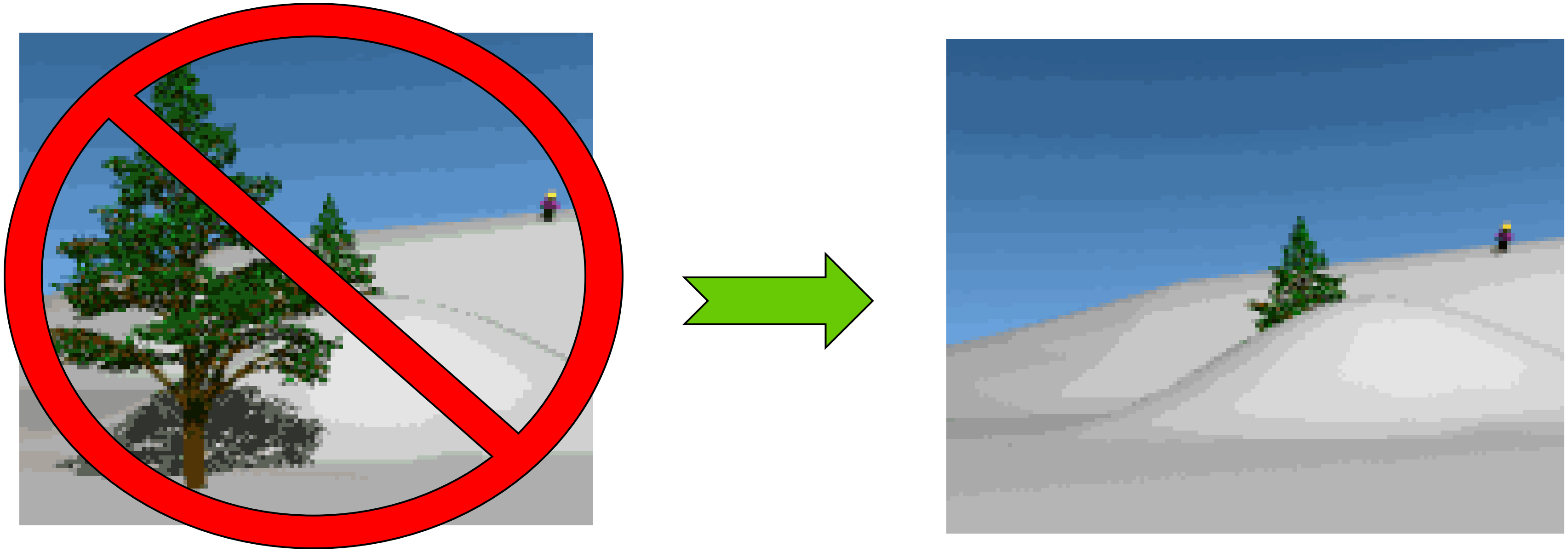
The total American R&D funding for this gadolinium-in-SK project has reached $400,000, with additional support coming from Japan.

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

[Snowbird photo by A. Kusenko]

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 are needed.

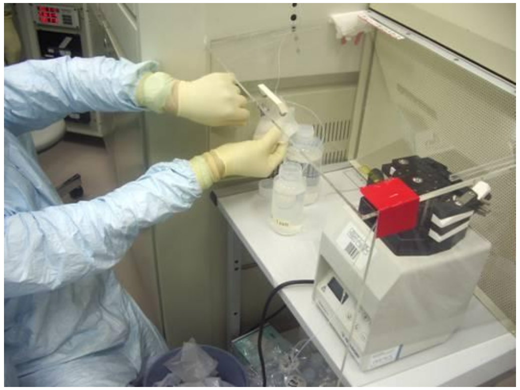


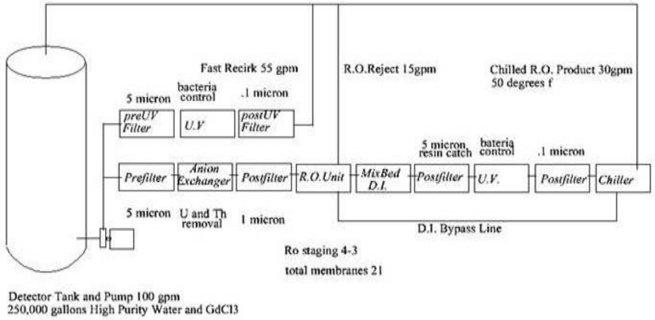
- What does gadolinium do the Super-K tank materials?
- Will the resulting water transparency be acceptable?
- Any strange Gd chemistry we need to know about?
- How will we filter the SK water but retain dissolved Gd?

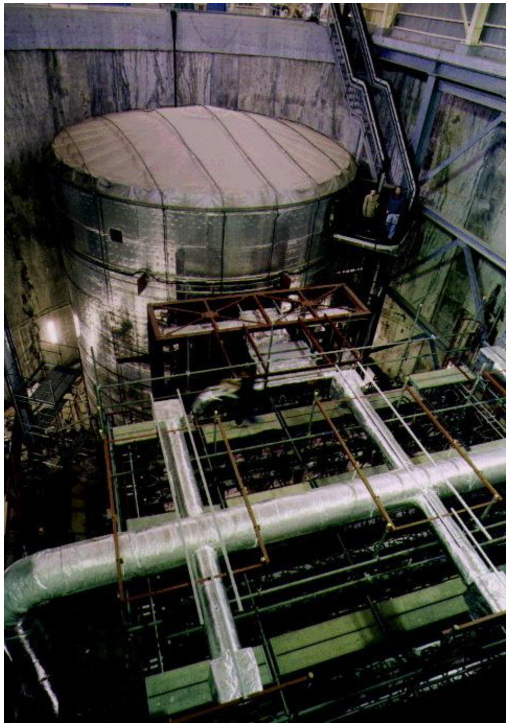
As a matter of fact, I very rapidly made two discoveries regarding $GdCl_3$ while carrying a sample from Los Angeles to Tokyo:

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

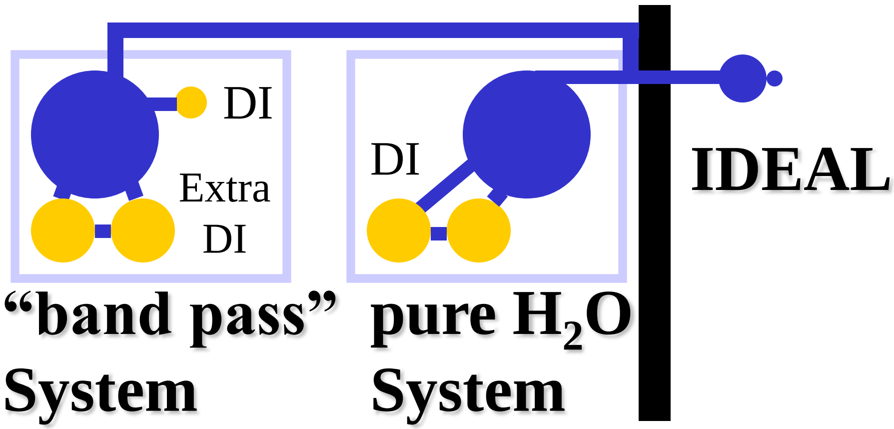
Over the last six years there have been a large number of Gd-related R&D studies carried out in the US and Japan:

