Neutrino Forecast:

Mostly Sunny, with a Good Chance of Supernovas

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HAνSE 2011

DESY, Hamburg July 23, 2011

HAνSE 2011

Hamburg Neutrinos from Supernova Explosions

DESY, Hamburg Site/Germany
19-23 July 2011

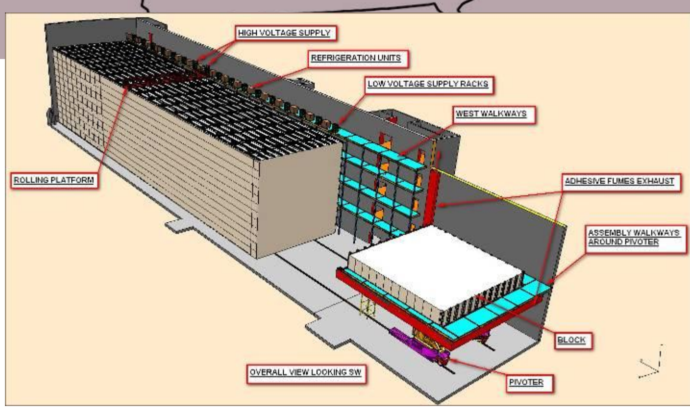
First of all, I’d like to thank the organizers:

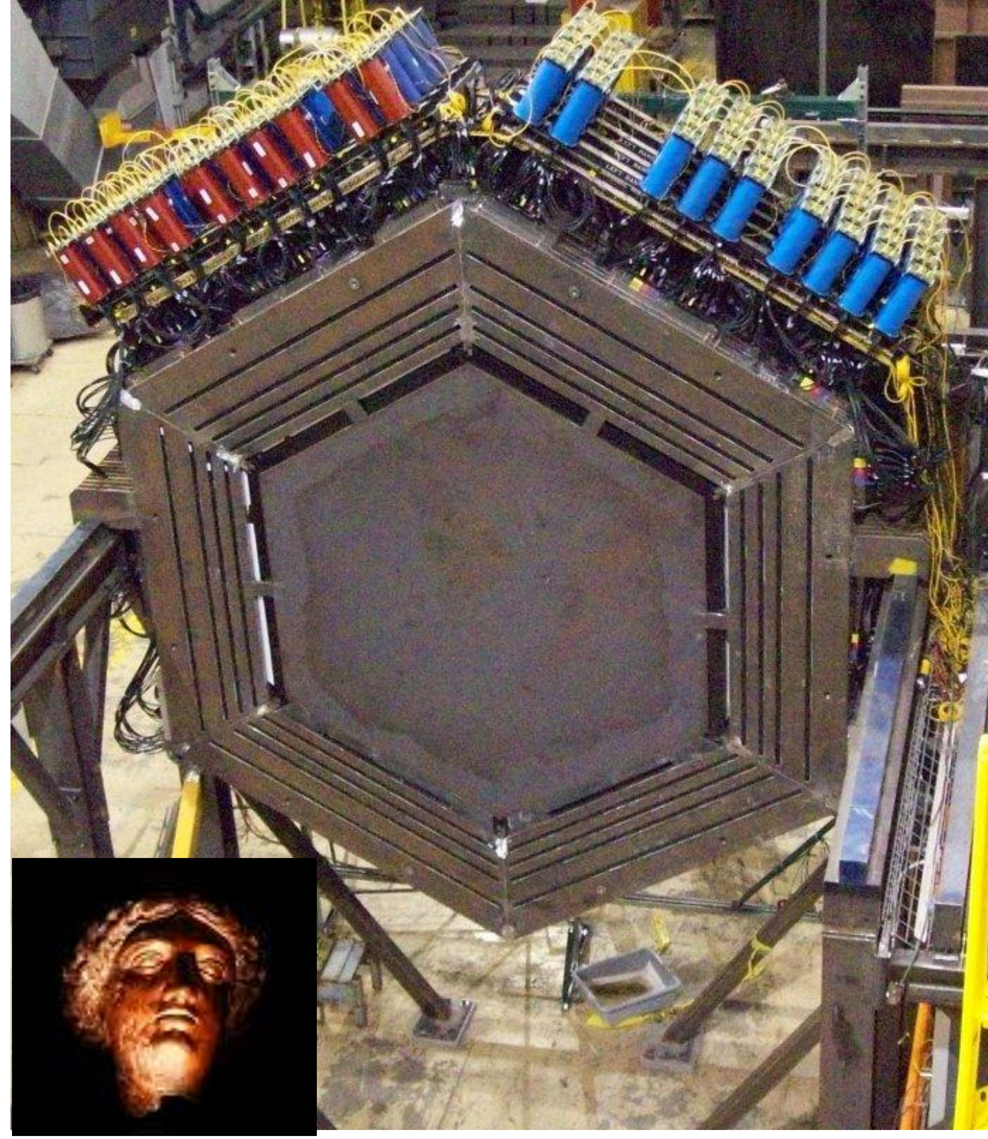
1) for asking me to give this sunny, concluding talk

2) for setting a good example in the proper use of our beloved “ν”

Of course “ν” *looks* like a “v”, but everyone knows it has an “n” sound.

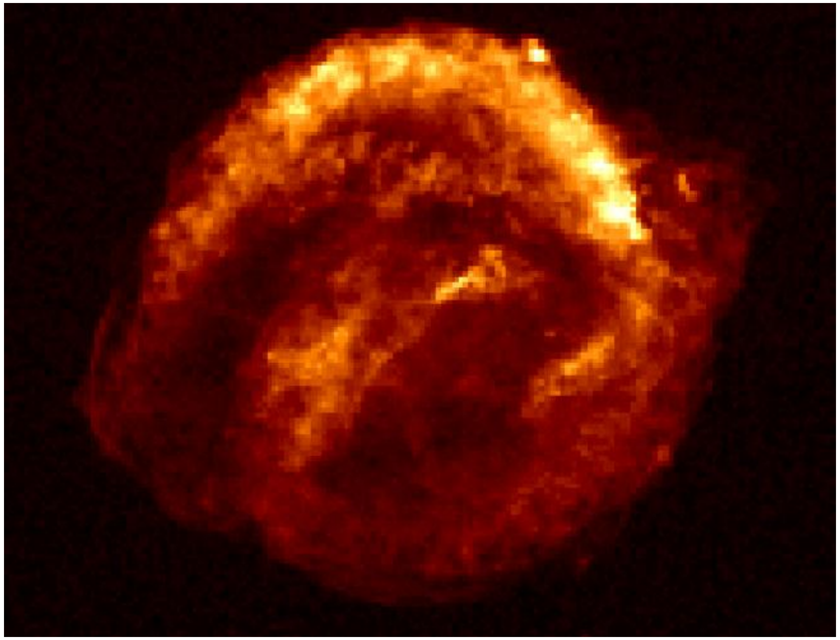
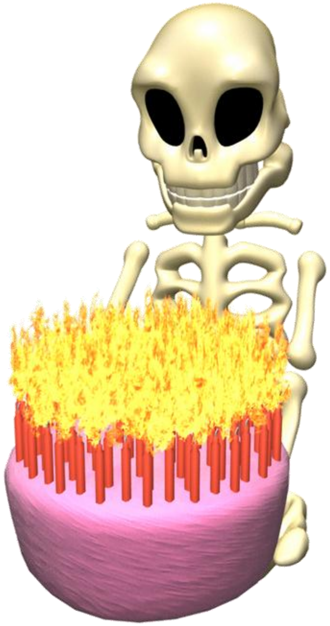
Well okay, maybe not <u>everyone</u>…





MINERνA

NOνA

It has been a couple of decades since SN1987A, and 406 years and 287 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!

Yes, it's been a long, cold winter for SN neutrinos…

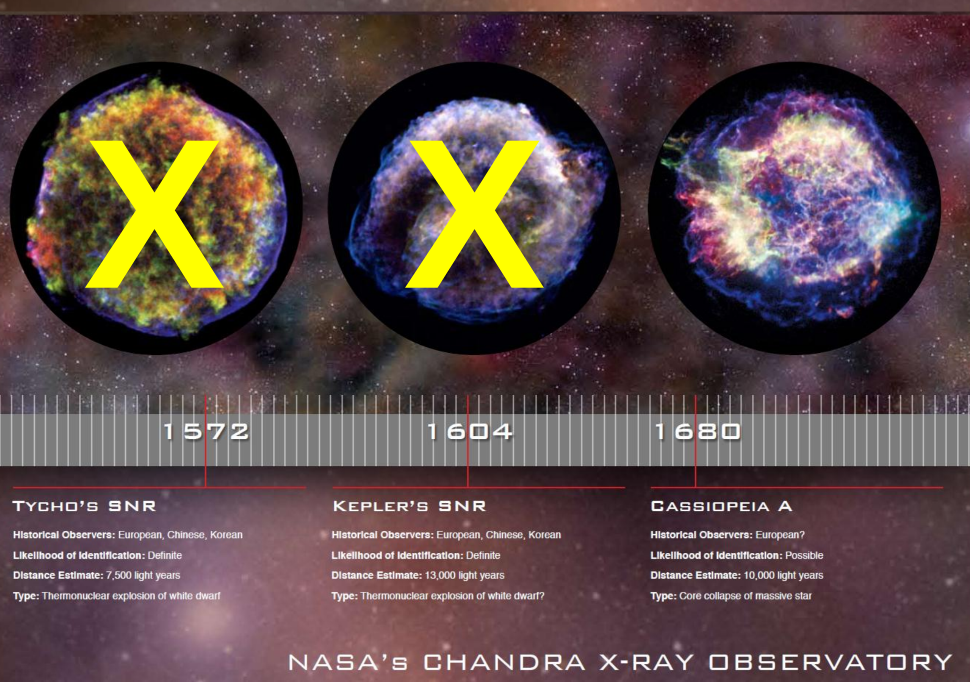
but there is hope!

You may have noticed that I am a pretty happy guy…

Sometimes this concerns my colleagues:

Why… are you smiling?

