MeV Neutrino Astrophysics: Supernova Neutrinos in a Gd-loaded Super-Kamiokande

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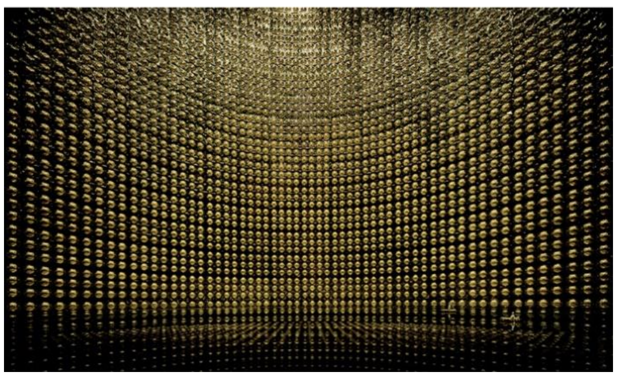
You may have noticed that I am a pretty happy guy…

THE SECRET OF HAPPINESS

What is the secret of (career) happiness?

- Imagine that you had enough money to live comfortably.

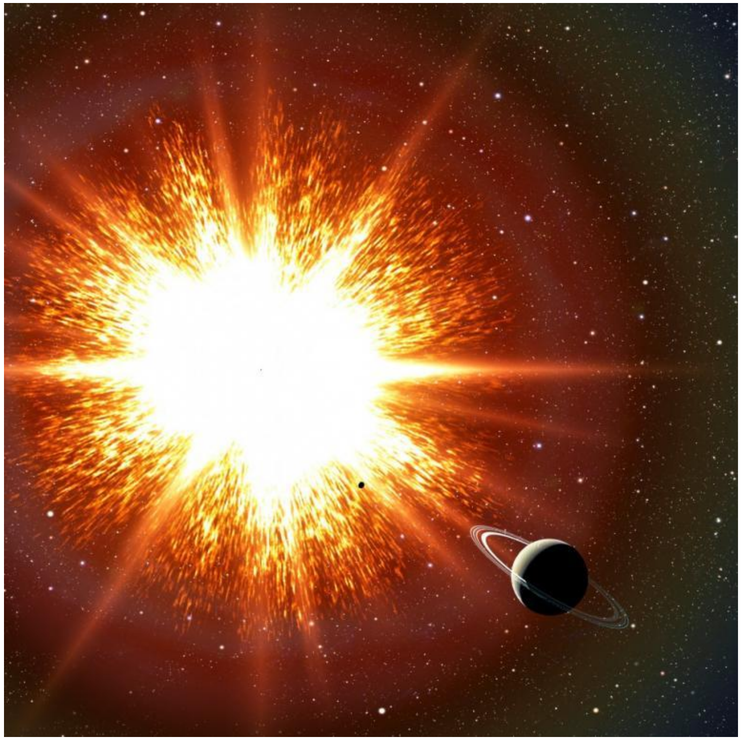


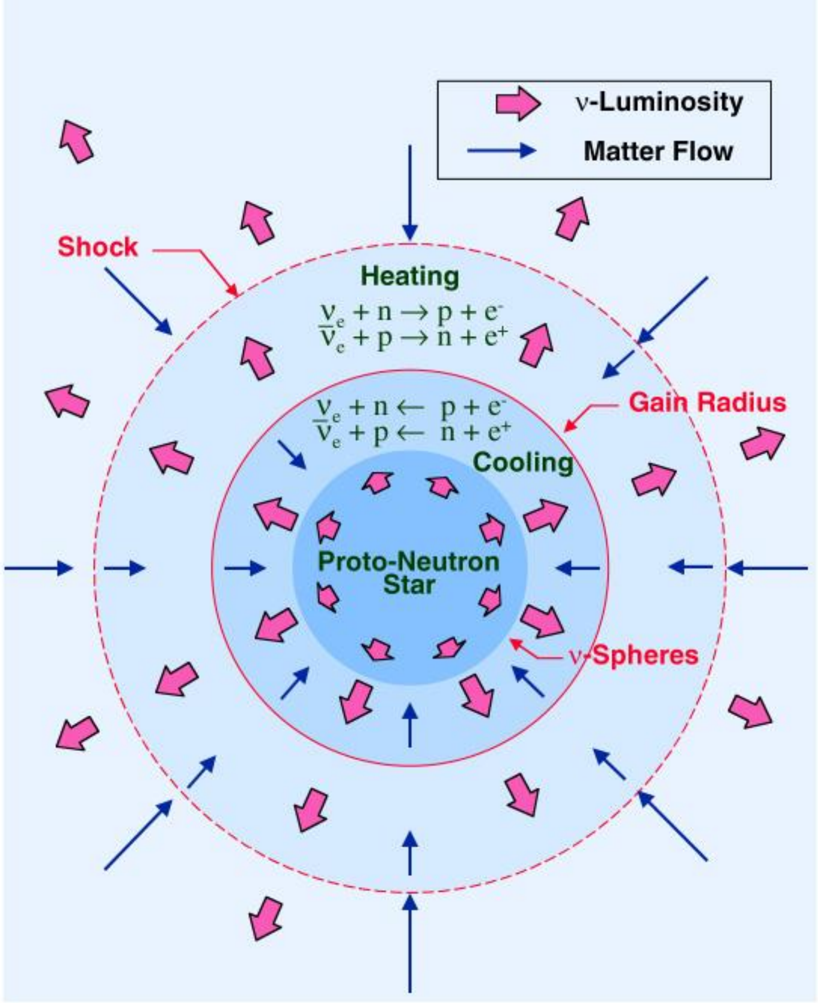
- What in the world would you spend all your free time doing?

- Now, get someone to pay you for doing exactly that!

A core-collapse supernova is a nearly perfect "neutrino bomb".

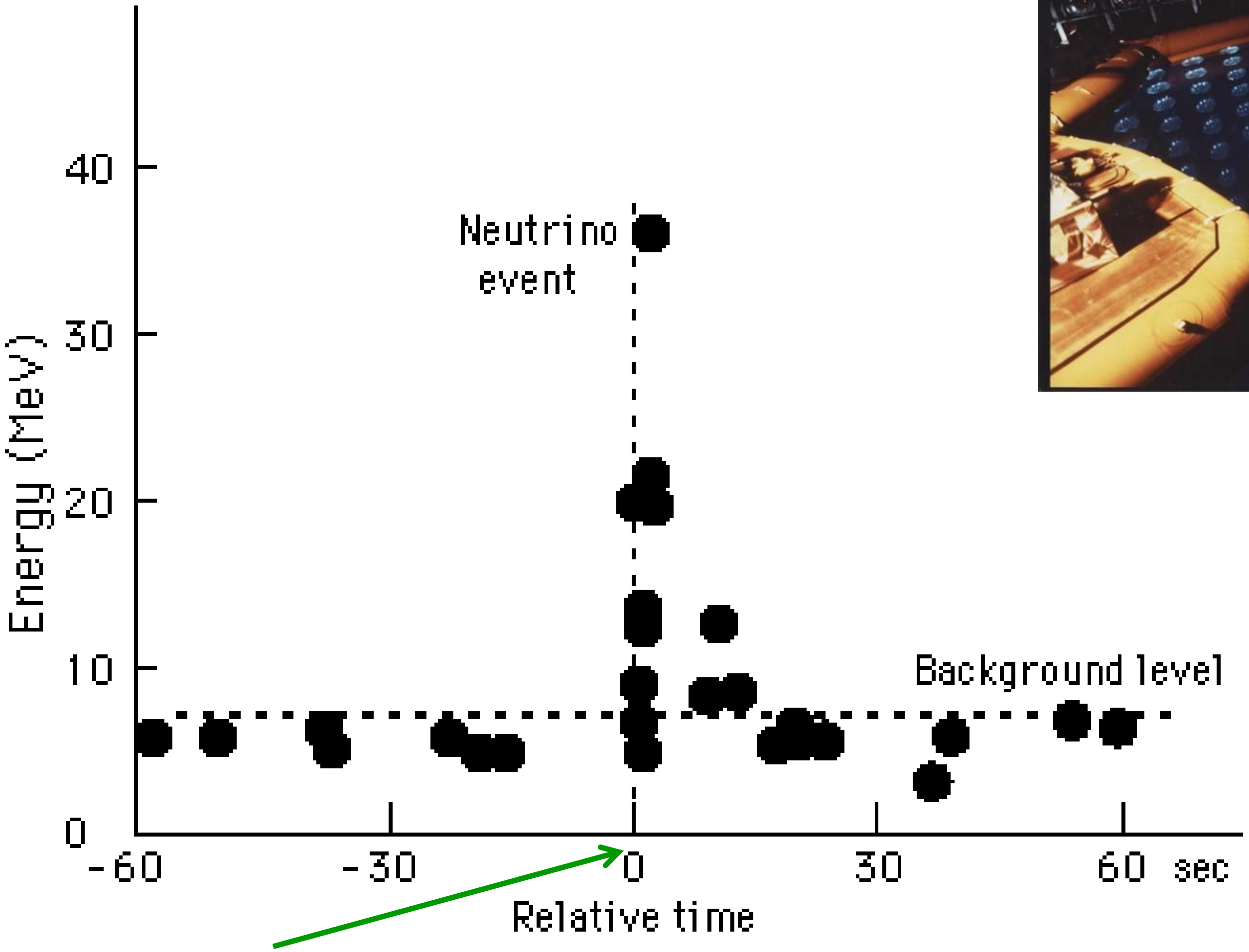
Within ten seconds of collapse it releases >98% of its huge energy (equal to 10^{12}, hydrogen bombs exploding every second since the beginning of the universe!) as neutrinos.