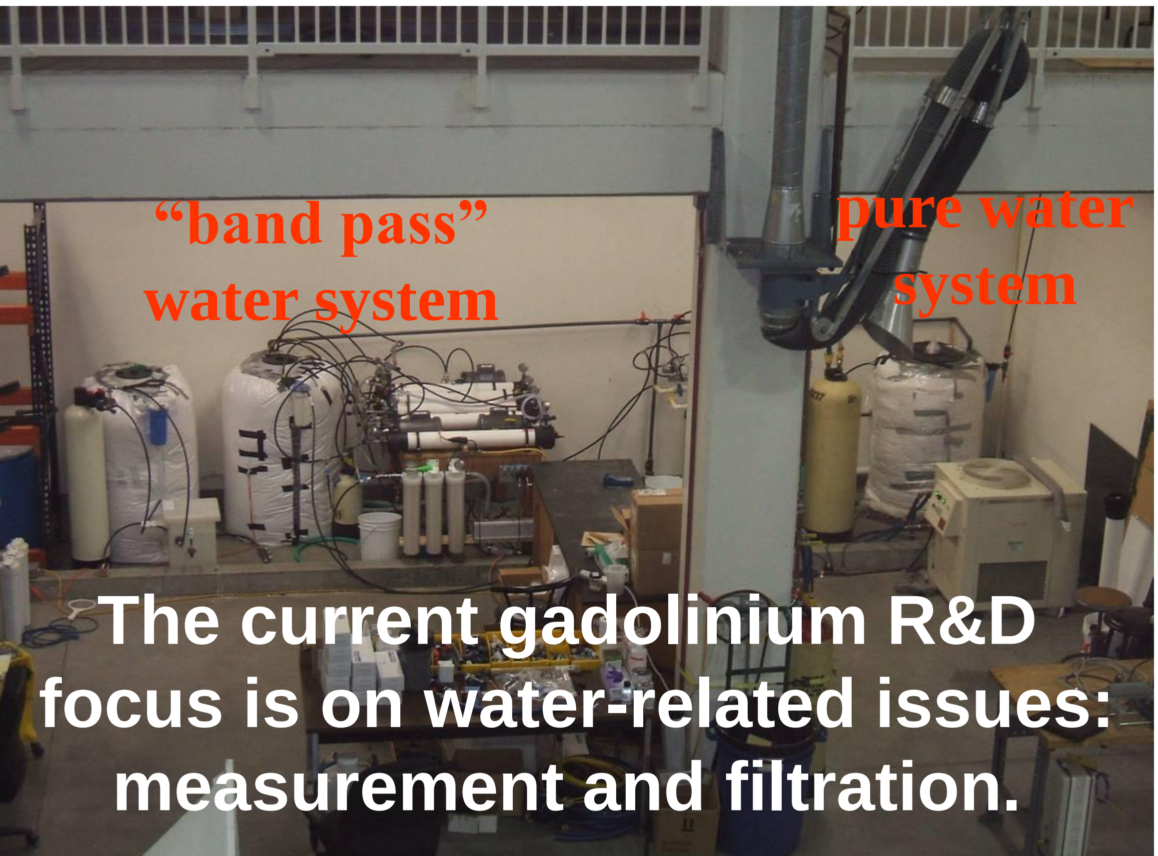


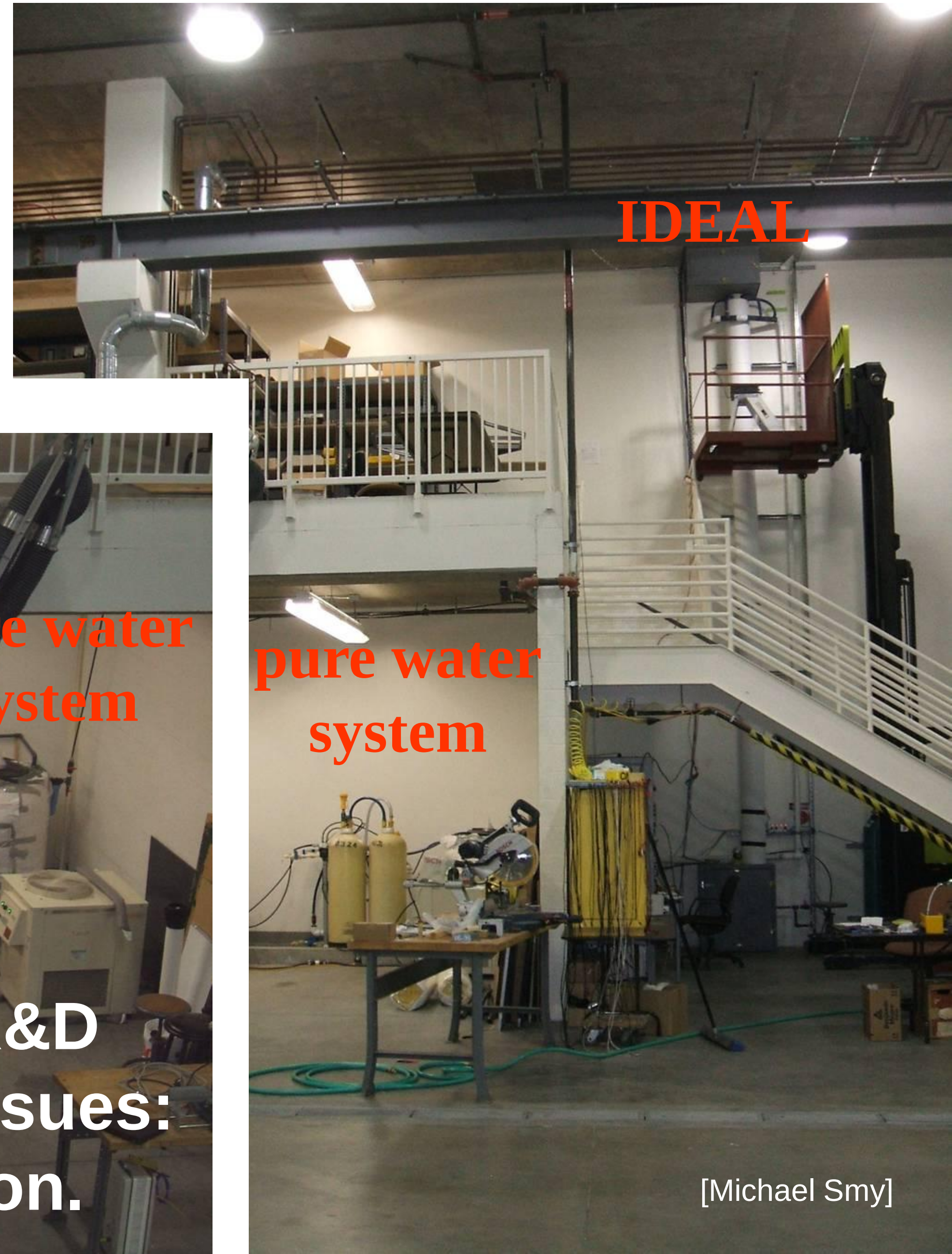




UCI High Bay Setup







The current gadolinium R&D focus is on water-related issues: measurement and filtration.