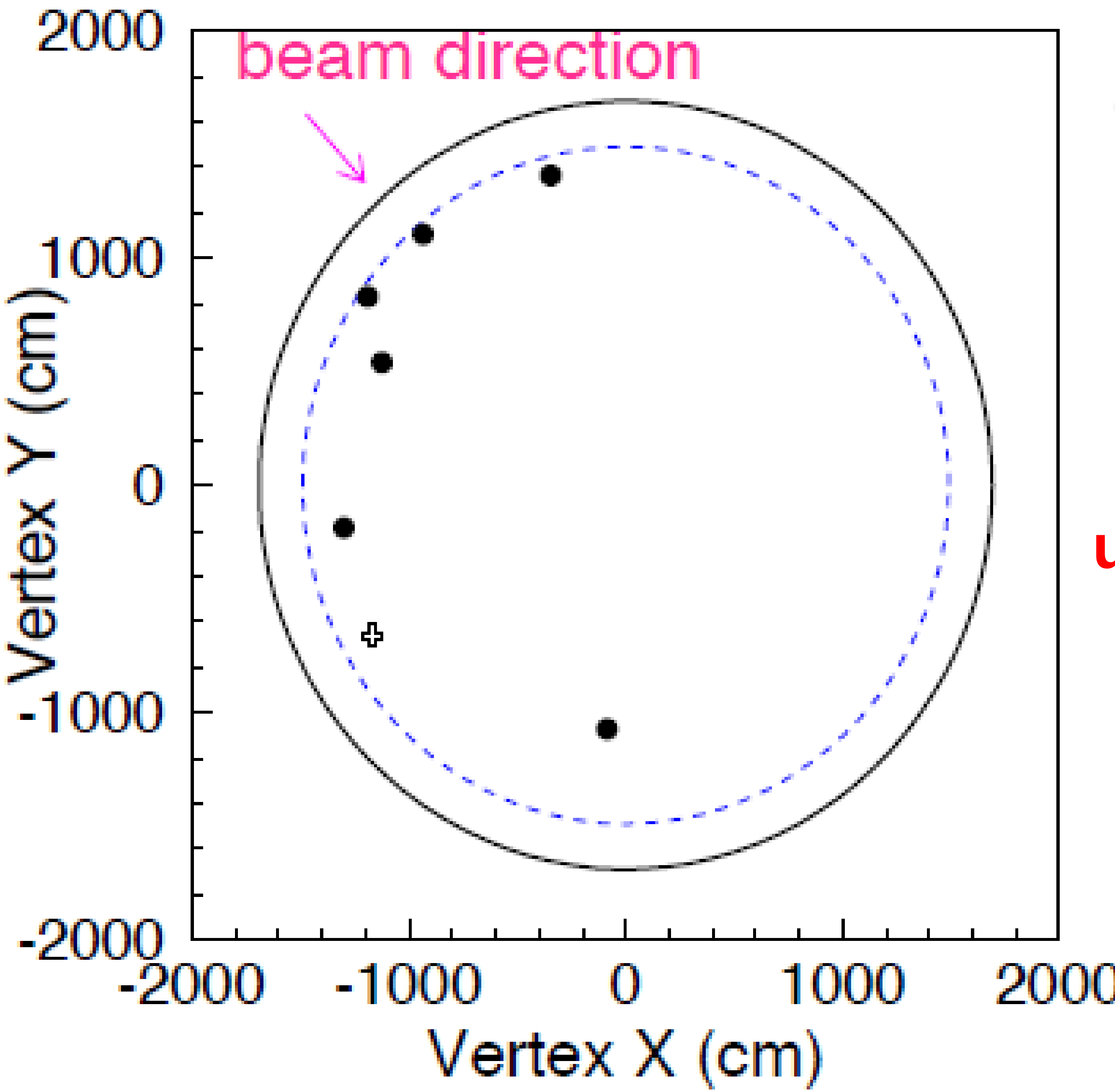
Why are you smiling?



So, about six → observed ← core collapse explosions in 1800 years…

Historic Milky Way Supernovas

1-3/century

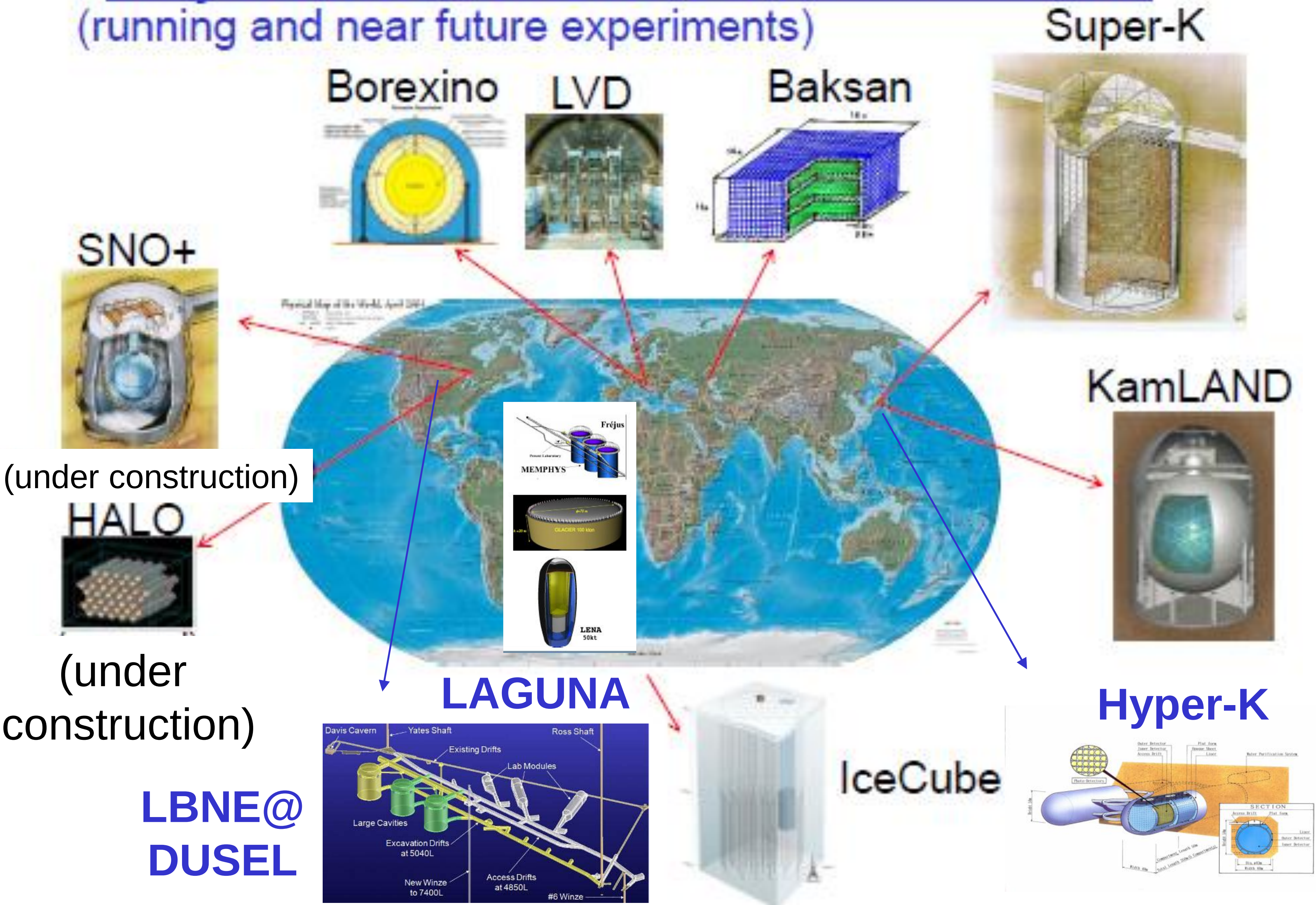


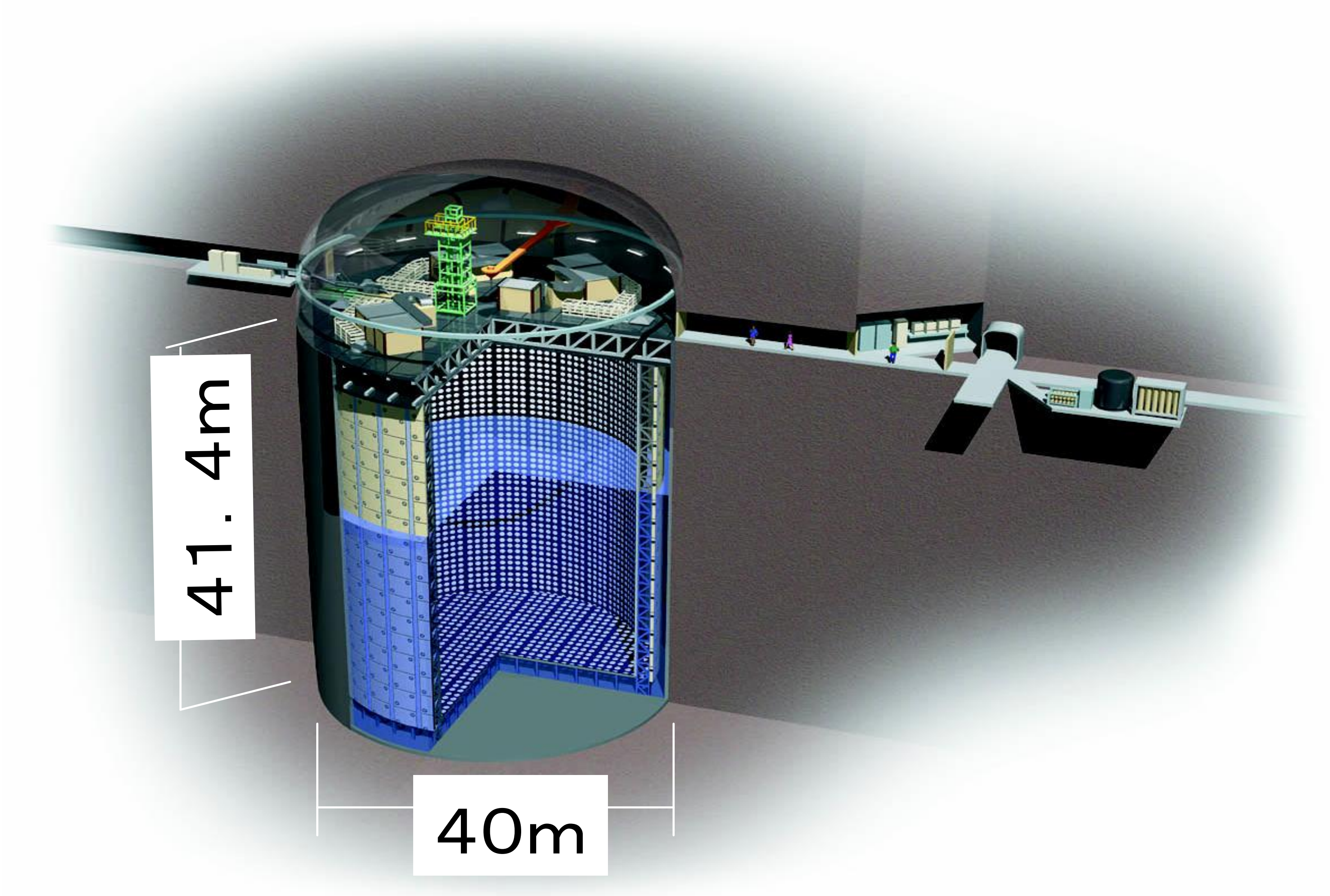
ν_e events

…but never underestimate the impact just six events can have!

Supernova detectors in the world

(running and near future experiments)