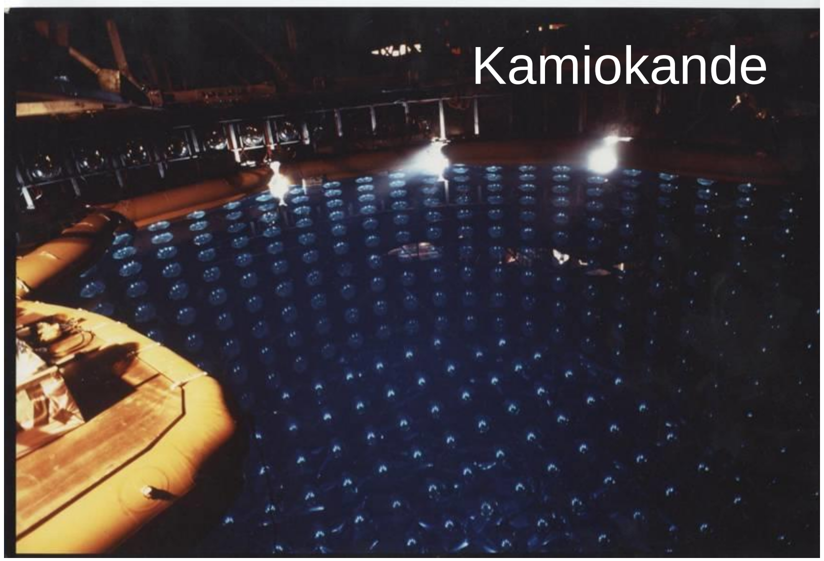


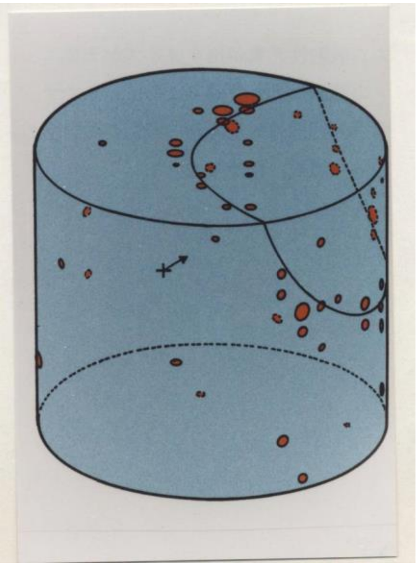


Neutrinos, along with gravitational waves, provide the only possible windows into core collapses' inner dynamics.