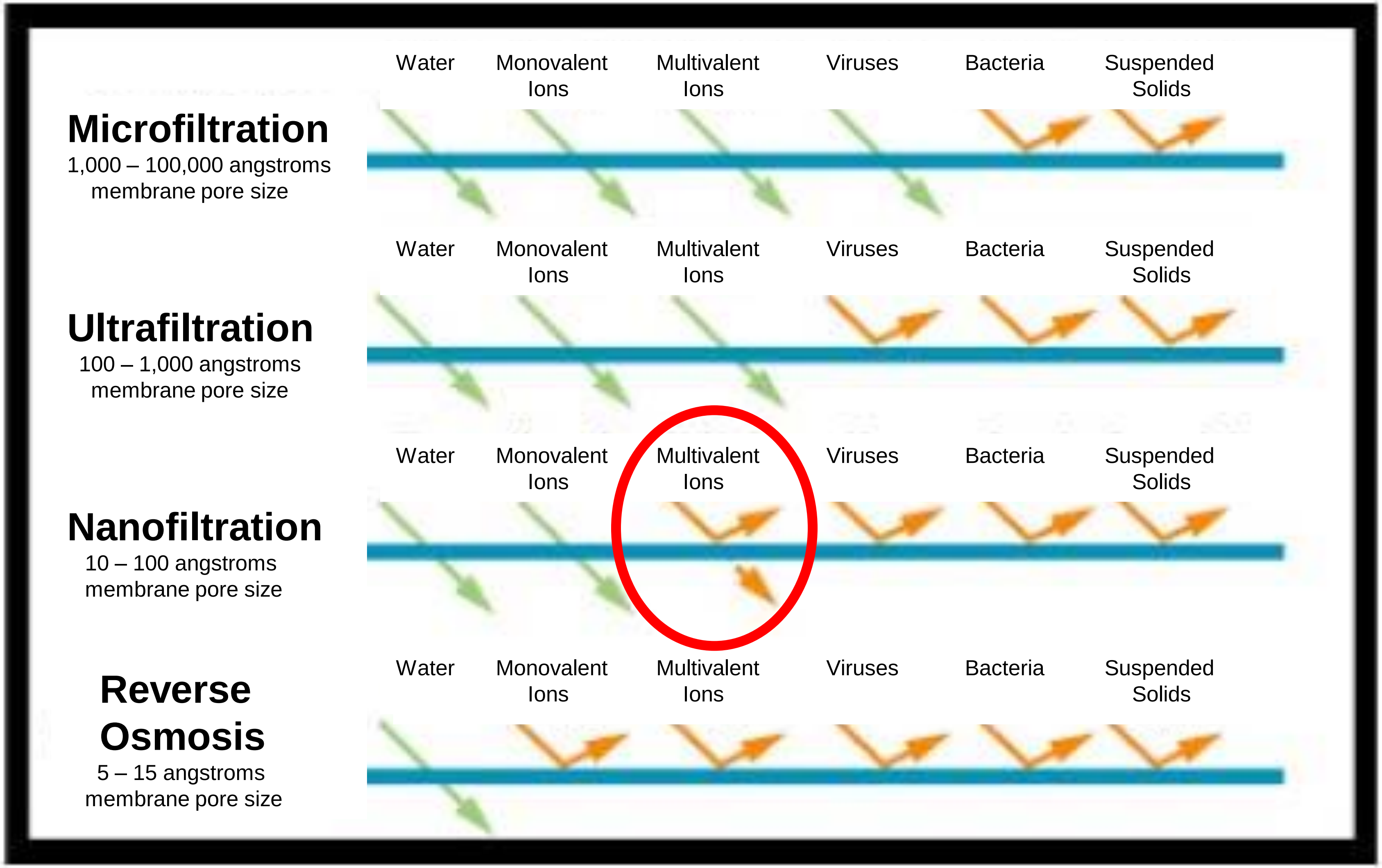
[Michael Smy]

To select the best gadolinium compound we will have to balance optical and mechanical effects:

Name	Formula	Pros	Cons
Gadolinium Chloride	$GdCl_3$	Low Cost High Solubility Safety Transparency	Corrosion
Gadolinium Nitrate	$Gd(NO_3)_3$	Low Cost High Solubility Low Corrosion	Absorbs UV
Gadolinium Sulfate	$Gd_2(SO_4)_3$	Transparency Low Corrosion	Low pH
Gadolinium Acetate	$Gd(C_2H_3O_2)_3$	High Solubility Low Corrosion	Mild UV Absorption

Selective Filtration: Membrane-based Filtering Technologies

$$Gd_2(SO_4)_3 \rightarrow 2\ Gd^{3+} + 3\ (SO_4)^{2-}$$



Original "Band-pass Filter"

> 98.5% $GdCl_3$
or $Gd_2(SO_4)_3$
(single stage NF Reject)

100% of $GdCl_3$ or $Gd_2(SO_4)_3$ plus smaller impurities (UF Product)

Pure water plus $GdCl_3$ or $Gd_2(SO_4)_3$ from SK

Ultrafilter

Nanofilter

Impurities larger than $GdCl_3$ or $Gd_2(SO_4)_3$ (UF Reject)

Impurities smaller than $GdCl_3$ or $Gd_2(SO_4)_3$ (NF Product)

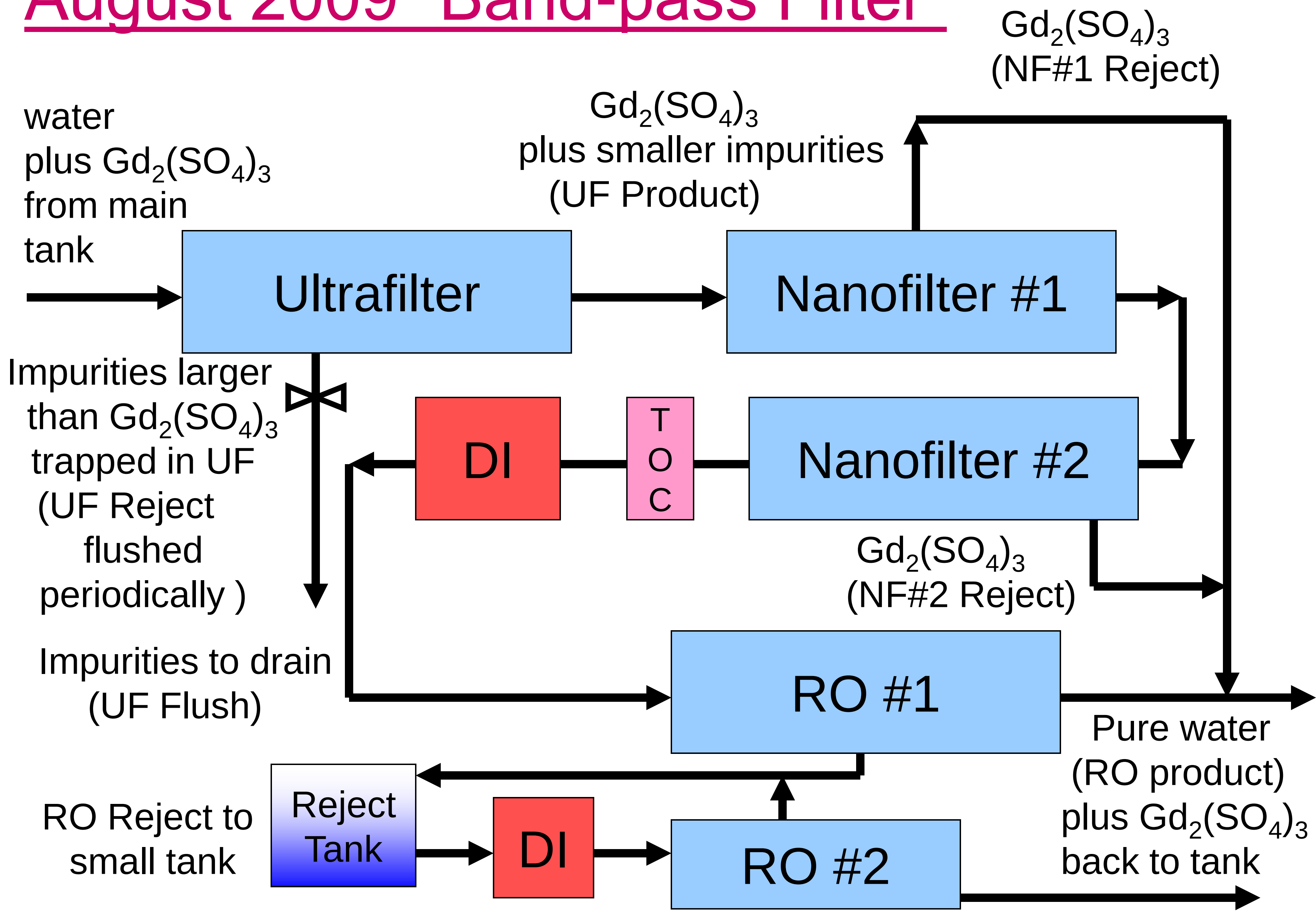
DI/RO

Impurities to drain (RO Reject)