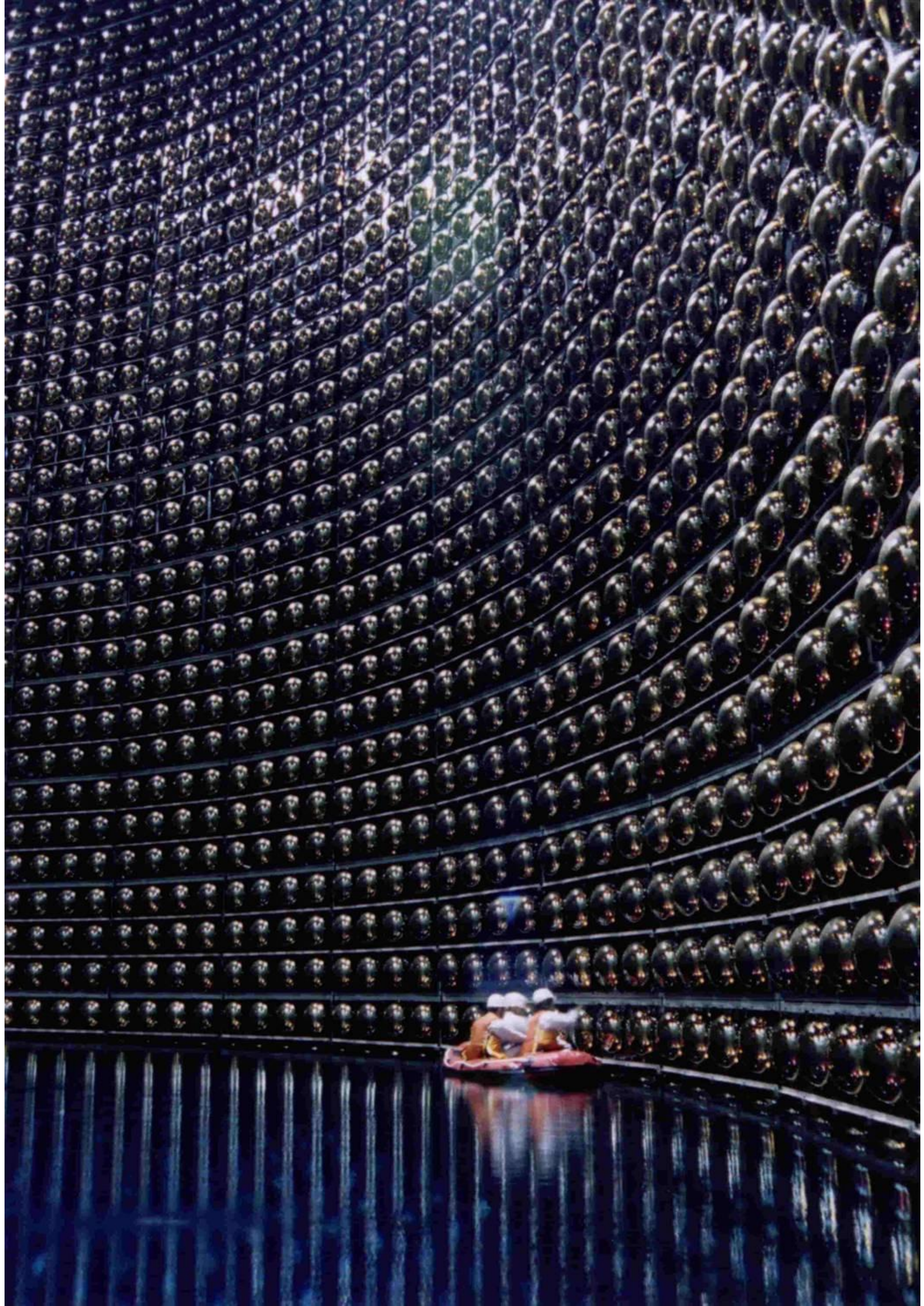


The Super-Kamiokande neutrino detector, in Mozumi, Japan.

50,000 tons of ultra-pure H_2O

13,000 light detectors

One kilometer underground

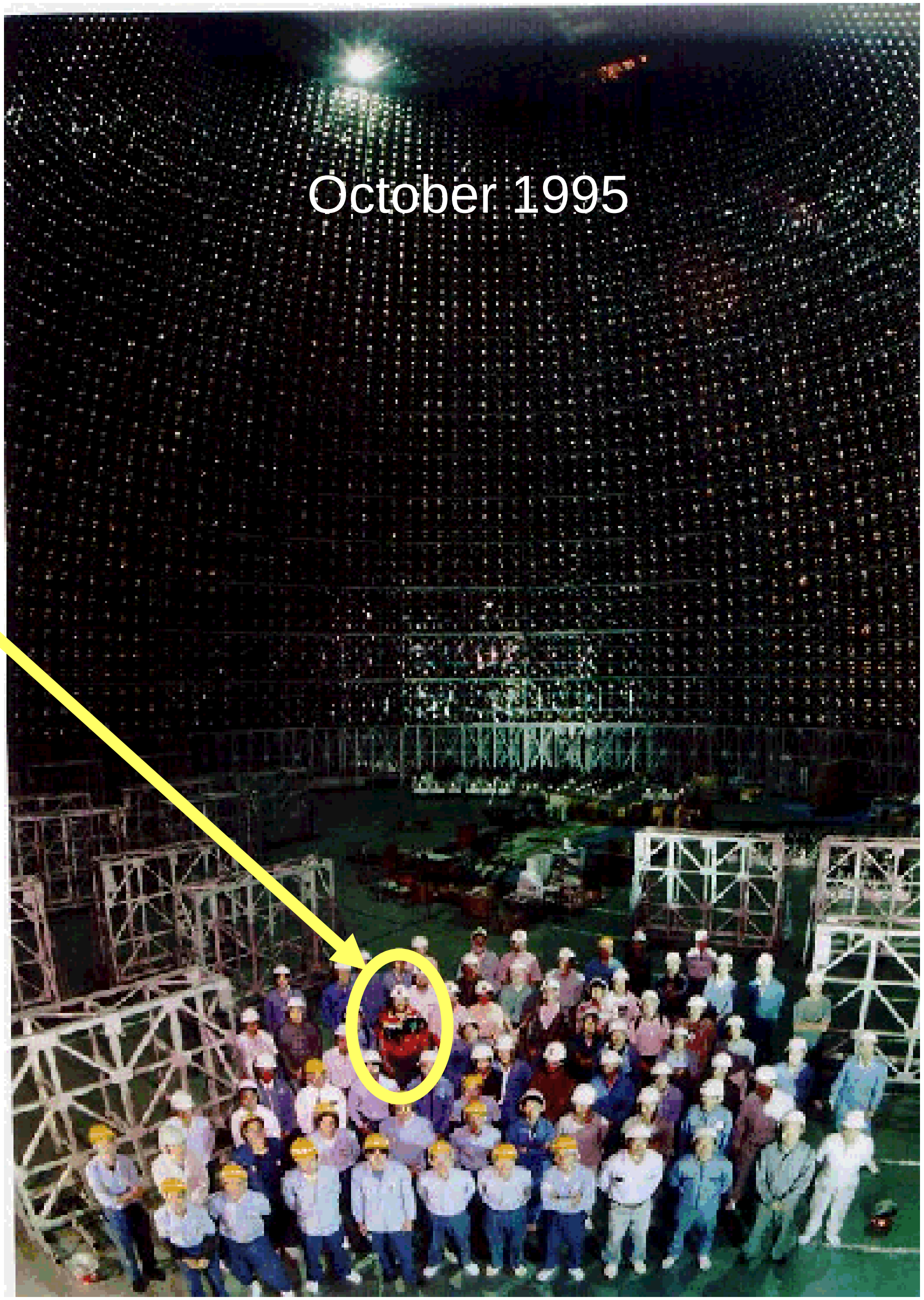


Observes solar neutrinos from the Sun and atmospheric neutrinos from cosmic rays.

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

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

January 1996

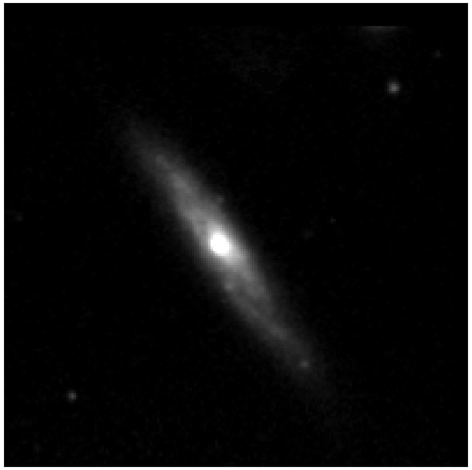


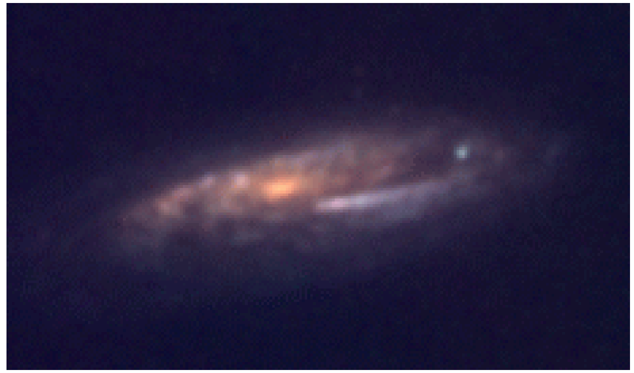
So, how can we be sure to see some supernova neutrinos without having to wait too long?

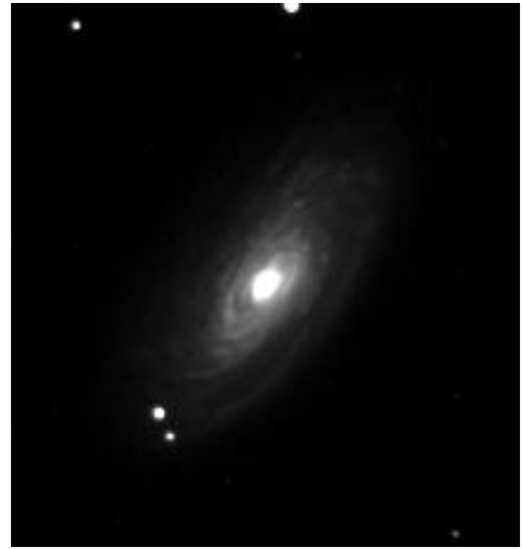
My forecast is a bit more optimistic than Glenn's… which is good, because it's Saturday!

This is not the typical view of a supernova! Which actually… is good.

Yes, nearby supernova explosions may be rare, but supernova explosions are quite common.







Here’s how most of them look to us (video is looped).

There are *__thousands of__* __supernova explosions per hour__ in the universe as a whole!

These produce a diffuse supernova neutrino background [DSNB], also known as the supernova relic neutrinos [SRN].

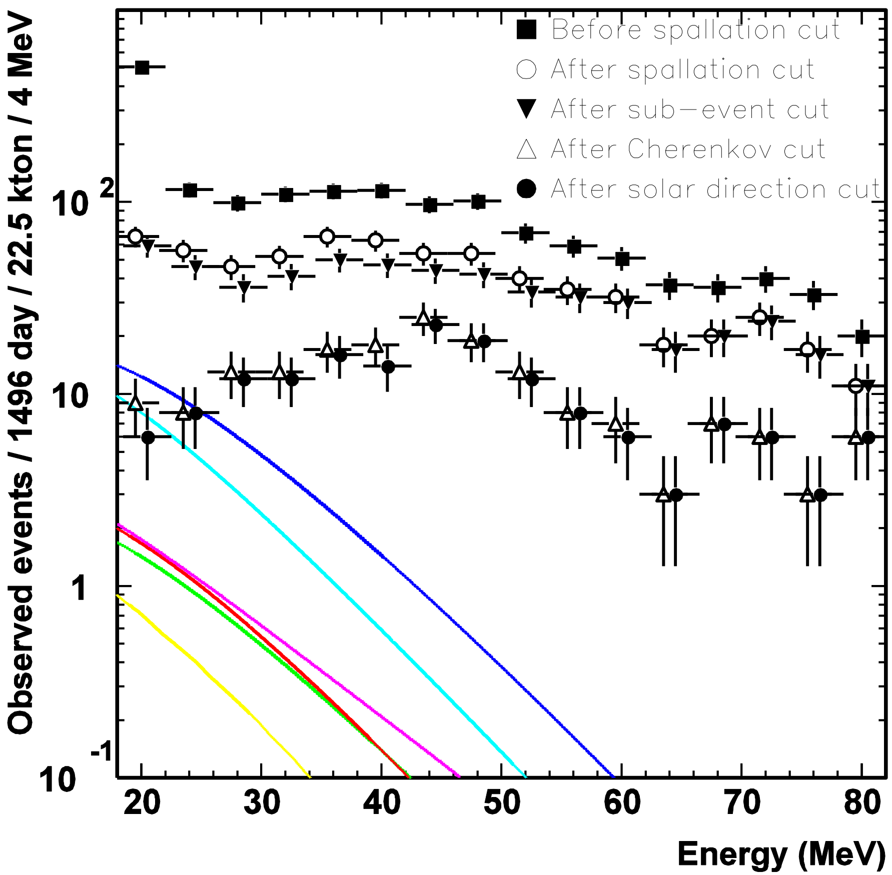
(May 31st, 2011)