Kamiokande's Burst Time Structure

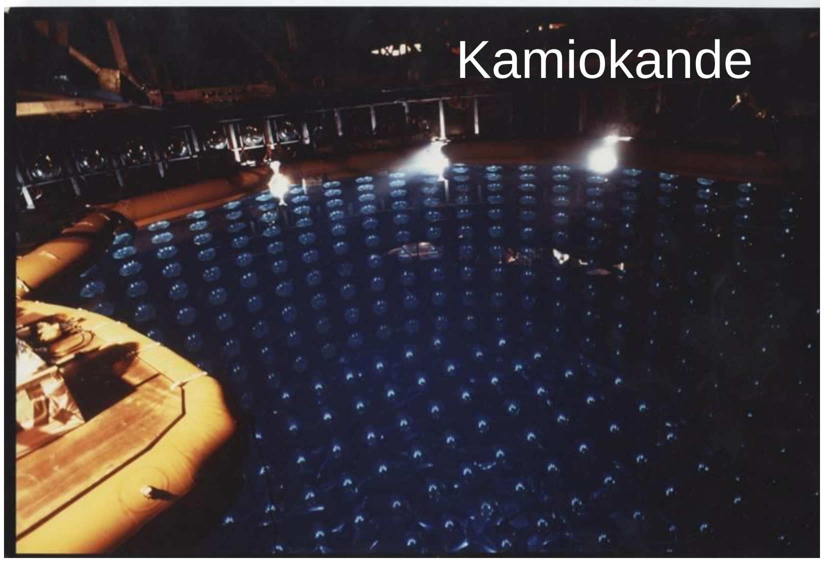


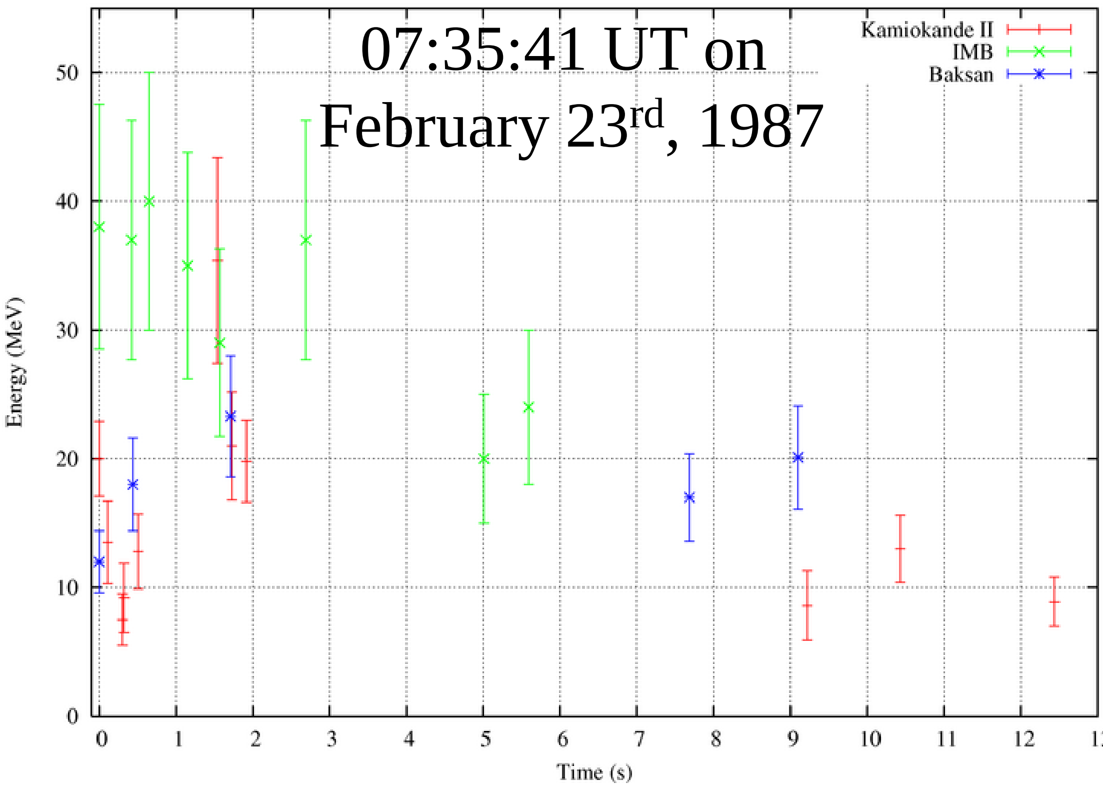




16:35:41 JST on February 23rd, 1987

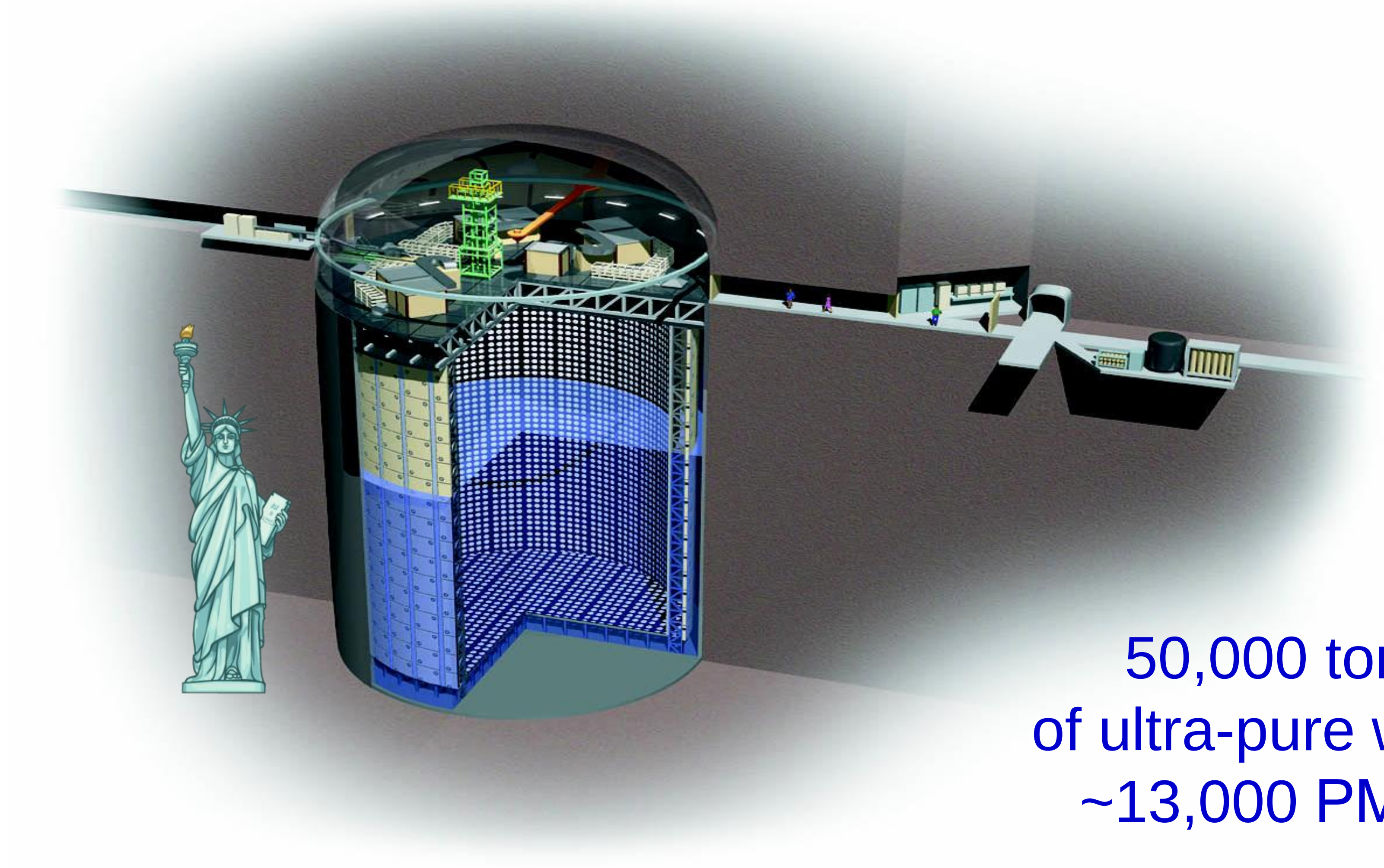
SN1987A's neutrinos also seen simultaneously by IMB (in the US) and Baksan (in the Soviet Union)





One paper every 10 days… for 32 years!

My beloved Super-Kamiokande
– already the best supernova ν detector in the world –
has been taking data, with an occasional interruption,
for over twenty years now… but no SN neutrinos so far!