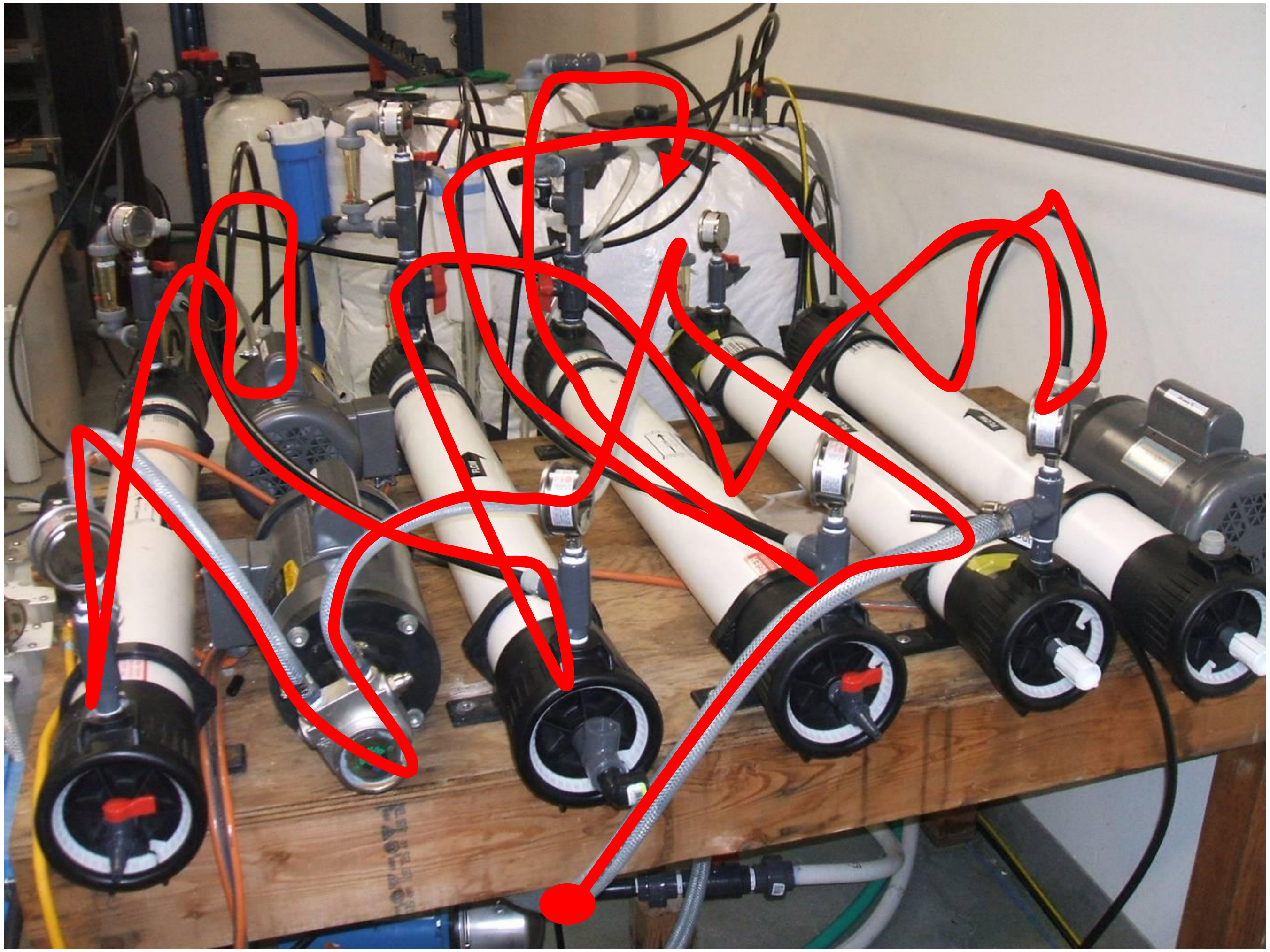
Pure water (RO/DI product) plus $GdCl_3$ or $Gd_2(SO_4)_3$ back to SK

[Undergoing testing at UCI]

August 2009 “Band-pass Filter”



Selective Filtration Setup @ UCI



Membrane
Pre-Flush

Nanofilter #1 | Nanofilter #2 | Reverse Osmosis | Ultrafilter

Membrane Type	Gd Remaining in Product Stream vs. Original Tank Concentration	SO_4 Remaining in Product Stream vs. Original Tank Concentration	Gd in Reject Streams	SO_4 in Reject Streams
NF Stage 1 (Nitto)	0.15%	<0.11%	99.85% (returned to tank by NF1)	>99.89% (returned to tank by NF1)
NF Stage 2 (Nitto)	<0.006%	<<0.11%	>99.994% (returned to tank by NF1+NF2)	>>99.89% (returned to tank by NF1+NF2)
RO (Koch)	<<0.006%	<<0.11%	<<0.006%	<<0.11%

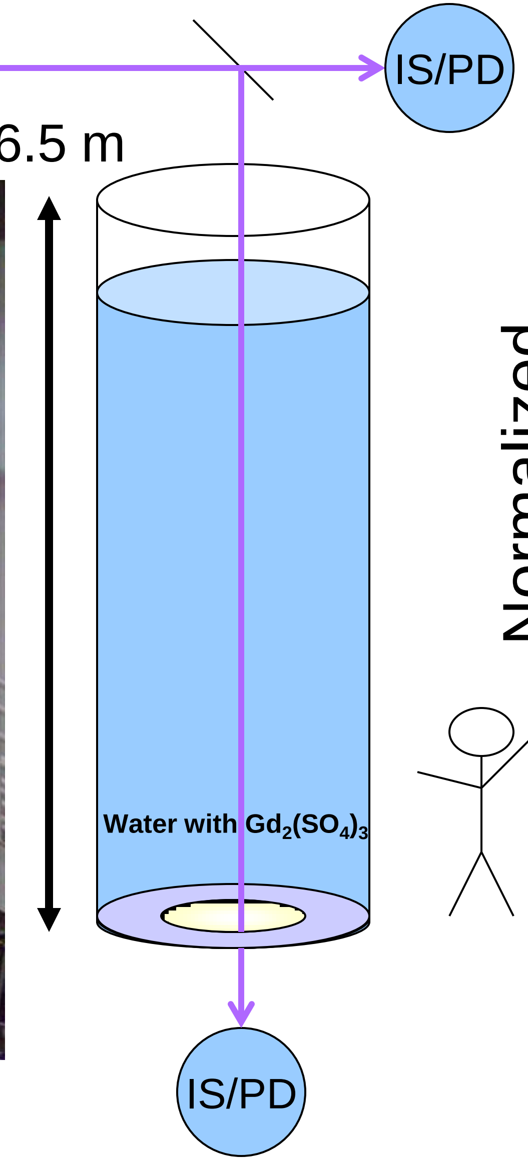
Ran continuously for six weeks – no filter or membrane clogging

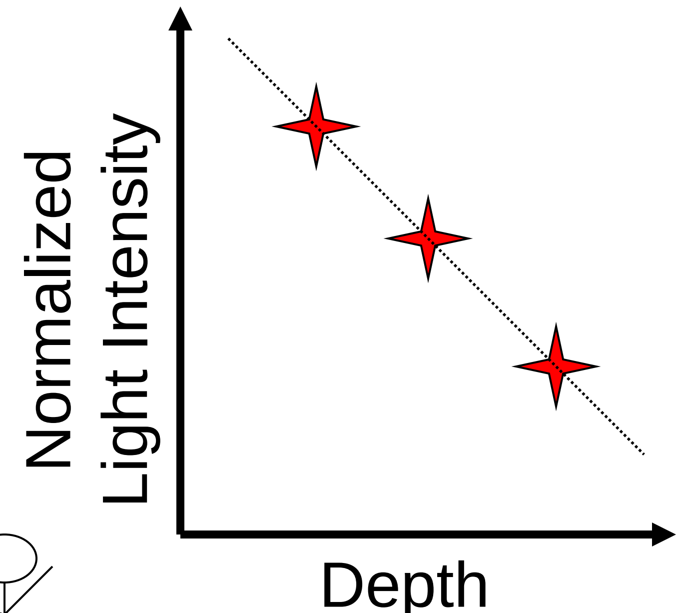
→ Gd separation works

Now we are increasing the water cleaning capability of the system

IDEAL: Irvine Device Evaluating Attenuation Length

[UCI High Bay Building]