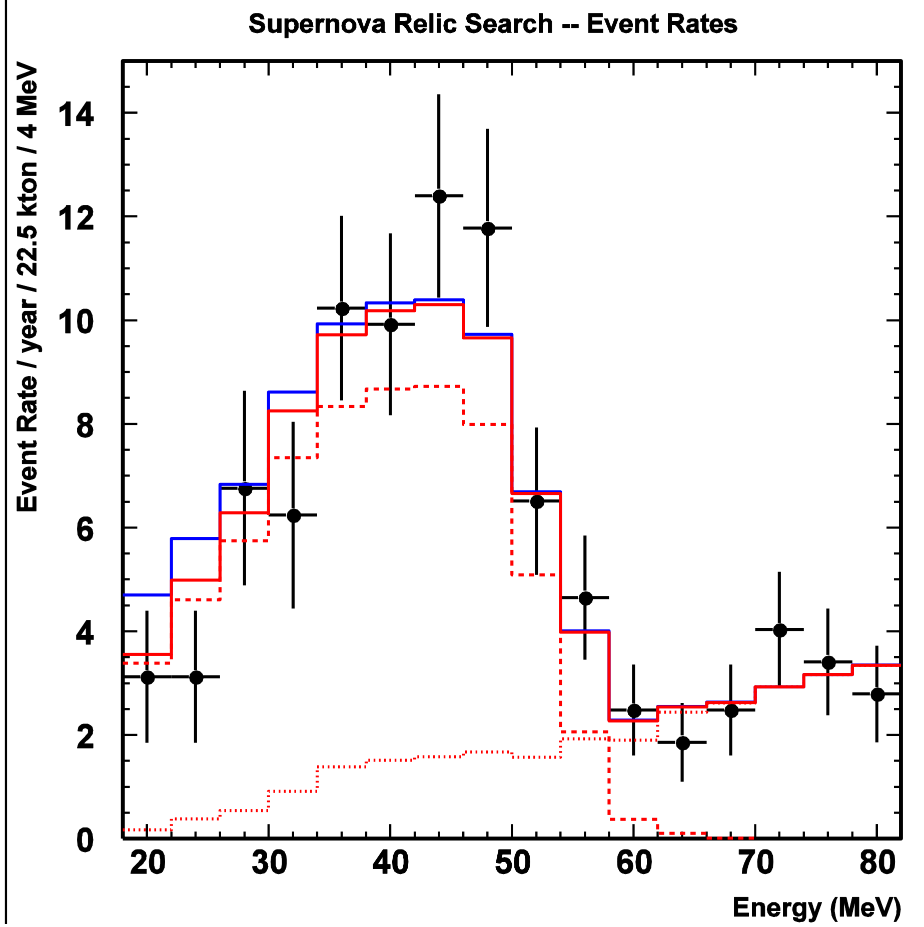

SN2011dh


SN2011dh

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)].

[see Sakuda-san's talk for most recent SK analysis]

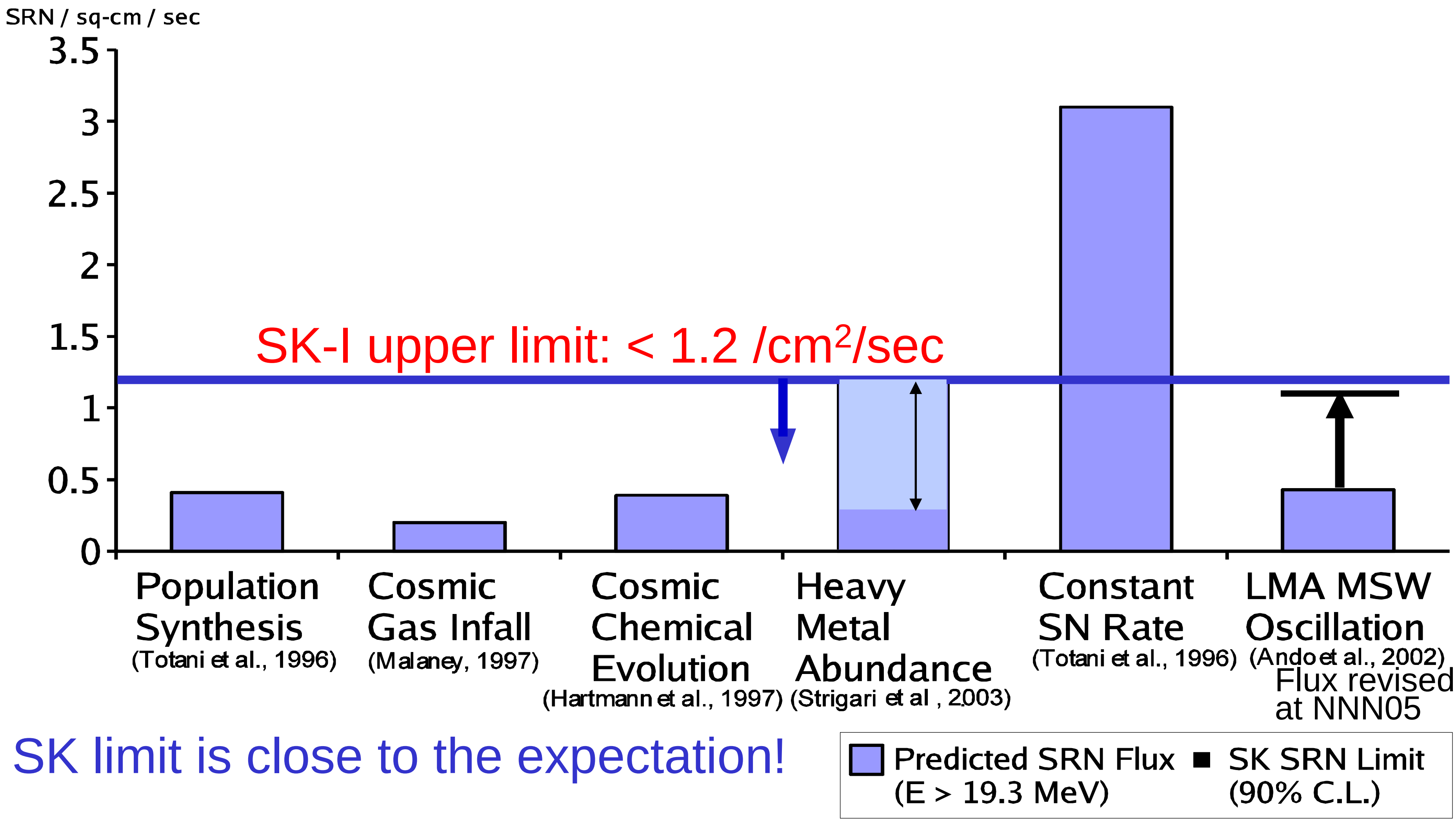




Unfortunately, the search was strongly limited by backgrounds, and no clear event excess was seen.

Flux limit and theoretical prediction

E_e>18 MeV (E_ν>19.3 MeV)



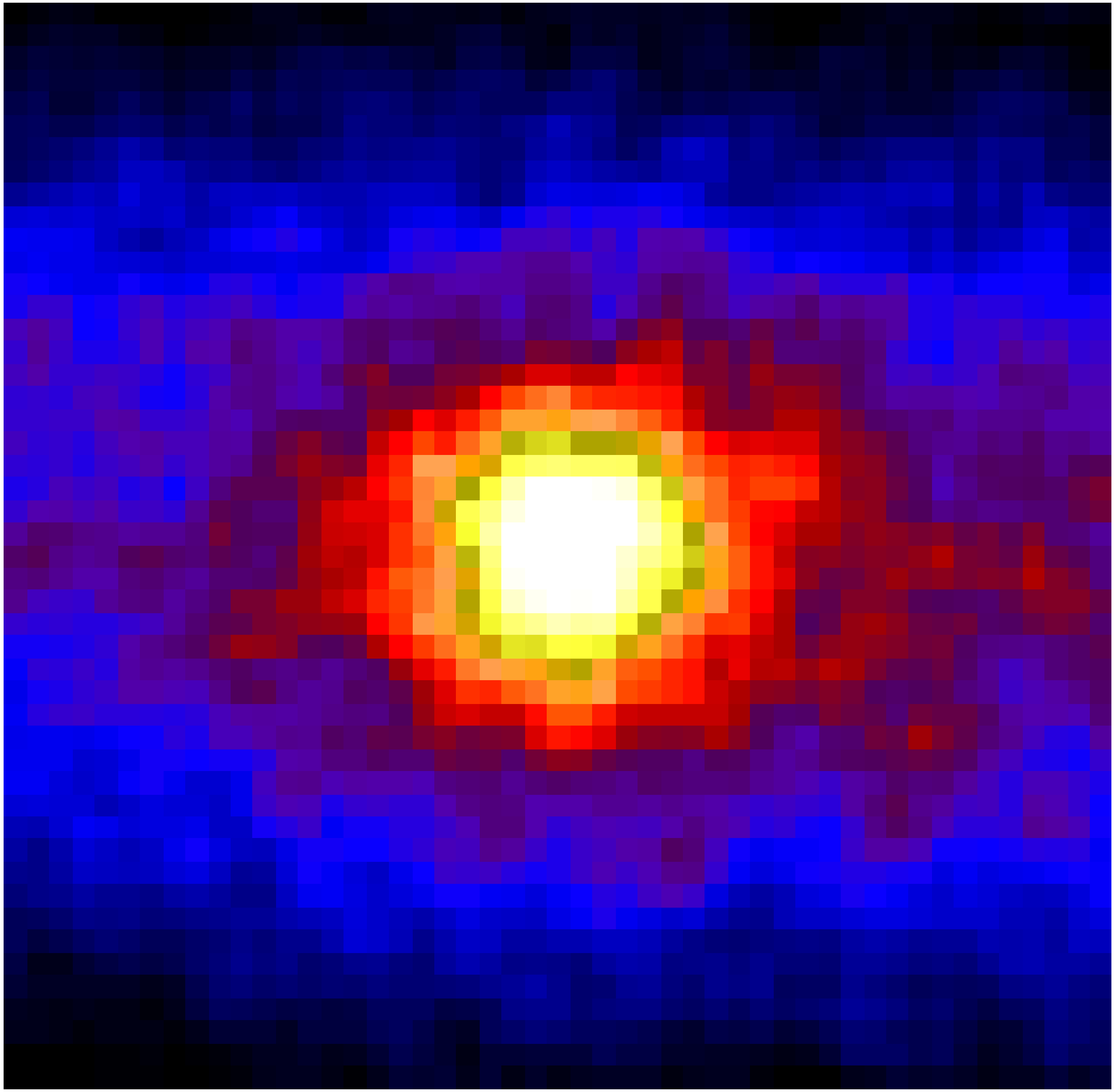
SK limit is close to the expectation!

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.