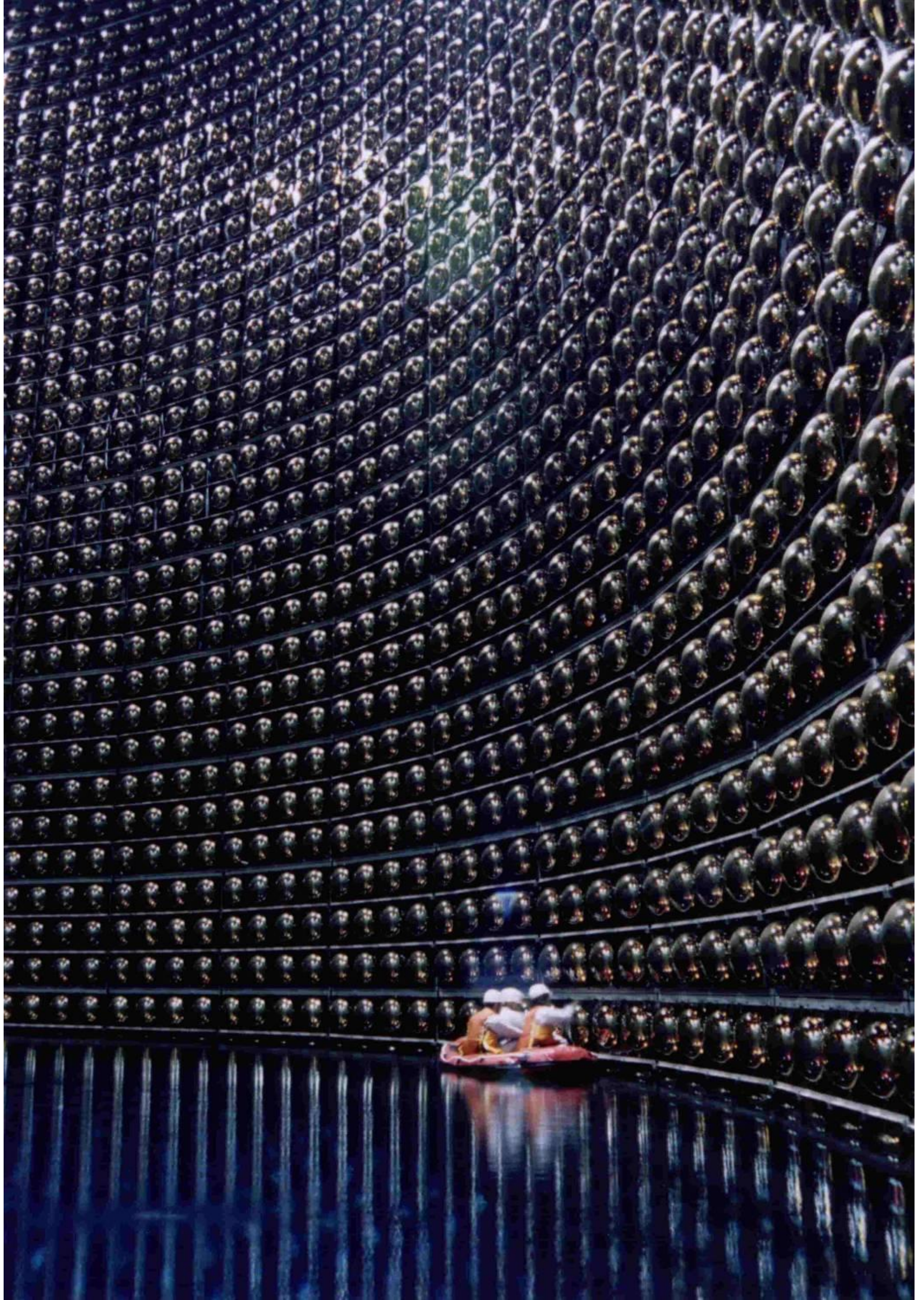


50,000 tons
of ultra-pure water,
~13,000 PMT's

50,000 tons of ultra-pure H_2O

13,000 light detectors

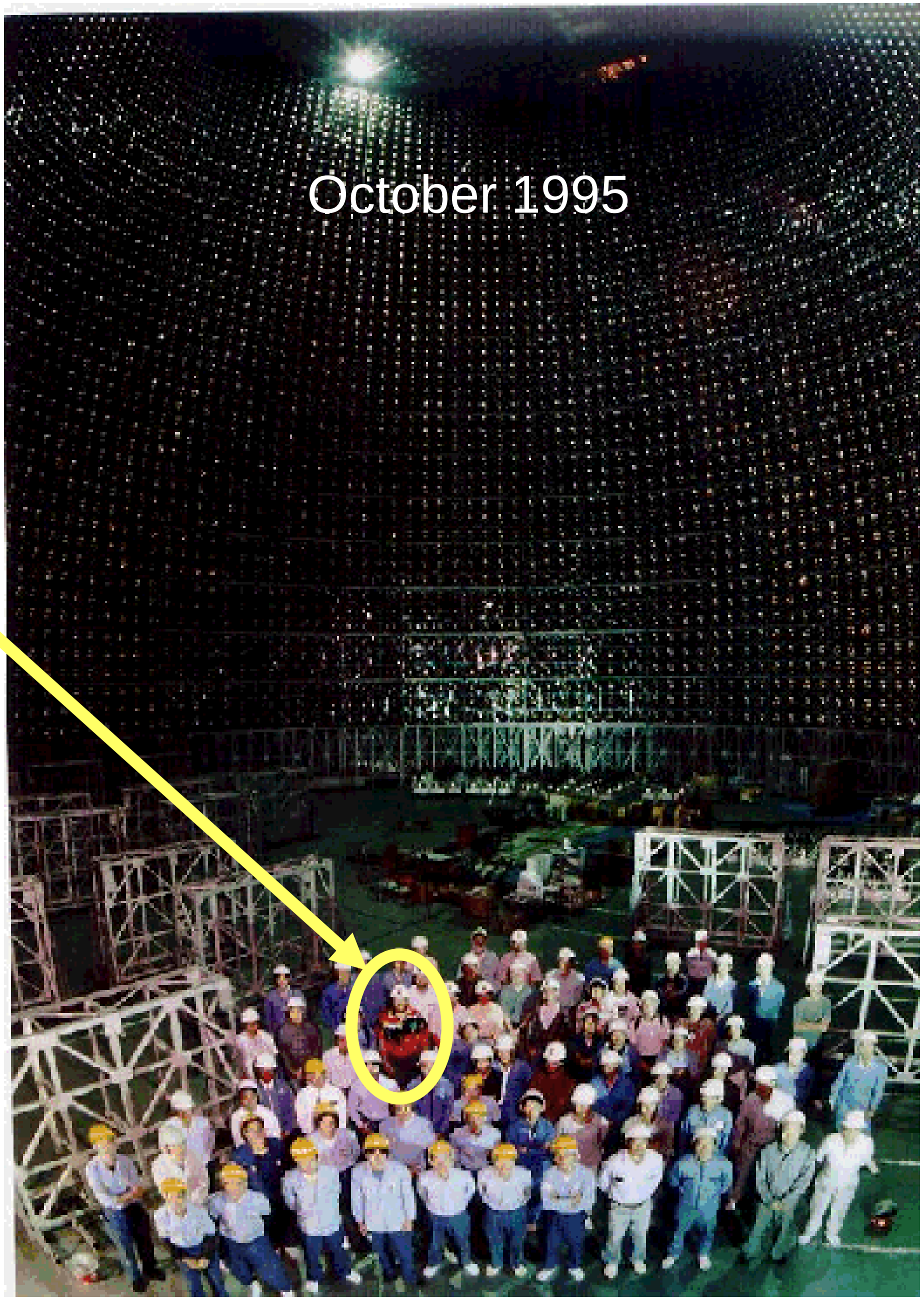
One kilometer underground



Observes particles from the Sun, supernovas, and cosmic rays

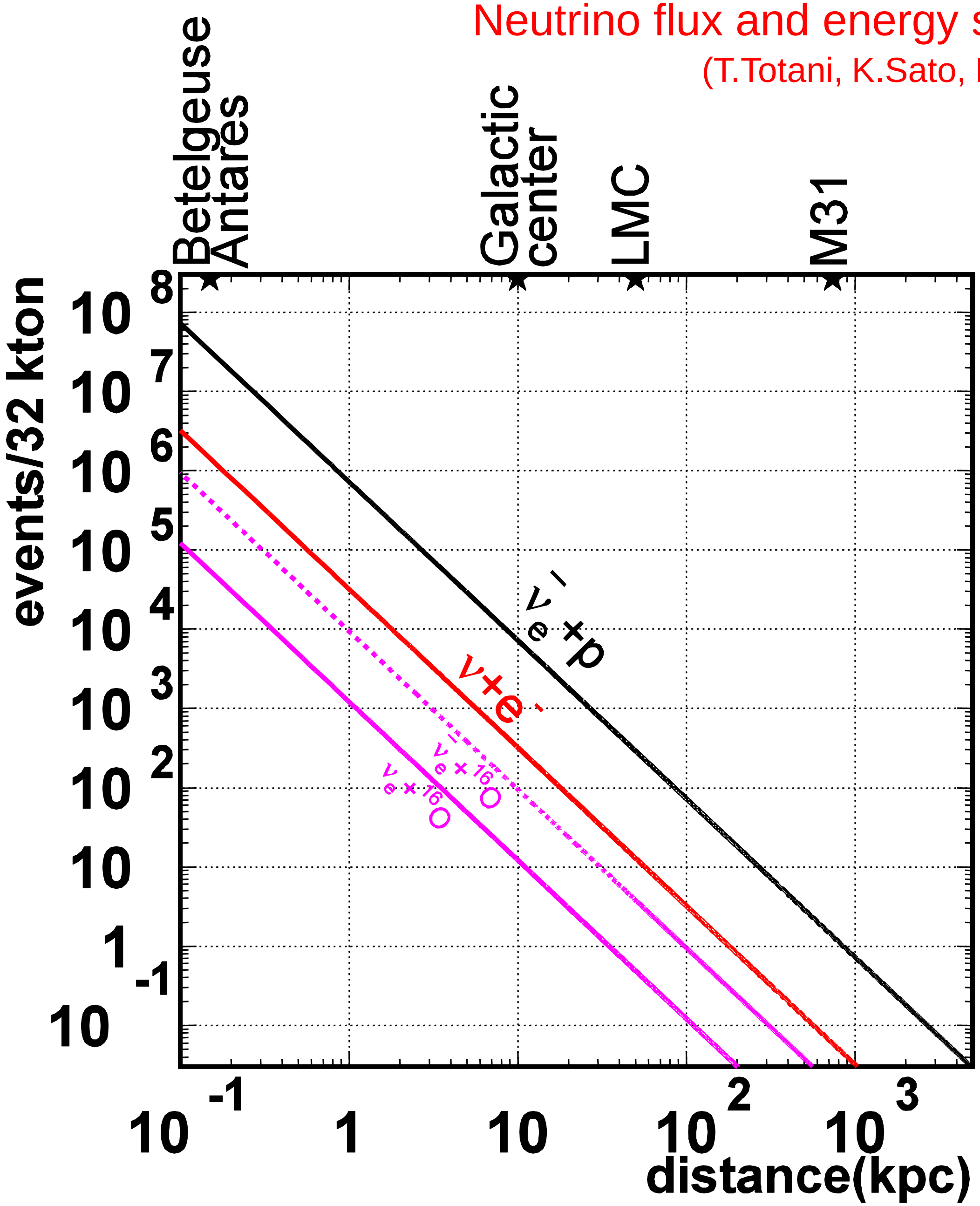
I've been a part of Super-K (and wearing brightly-colored shirts) from its very early days…

January 1996



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))