This is an upgrade of a 1-meter long device successfully used for IMB

Meanwhile, at Super-K, a calibration source using $GdCl_3$ has been developed and deployed inside the detector:

Am/Be source

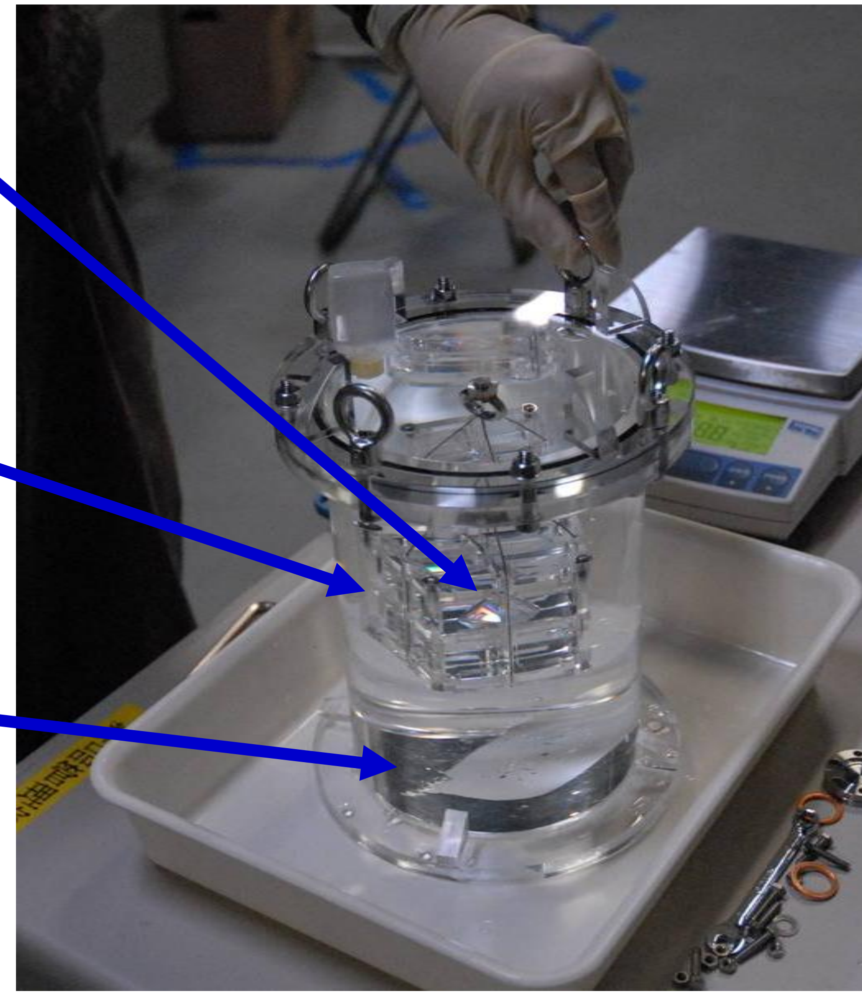
$$\alpha + {}^{9}Be \rightarrow {}^{12}C^{*} + n$$

$$^{12}C^{*} \rightarrow {}^{12}C + \gamma(4.4\ \text{MeV})$$

Inside a BGO crystal array

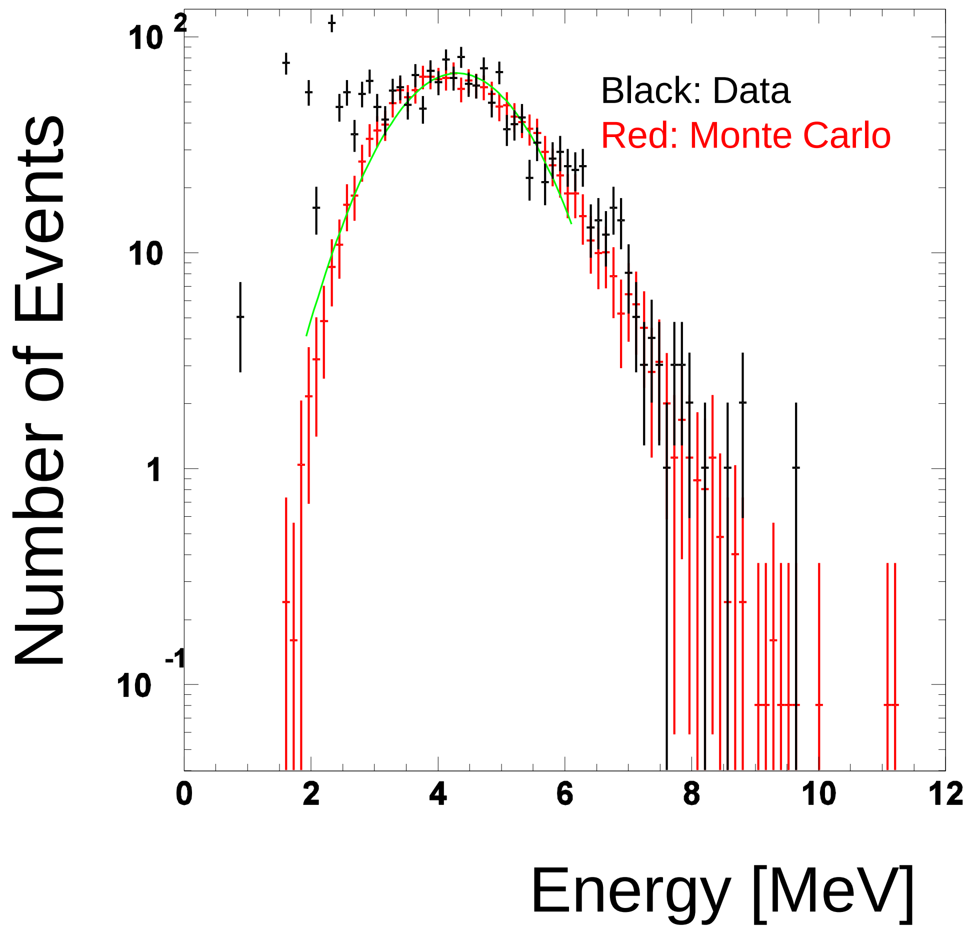
(BGO = $Bi_4Ge_3O_{12}$)

Suspended in 2 liters of 0.2% $GdCl_3$ solution



Data was taken starting in early 2007.

We made the world's first spectrum of $GdCl_3$'s neutron capture gammas producing Cherenkov light:



First $GdCl_3$ "in" SK!

A paper on neutron tagging in Super-K, signed by the entire Collaboration, has just been published:

*Astropart.Phys **31**:320 (2009)*

What else is new? In 2008 I underwent a significant transformation…

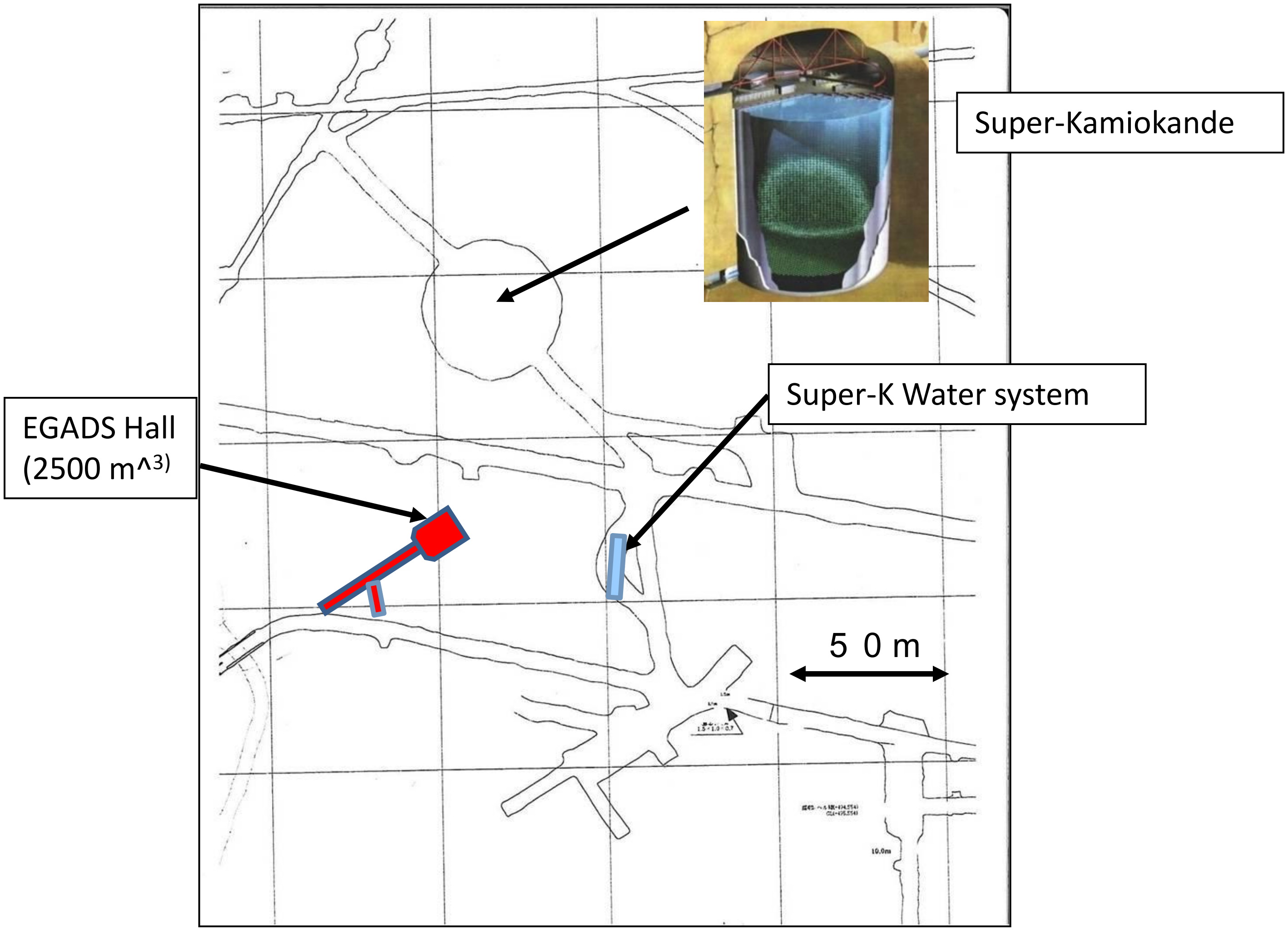
I joined UTokyo's newly-formed IPMU as their first full-time *gaijin* professor, though I still retain a "without salary" position at UCI and will continue Gd studies there.

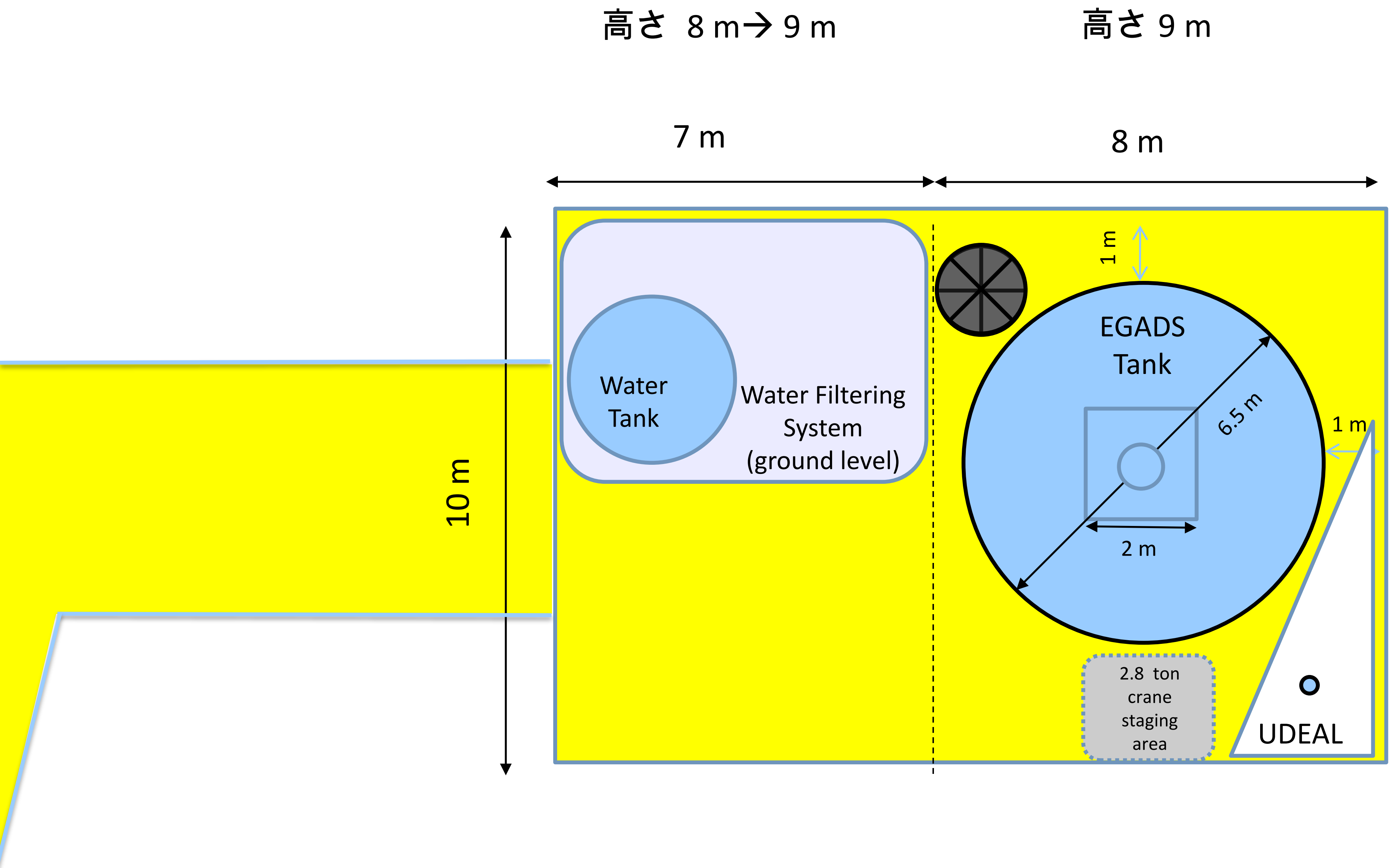
<u>I was explicitly hired to make gadolinium work in water!</u>