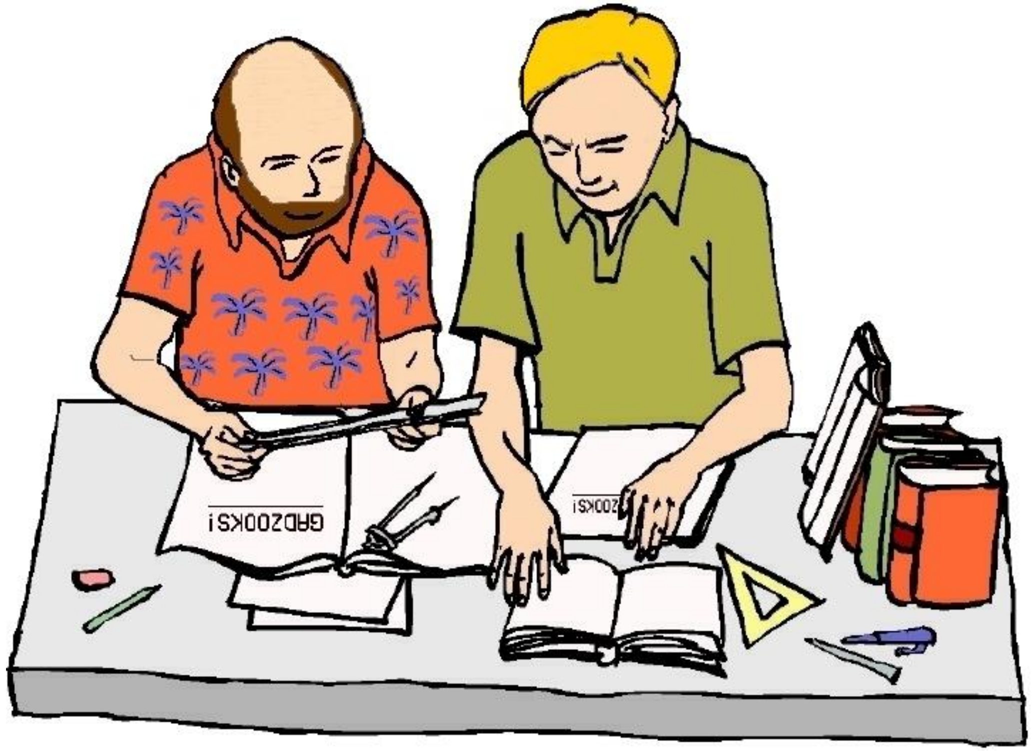
And this rate is actually very low… just <u>three events per cubic meter per *year.*</u>

An SK picture of the Sun in solar neutrino “light”.



Solar flux = 10^6 X DSNB

Galactic SN = $10^{6\text{-}11}$ X solar flux



With this 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:

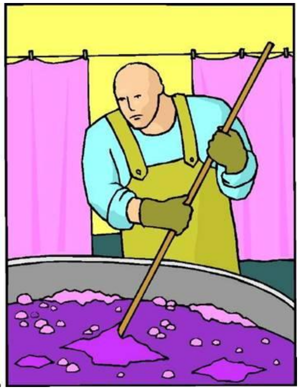
[Beacom and Vagins, *Phys. Rev. Lett.*, **93**:171101, 2004]

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

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

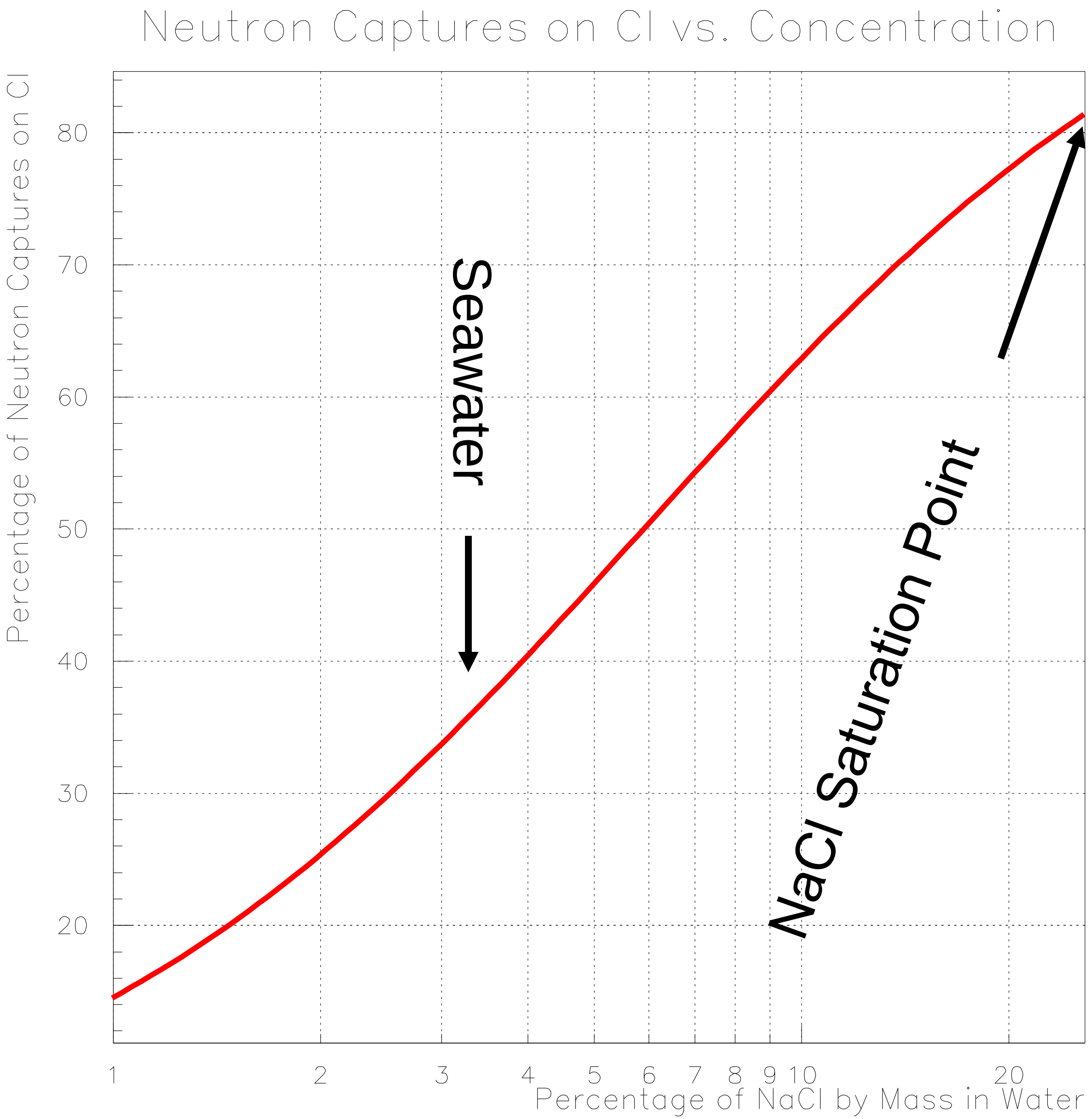
As we approach the megaton scale, you can forget about using liquid scintillator, ^{3}He counters, or heavy water!

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!

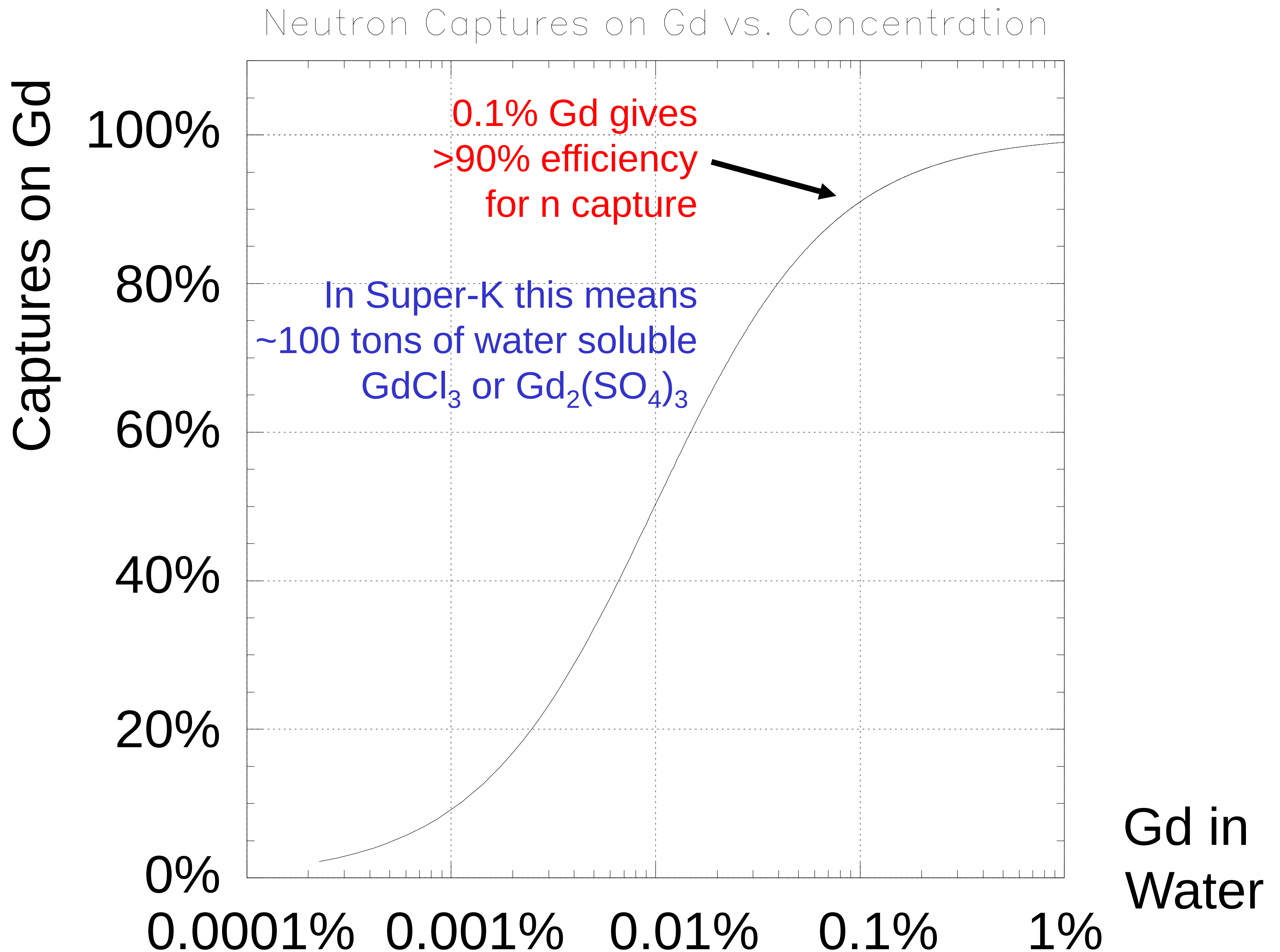
To get 50% neutron capture on Cl
(the other 50% will be on the hydrogen
in the water and essentially invisible)
you'll need to use 6% NaCl by mass:
→ *3 kilotons of salt for a 50 kton detector!* ←



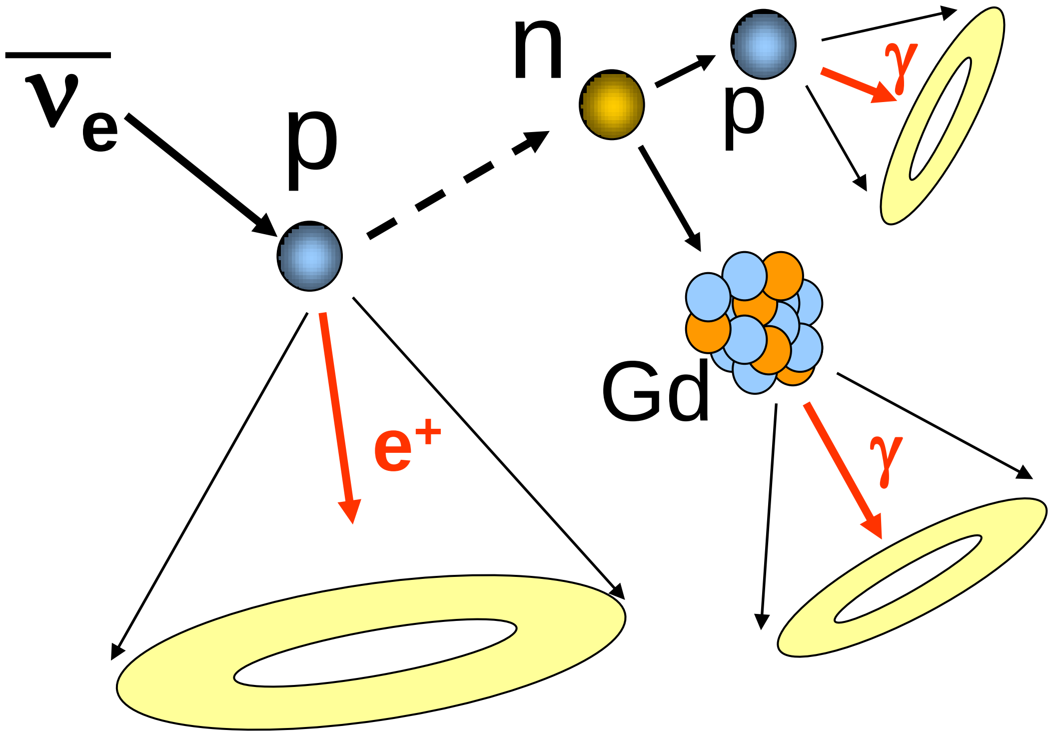
Neutron Captures on Cl vs. Concentration
Percentage of Neutron Captures on Cl
80
70
60
50
40
30
20
1
2
3
4
5
6
7
8
9
10
20
Percentage of NaCl by Mass in Water
Seawater
NaCl Saturation Point

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?