For 10 kpc, 5 MeV threshold, no oscilation

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

~300 ν+e events

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

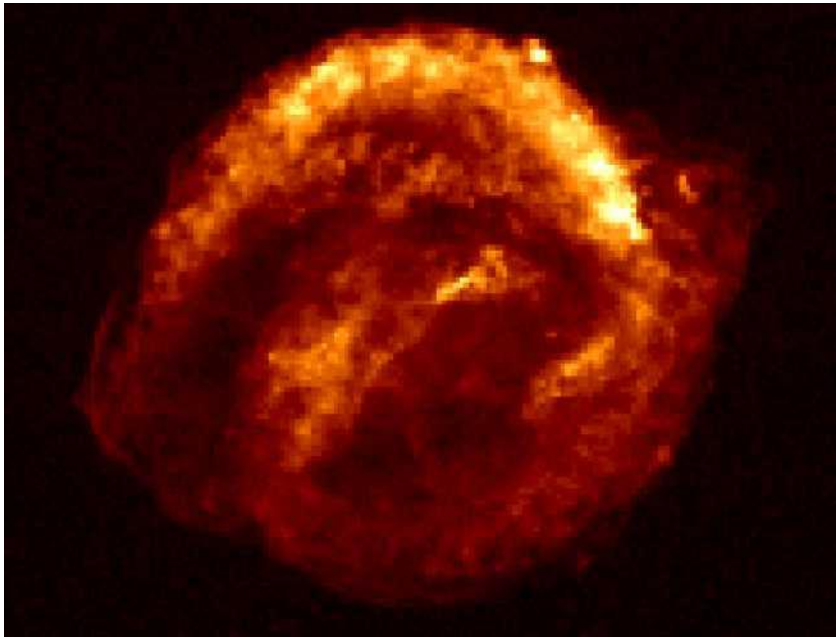
~5^o pointing from ν+e ES

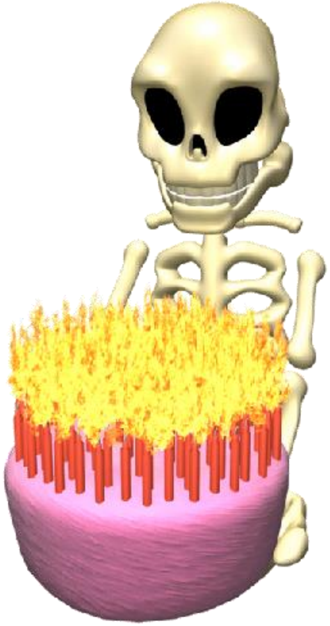
Nakazato simulation: ~50% less flux
(K.Nakazato, K.Sumiyoshi, H.Suzuki, T.Totani, H.Umeda,and S.Yamada, ApJ.Suppl. 205 (2013) 2)

Super-Kamiokande is ready and
waiting to detect supernova neutrinos from
an explosion anywhere in our galaxy.

→ We will let the world know the light is on its way. ←

Indeed, we would very much like to collect some more supernova neutrinos!





But it has already been nearly a third of a century since SN1987A, and as of today it has been exactly <u>414 years and 187 days</u> since the last time a supernova was definitely observed within our own galaxy.

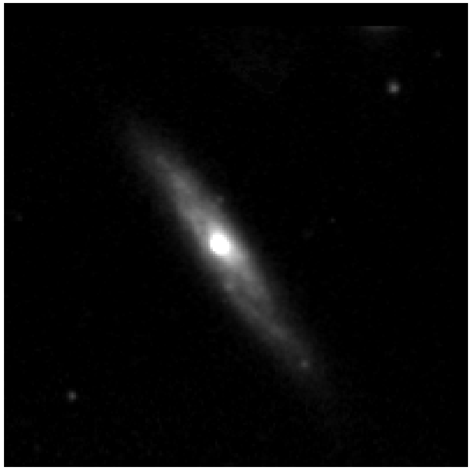
Yes, it's been a long, cold winter for SN neutrinos…

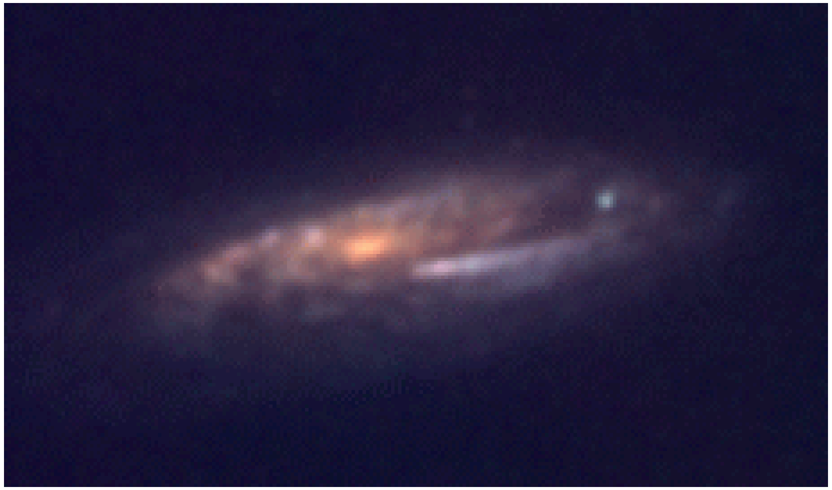
but there is hope!

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

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

Yes, <u>nearby</u> supernova explosions may be rare, but supernova explosions are extremely common.



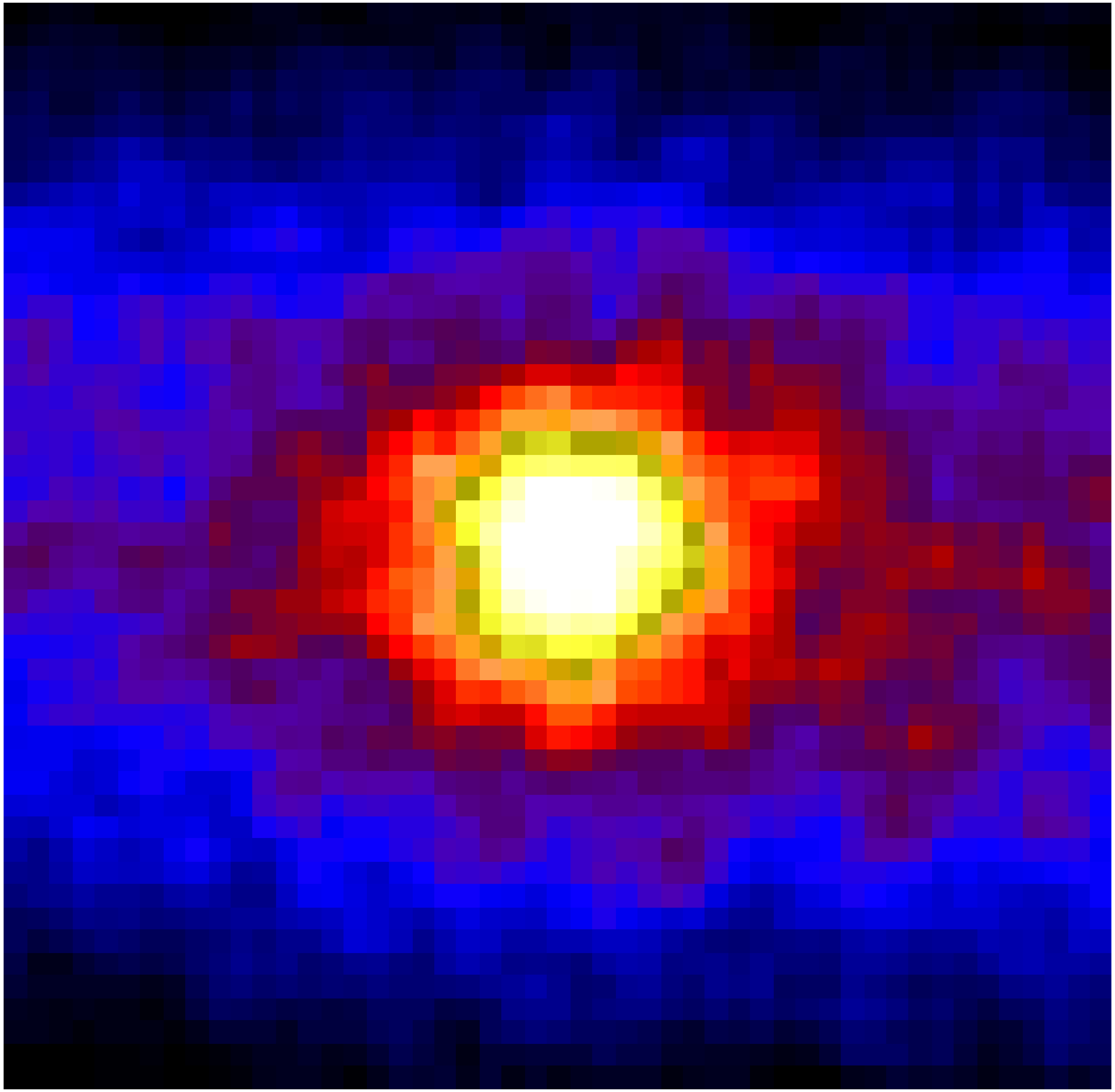


Here's how most supernovas look to us (video is looped).