IPMU INSTITUTE FOR THE PHYSICS AND MATHEMATICS OF THE UNIVERSE

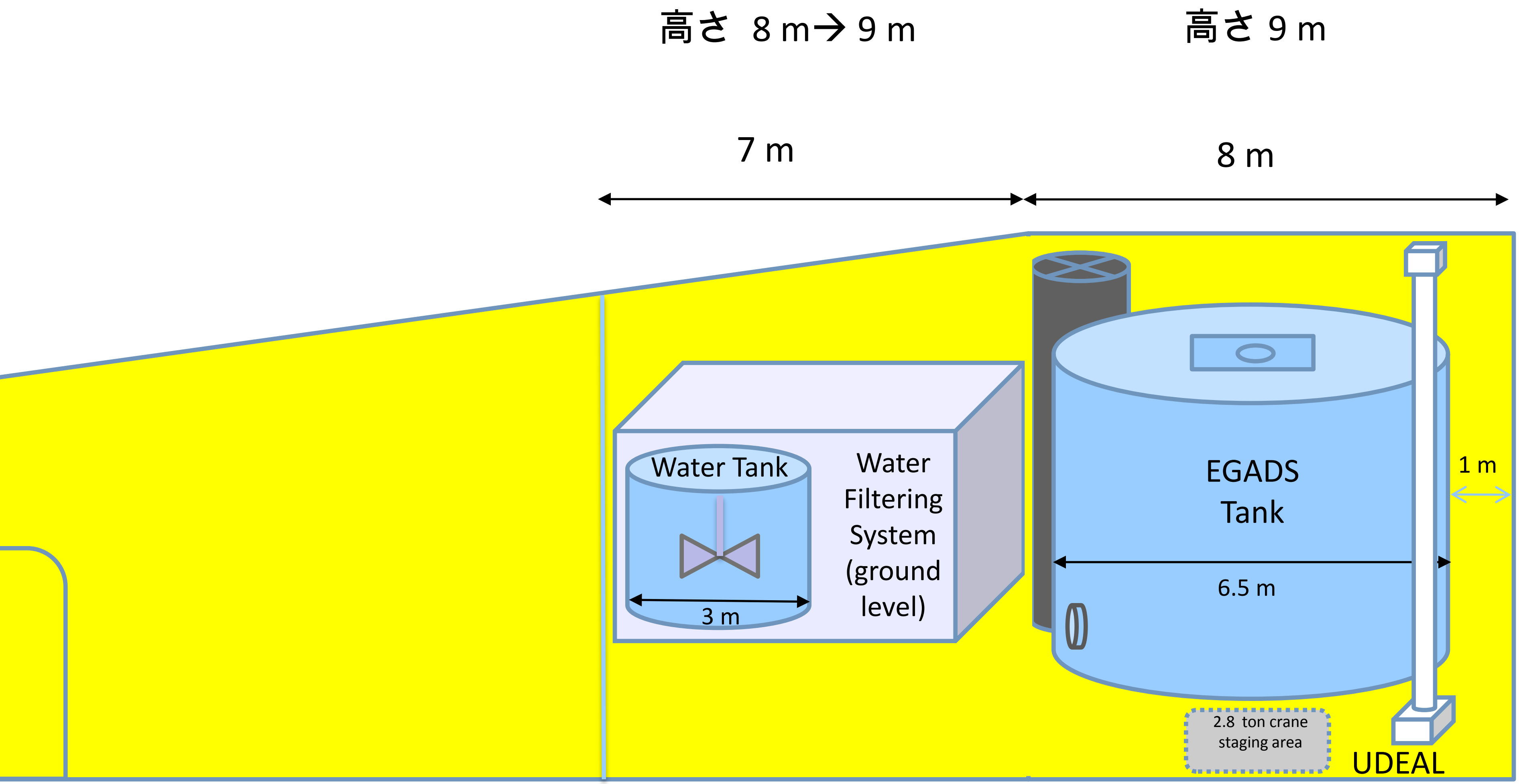
Now, we're building a dedicated Gd test facility, complete with its own water filtration system, 50-cm PMT's, and DAQ electronics.

This 200 ton-scale R&D project is called EGADS – Evaluating Gadolinium's Action on Detector Systems.



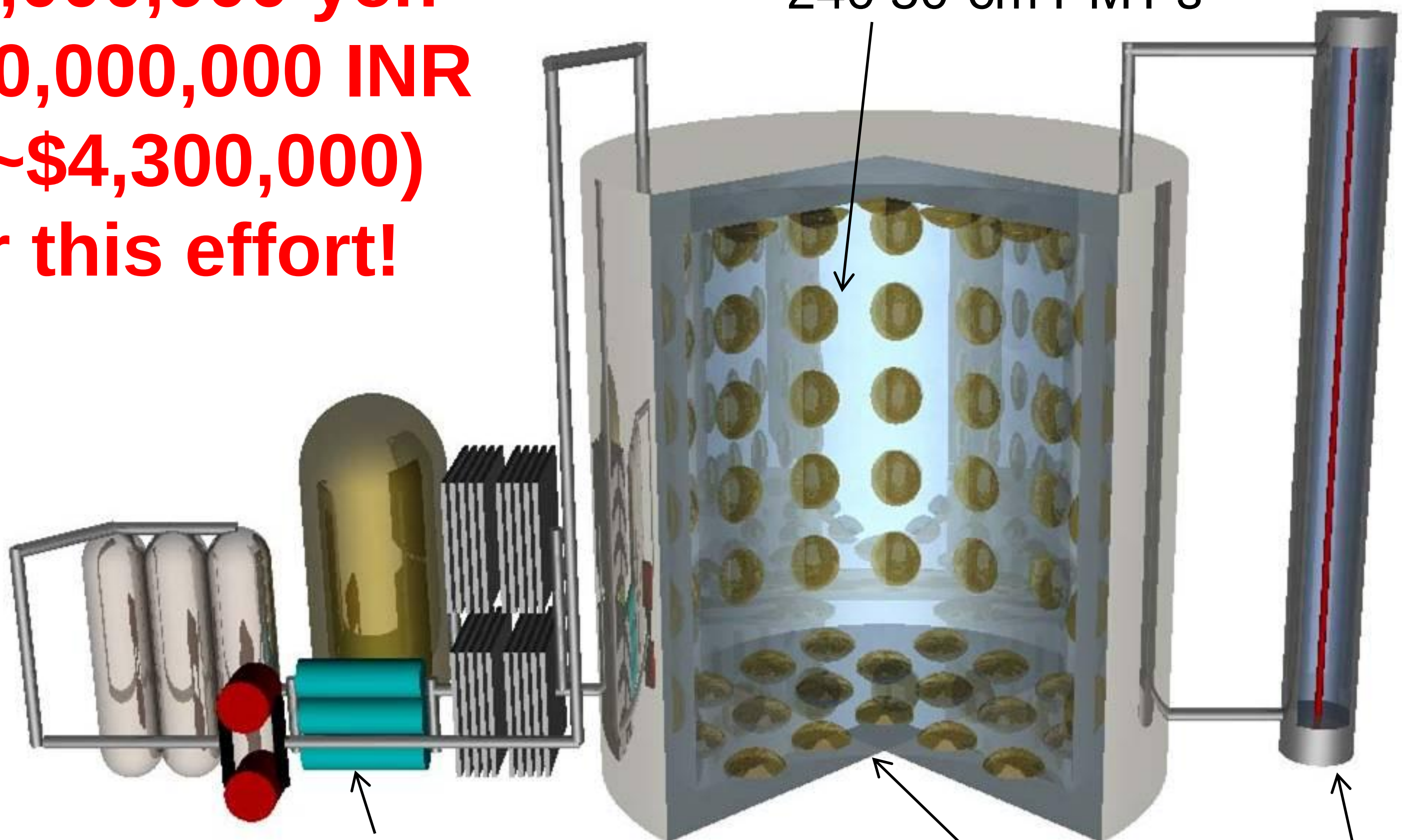


高さ 8 m→ 9 m
高さ 9 m
7 m
8 m
10 m
Water Tank
Water Filtering System (ground level)
1 m
EGADS Tank
6.5 m
1 m
2 m
2.8 ton crane staging area
UDEAL