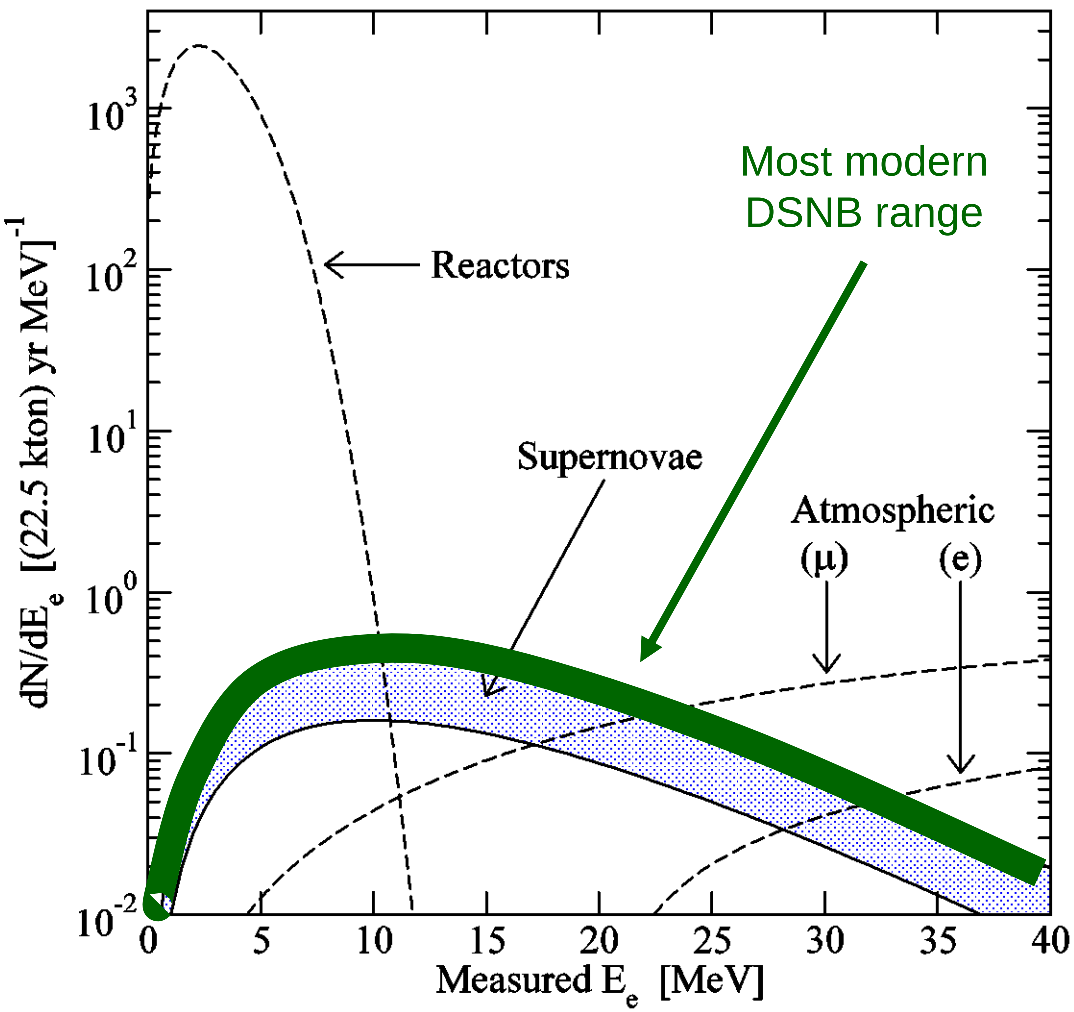
In 1984: $4000/kg –> $400,000,000
In 1993: $485/kg –> $48,500,000
In 1999: $115/kg –> $11,500,000
In 2010: $5/kg –> $500,000

These low, low prices are for real.

Back in 2005, \$24,000 bought me 4,000 kg of $GdCl_3$.

Shipping from Inner Mongolia to Japan was included!

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):



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

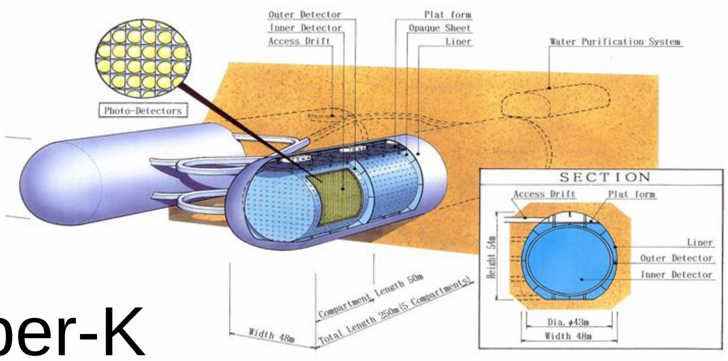
spatial and temporal separation between prompt e^+ Cherenkov light and delayed Gd neutron capture gamma cascade:

λ=~4cm, τ=~30μs

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

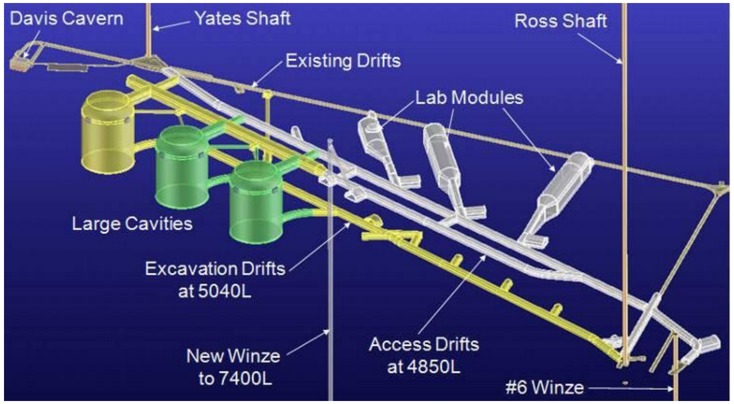
So, perhaps Super-K <u>can</u> be turned into a great big antineutrino detector… it would then steadily collect a handful of extragalactic DSNB events <u>every year</u> with greatly reduced backgrounds.

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



Hyper-K

LBNE@
DUSEL



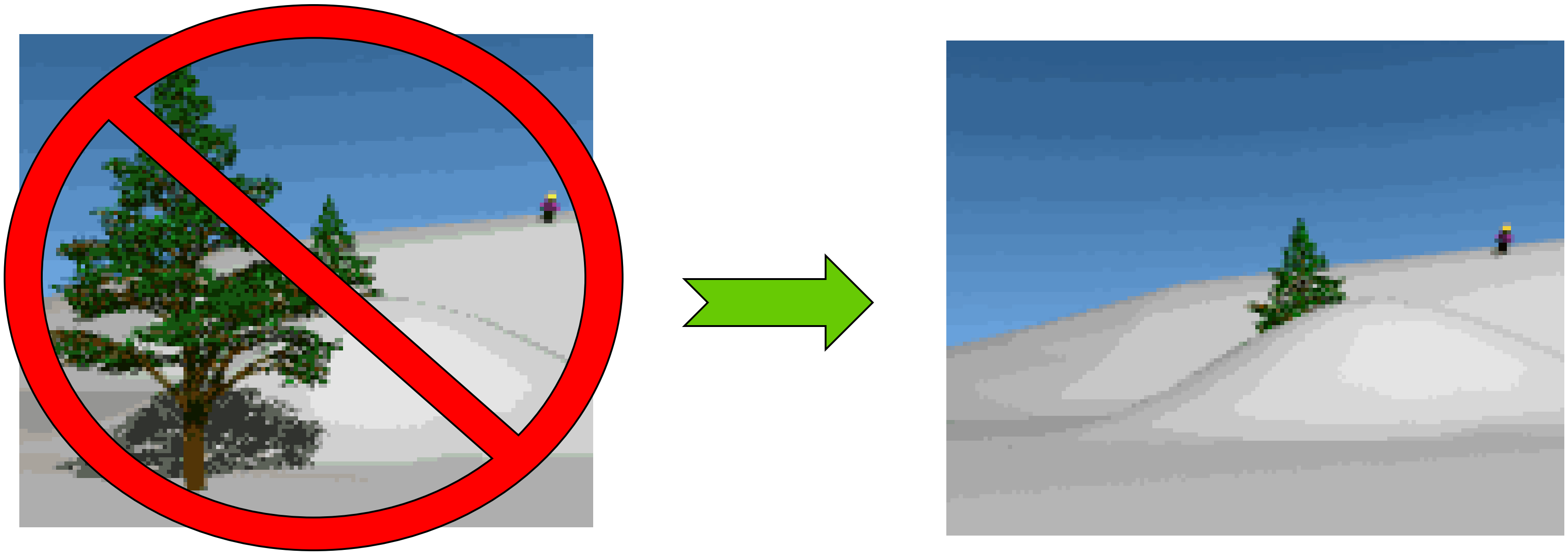
N.B.: This is the <u>only</u> neutron detection technique which is extensible to Mton scales, and at minimal expense, too: ~1% of the detector construction costs

After all, John 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.

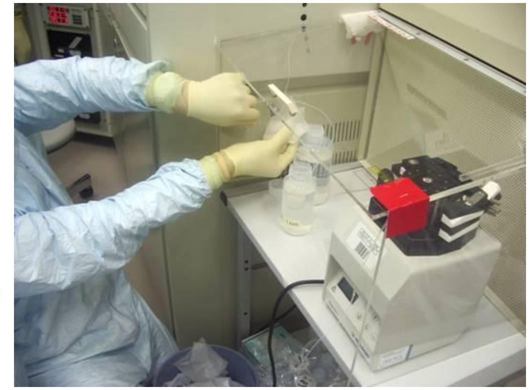


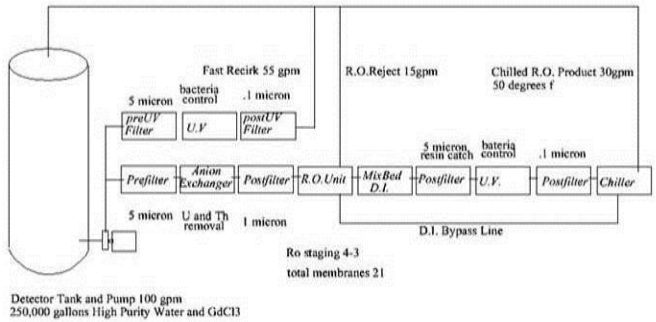
- What does gadolinium do the Super-K tank materials?
- Will the resulting water transparency be acceptable?
- Any strange Gd chemistry we need to know about?
- How will we filter the SK water but retain dissolved Gd?