There is about ***one SN explosion per second*** in the universe as a whole.

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

A Super-K image of the Sun in MeV solar neutrino "light".



Solar flux = 10^6 X DSNB

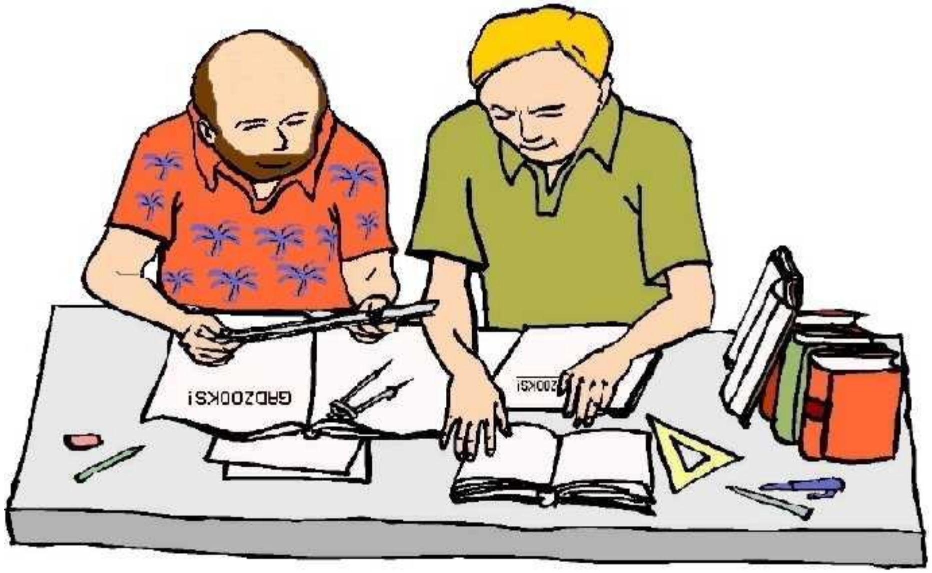
Galactic SN = 10^{6-11} X solar flux

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."

גדוליניום

"Gadol" = Great!



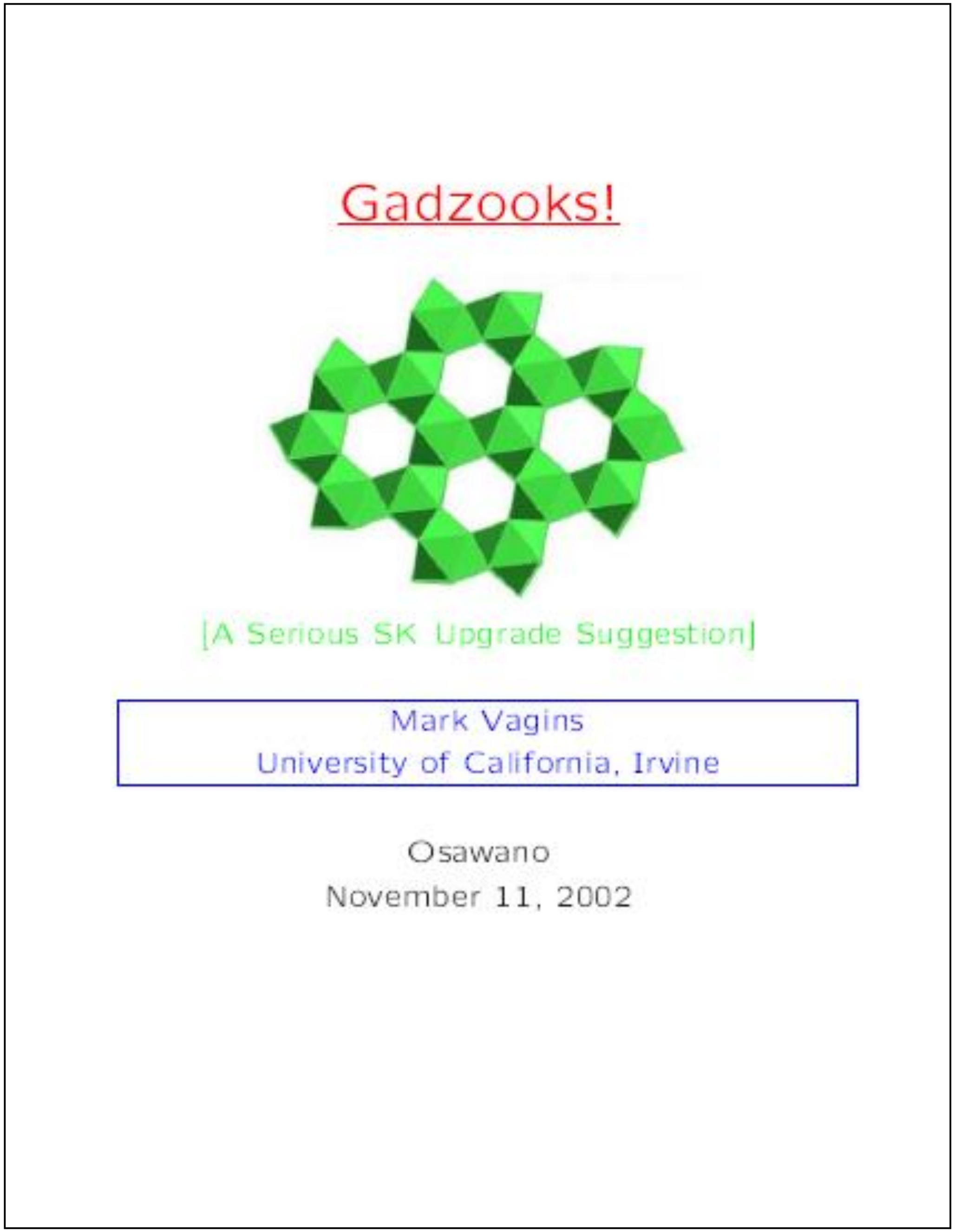
Inspired by this call to action, theorist John Beacom and I wrote the original GADZOOKS!

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

It proposed loading big WC detectors, specifically Super-K, with water soluble gadolinium, and evaluated the physics potential and backgrounds of a giant antineutrino detector.

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

(359 citations → one every 15 days for fifteen years)