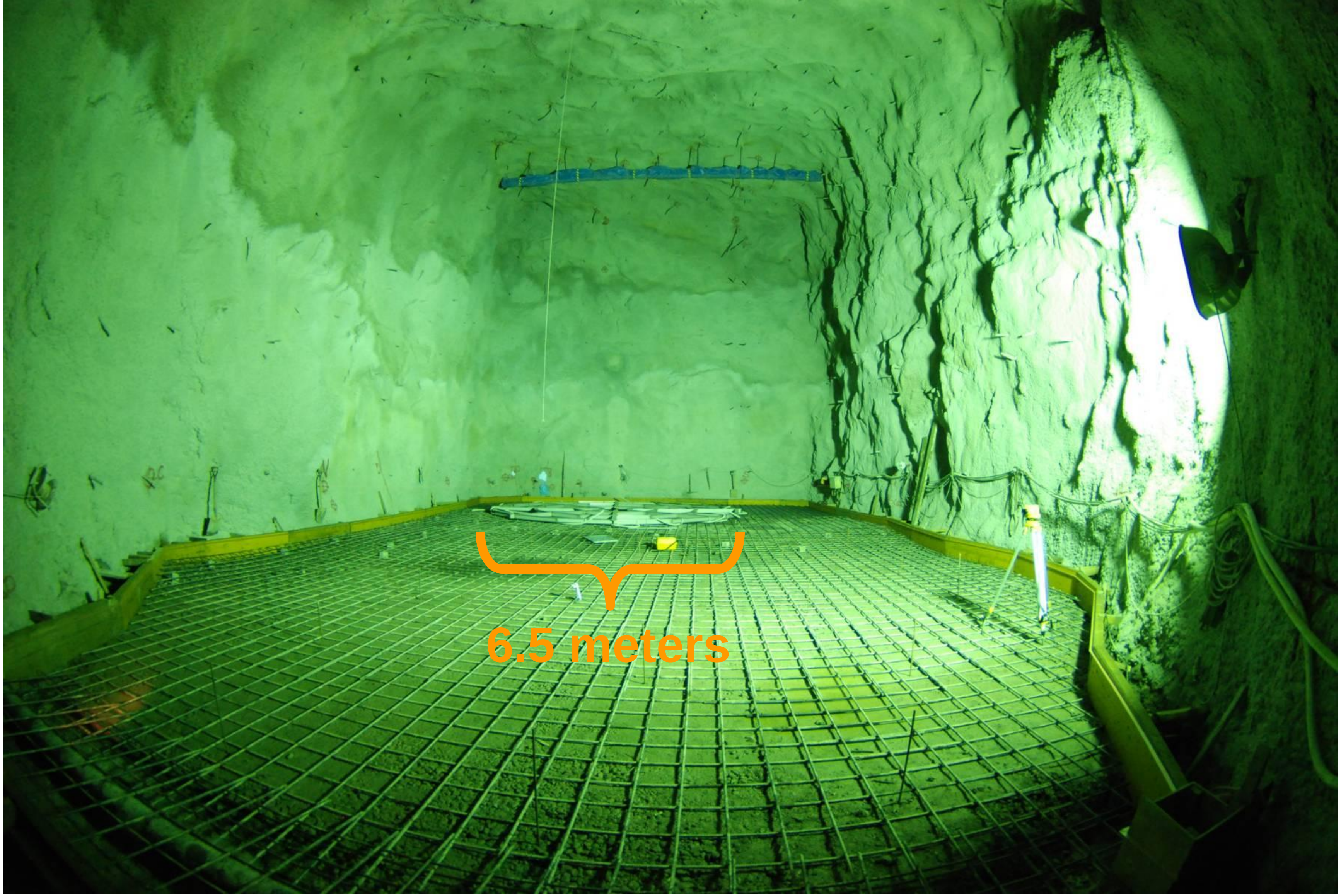

高さ 8 m→ 9 m
高さ 9 m
7 m
8 m
Water Tank
3 m
Water
Filtering
System
(ground
level)
EGADS
Tank
6.5 m
1 m
2.8 ton crane
staging area
UDEAL

EGADS Facility

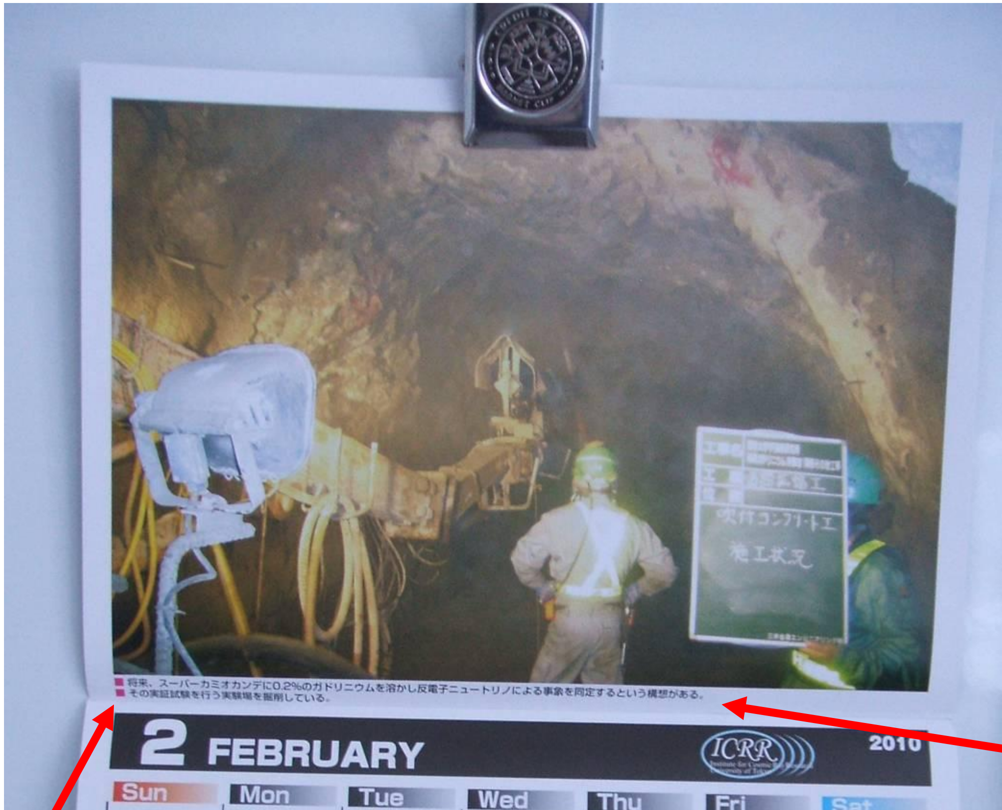
In June 2009 we received 390,000,000 yen (~200,000,000 INR or ~$4,300,000) for this effort!



[graphic by A. Kibayashi]

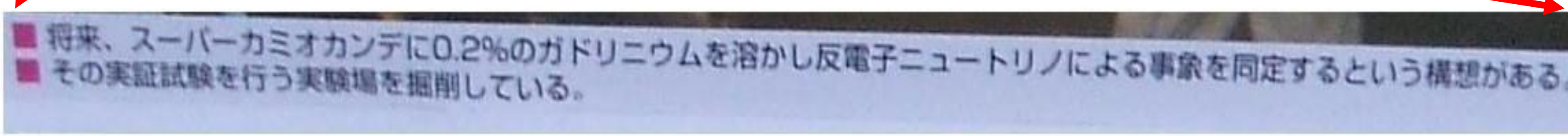


EGADS Cavern as of December 14, 2009



Here's the official Institute for Cosmic Ray Research [ICRR] calendar for 2010:

EGADS is Miss February!



What are the goals of EGADS?

A large-scale test tank will allow us to conclusively address the following questions:

1. How fast can a Gd compound be added to the water? We will find out by dissolving the most promising Gd compound(s).
2. Will the dissolved Gd distribute itself uniformly in a large volume? Resistivity probes mounted throughout the volume will tell us.
3. How quickly/economically/completely can the Gd be removed? We will remove the compound(s) with different methods and assess the effectiveness via the *in situ* resistivity probes and water samples.
4. Are there any materials effects to worry about? Examination of the tank components and water system over time will augment sample soaking tests. Also, any variations in water transparency will be closely monitored.
5. Does selective filtering work, i.e., can we keep the water clear over extended periods of time? Water quality will be continuously checked with 理想 (“risou”).
6. Will ambient neutron backgrounds cause trouble? Event rates throughout the volume will be measured and compared with expectations.

These are issues which must be conclusively studied before introducing Gd into Super-K.

What's the schedule for EGADS?

EGADS is fully funded, and the schedule is now fixed as follows:

2009-10: Excavation of new underground experimental hall,
construction of stainless steel test tank and
PMT-supporting structure (completion May 2010)

2010-11: Assembly of main water filtration system,
tube prep, mounting of PMT's, installation
of electronics and DAQ computers

2011-13: Experimental program to address
technical issues on previous slide

At the same time, material aging studies will be carried out in Japan, and transparency and water filtration studies will continue in Irvine.

If all goes well we should be prepared to enrich Super-K with gadolinium early in the coming decade!