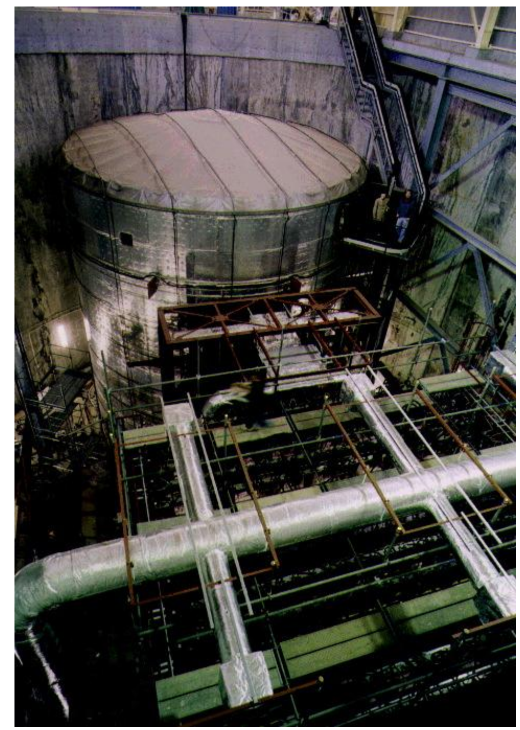
As a matter of fact, I very rapidly made two discoveries regarding $GdCl_3$ while carrying a sample from Los Angeles to Tokyo:

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

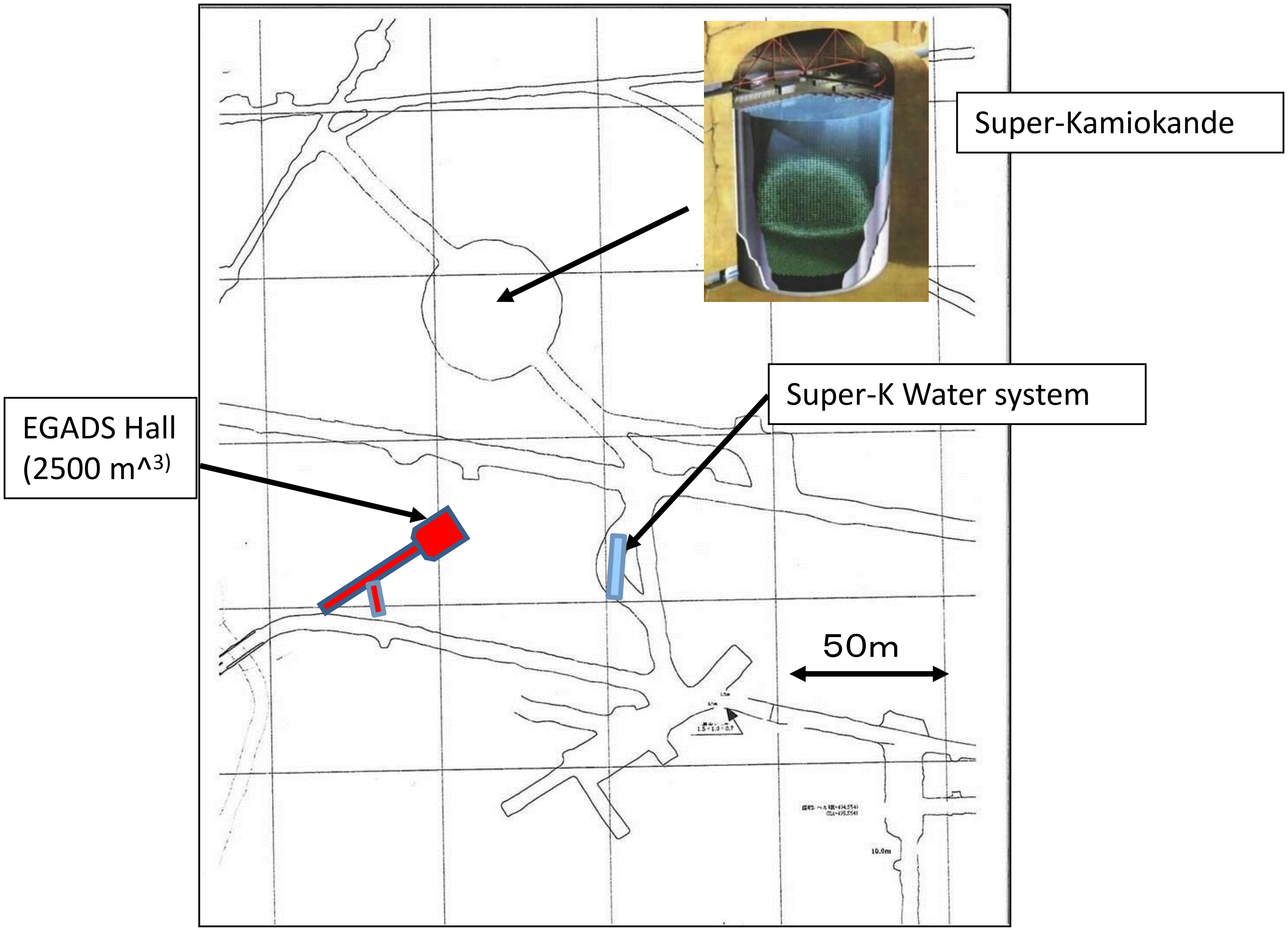






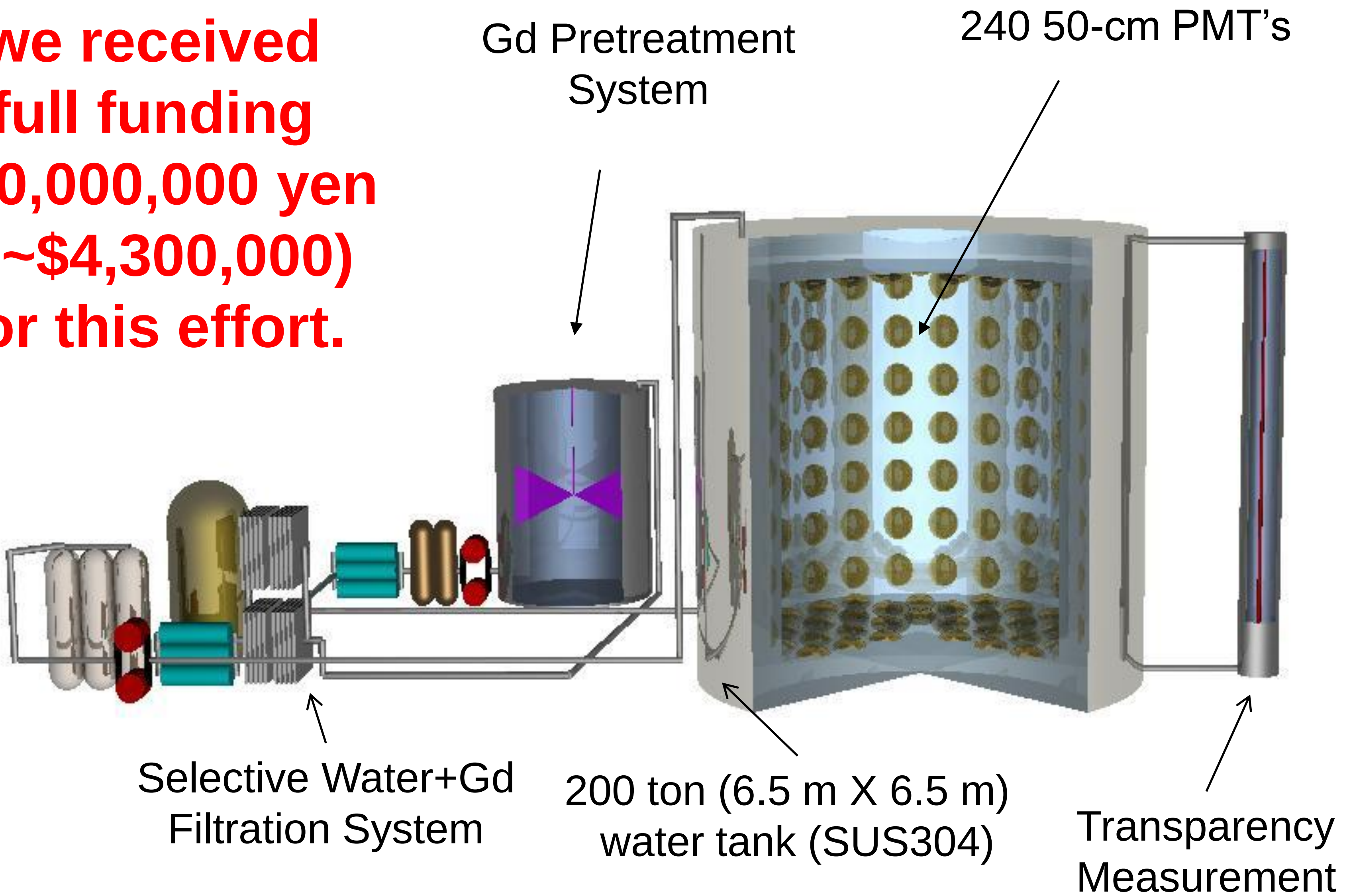
Now, we've built a dedicated Gd test facility, complete with its own water filtration system, 50-cm PMT's, and DAQ electronics.