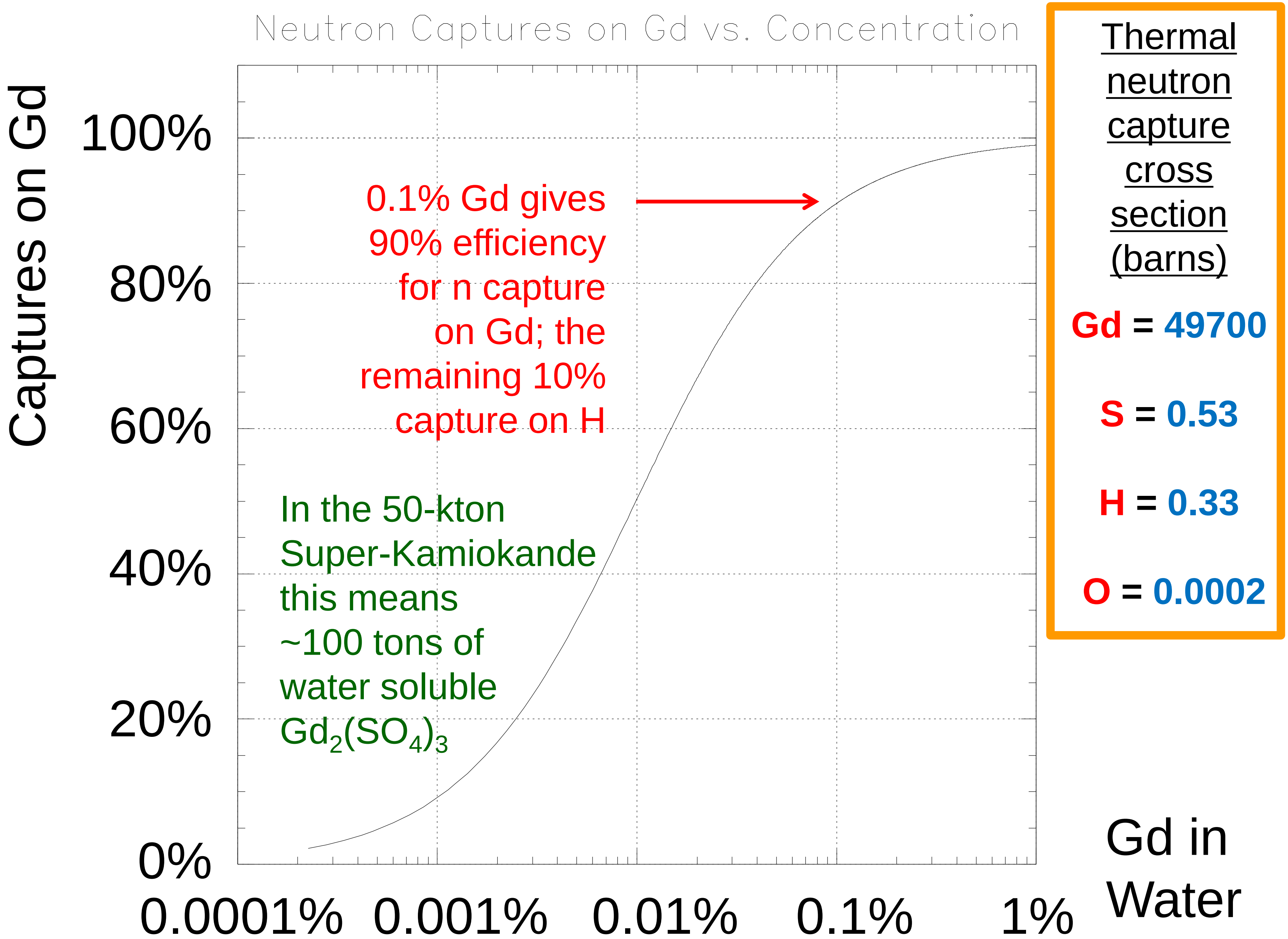


Here's the very first transparency (i.e., what we older folks used before PowerPoint but after glass slides) I ever showed on the topic…

over sixteen years ago.

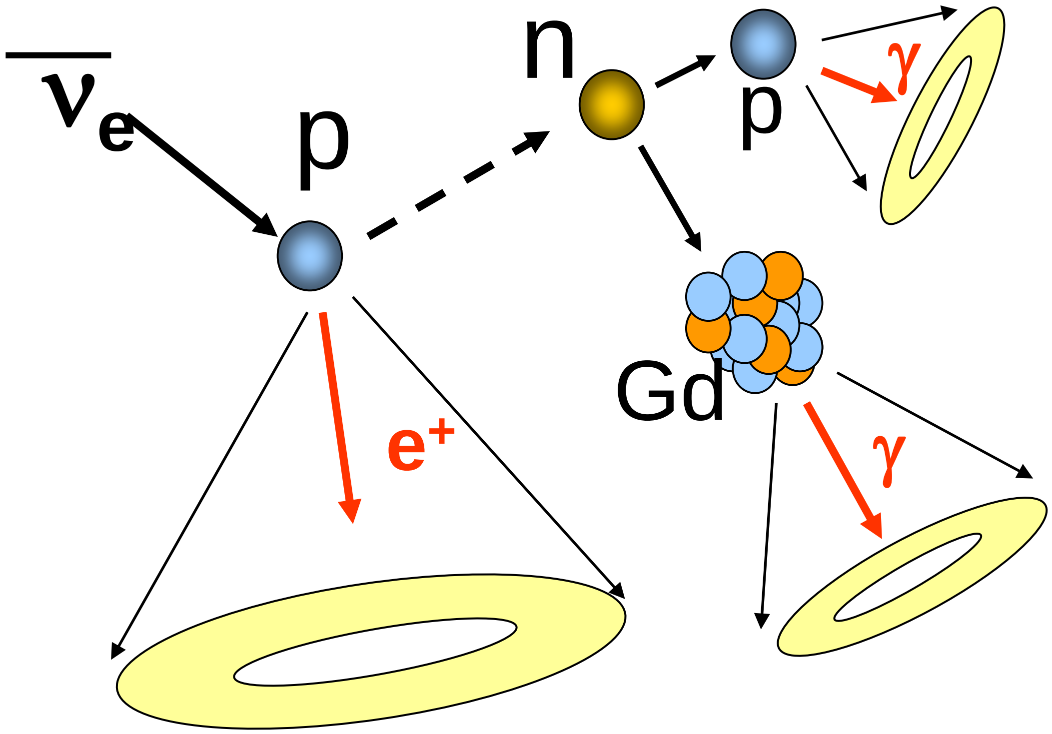
Please note the subtitle:

"A Serious SK Upgrade Suggestion"



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 on Gd; the remaining 10% capture on H
In the 50-kton Super-Kamiokande this means ~100 tons of water soluble $Gd_2(SO_4)_3$
Thermal neutron capture cross section (barns)
Gd = 49700
S = 0.53
H = 0.33
O = 0.0002

Basically, we said, “Let’s add 0.2% of a water soluble gadolinium compound to Super-K!”



Possibility 1: 10% or less

$n+p \rightarrow d + \gamma$

2.2 MeV 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.

Super-K currently records just <u>three fake neutrino-like singles (events) per cubic meter per year,</u> but this still overwhelms the faint DSNB signal.

[K. Bays *et al.*, Phys.Rev. D85 (2012) 052007].

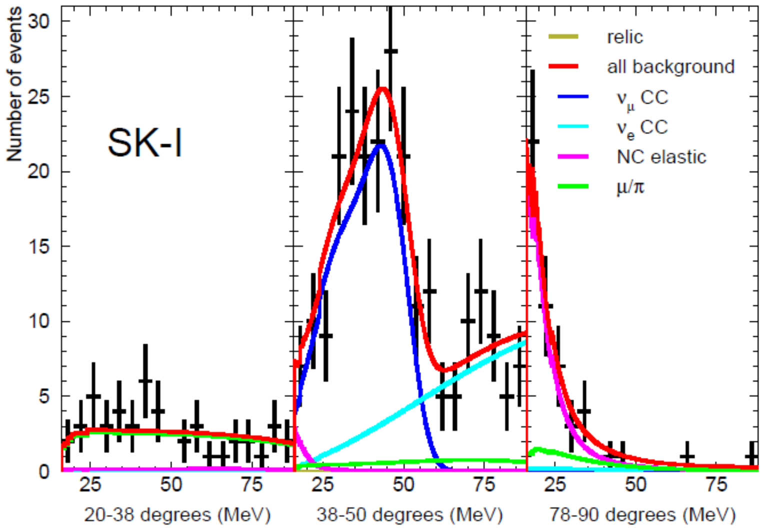


FIG. 14. SK-I LMA best fit result. The relic best fit is negative, so a relic fit of 0 is shown.

The Gd tagging technique will greatly reduce the fakes, allowing event-by-event identification of true SN events.

We would expect to collect an SN1987A-scale neutrino sample in Super-K <u>every two years.</u>

But, um, didn't you just say 100 *tons* of gadolinium? What's that going to cost?