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



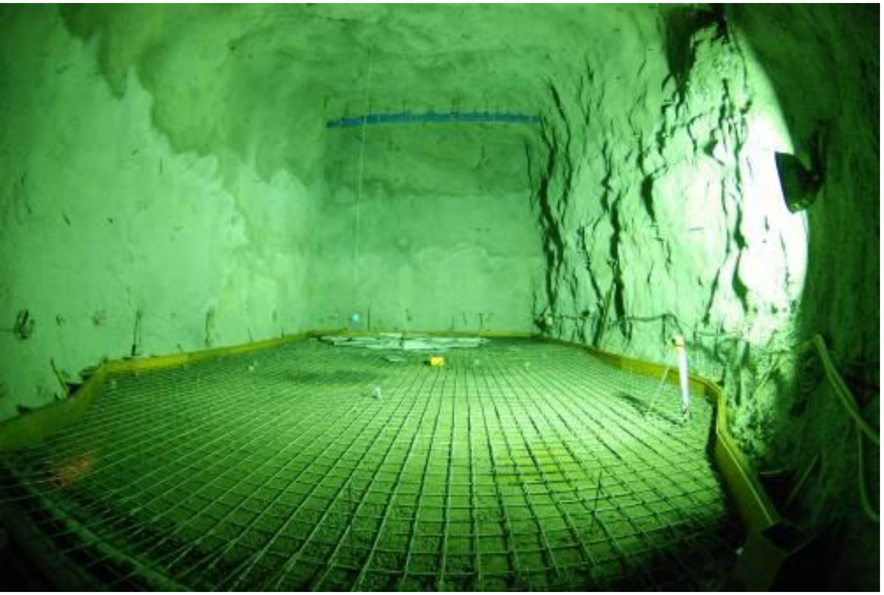
EGADS Facility

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



Hall E and EGADS

12/2009



2/2010

6/2010

12/2010

Adding 383 grams $Gd_2(SO_4)_3$ to 191 liters of H_2O; January 5th, 2011

Resulting solution is rather cloudy; January 5th, 2011

After treating with H_2SO_4, solution is completely clear; January 5th, 2011

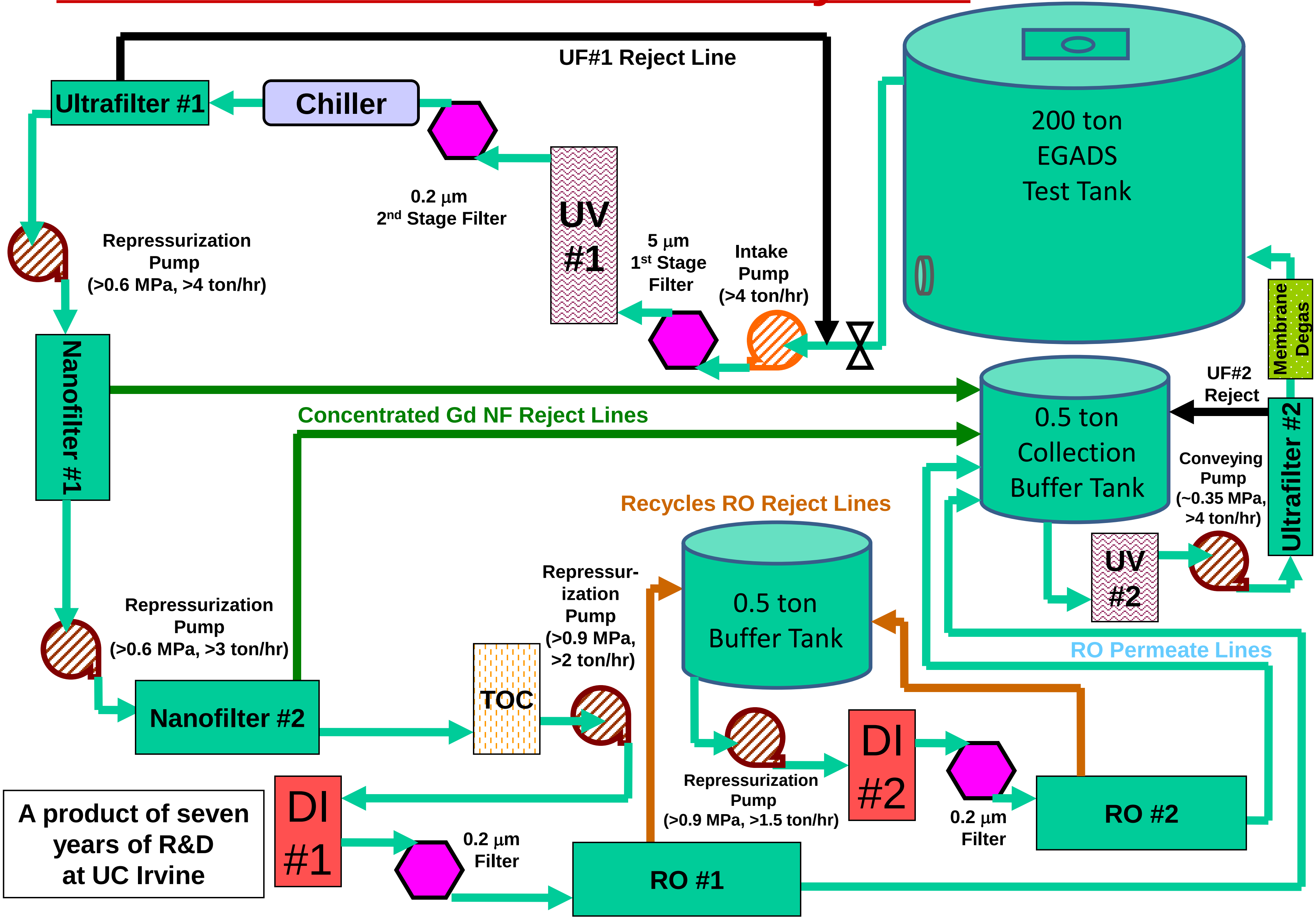
5/2011

2/2011

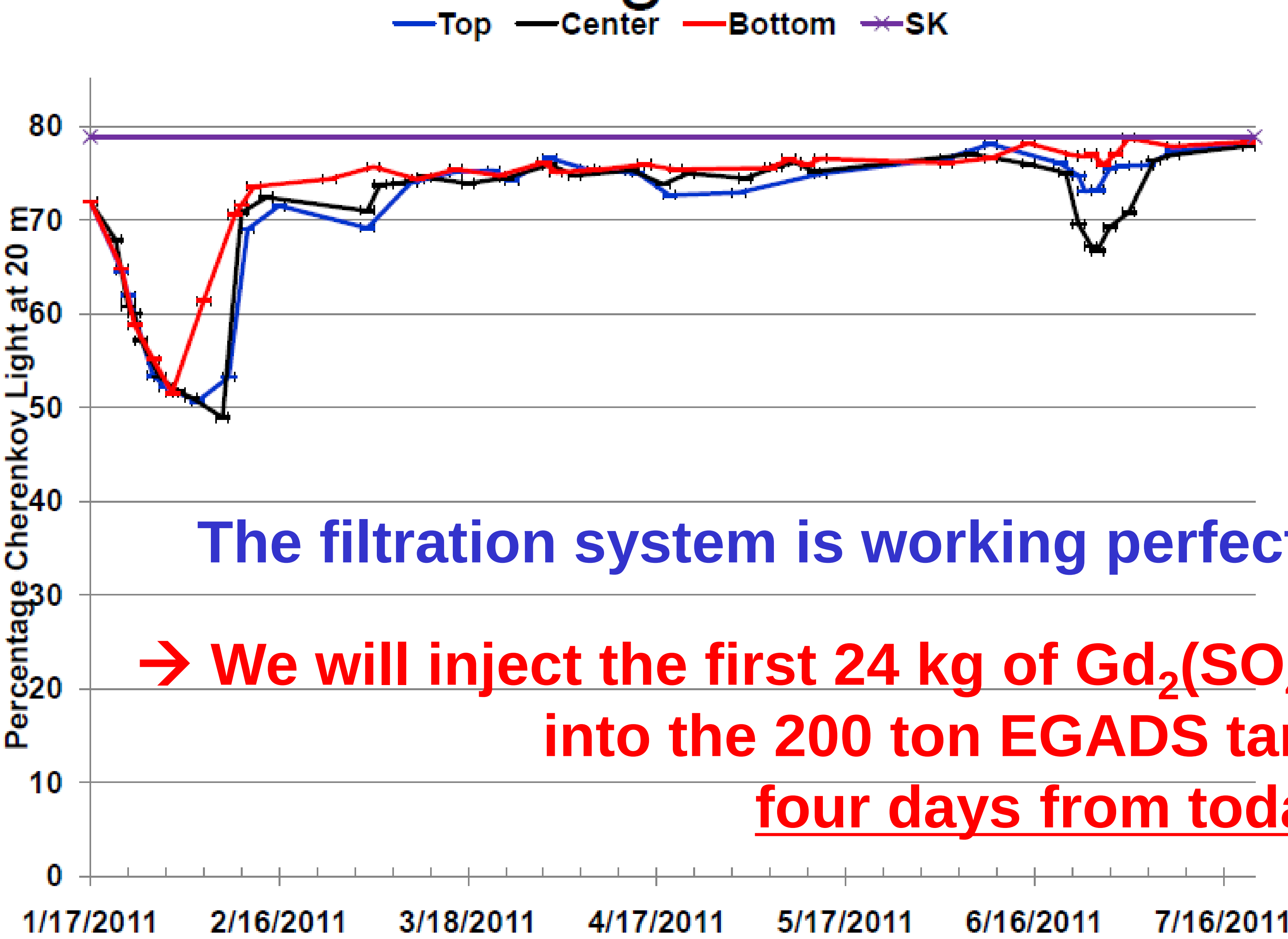
Hall E and EGADS

EGADS Selective Filtration System

June 2011



Cherenkov Light Left At 20 m



The filtration system is working perfectly.

→ We will inject the first 24 kg of $Gd_2(SO_4)_3$ into the 200 ton EGADS tank <u>four days from today!</u>

EGADS Schedule

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

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

2011-13: Experimental program, long-term stability assessment

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

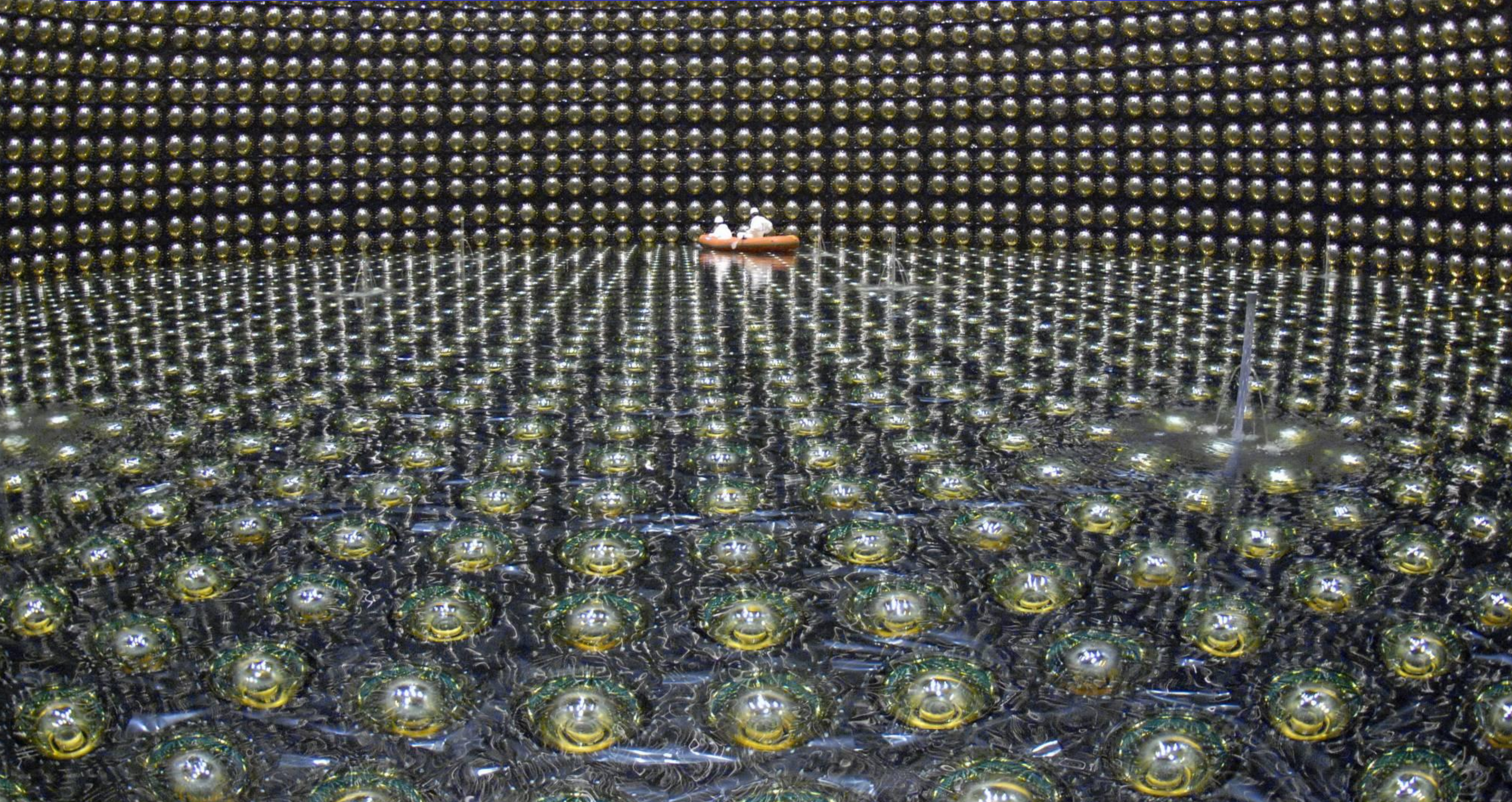
The goal is to be able to state conclusively whether or not gadolinium loading of Super-Kamiokande will be safe and effective.

Target date for decision = mid-2012

→ Gadolinium in SK by 2015, DSNB by 2016! ←

In conclusion:

The experimental community is ready and eager to detect the next galactic supernova.



Exciting discoveries surely await us in the near future!