In 1984: \$4000/kg –> \$400,000,000

In 1993: \$485/kg –> \$48,500,000

In 1999: \$115/kg –> \$11,500,000

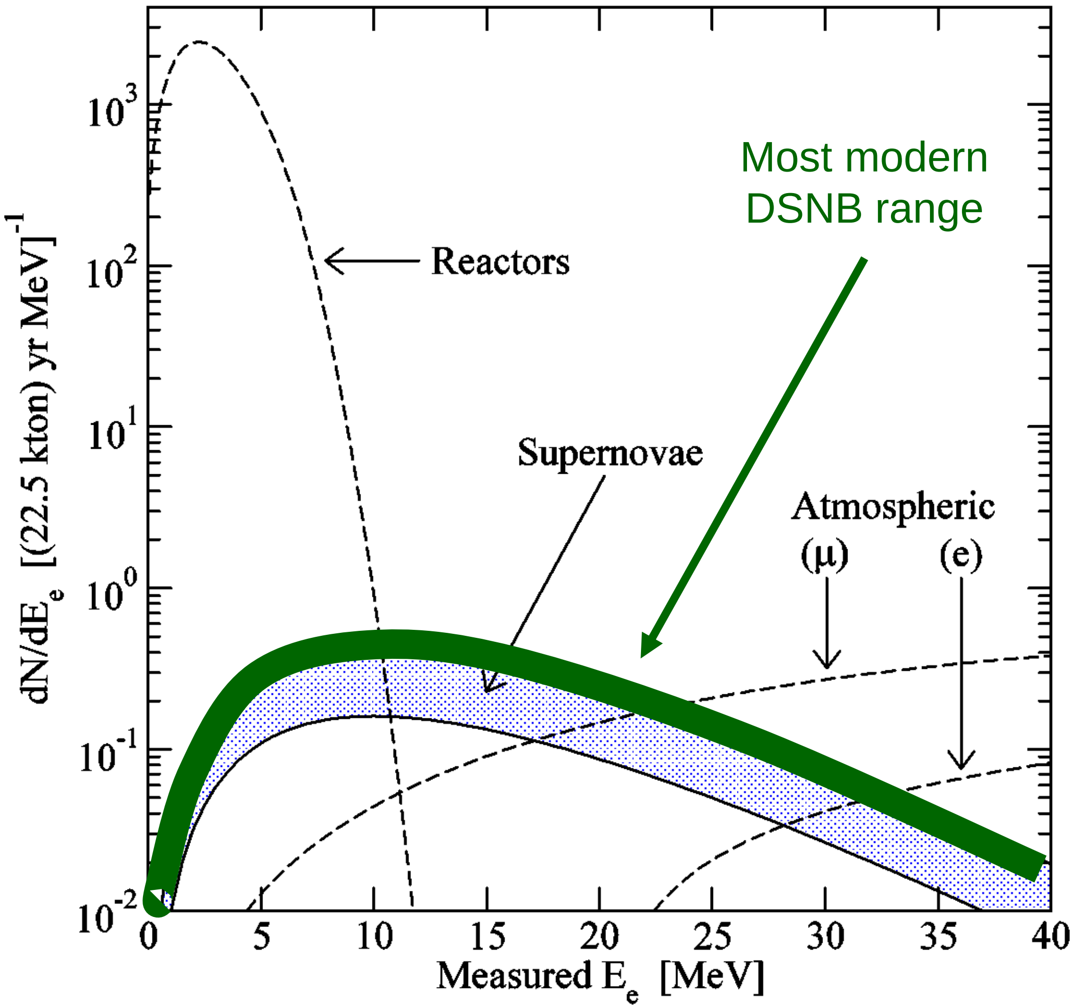
In 2006: \$5/kg –> \$500,000

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):



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

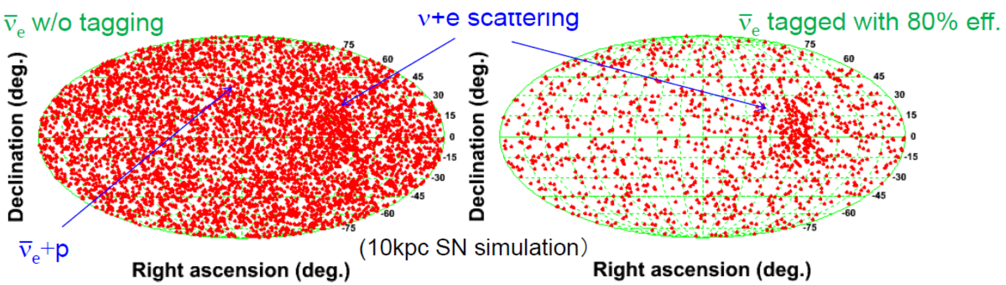
spatial and temporal separation between prompt e^+ Cherenkov light and delayed Gd neutron capture gamma cascade:

λ=~4cm, τ=~30μs

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

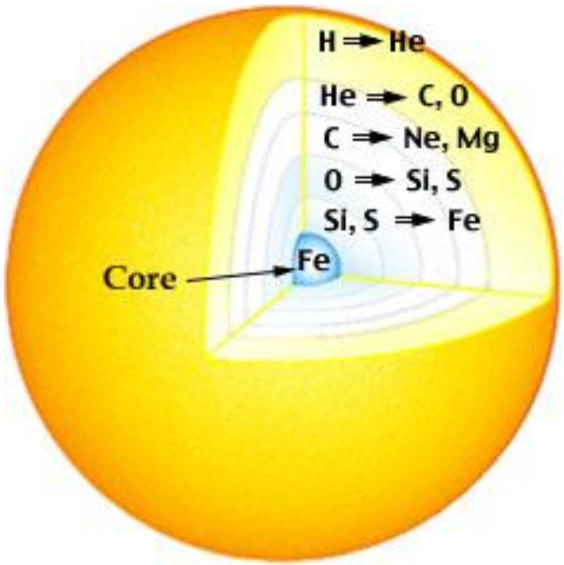
In the case of a galactic supernova, having $Gd_2(SO_4)_3$ in Super-K will provide many important benefits:

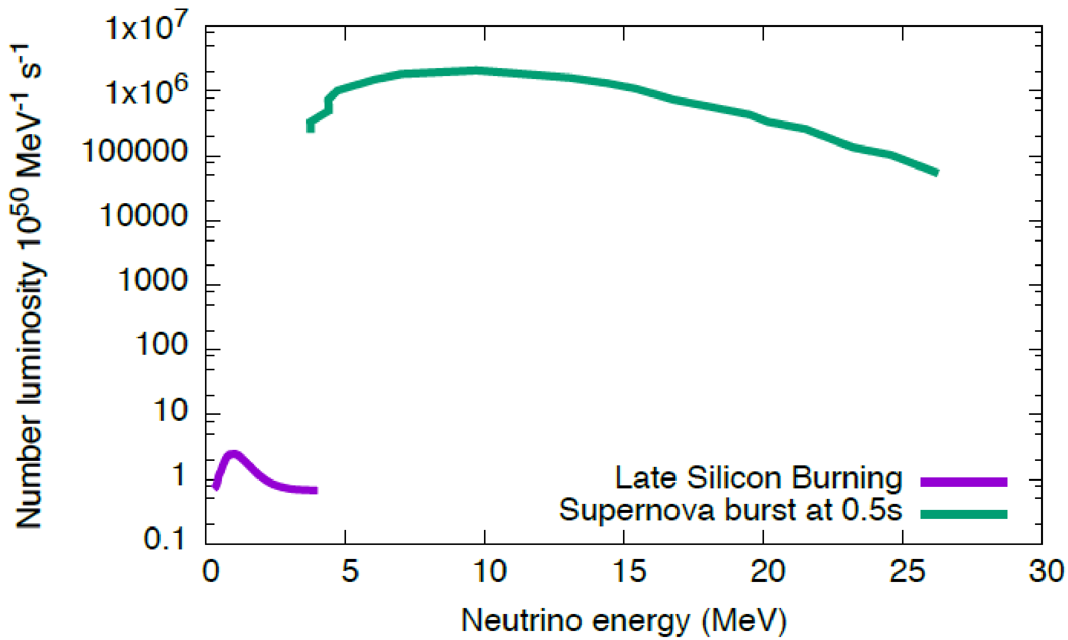
- Allows the exact $\bar{\nu}_e$ flux, energy spectrum, and time profile to be determined via the extraction of a tagged, pure sample of inverse beta events.
- Instantly identifies a burst as genuine via “Gd heartbeat”.
- Doubles the ES pointing accuracy. Error circle cut by 75%.



- Helps to identify the other neutrino signals, especially the weak neutronization burst of ν_e.
- Enables a search for very late time black hole formation.
- Provides for very early warning of the most spectacular, nearby explosions so we can be sure not to miss them.

Odrzywodek *et al.* were the first to suggest that late-stage Si burning in very large, very close stars could provide useful early warning of a core collapse supernova in a Gd-loaded Super-Kamiokande.





[C. Simpson]

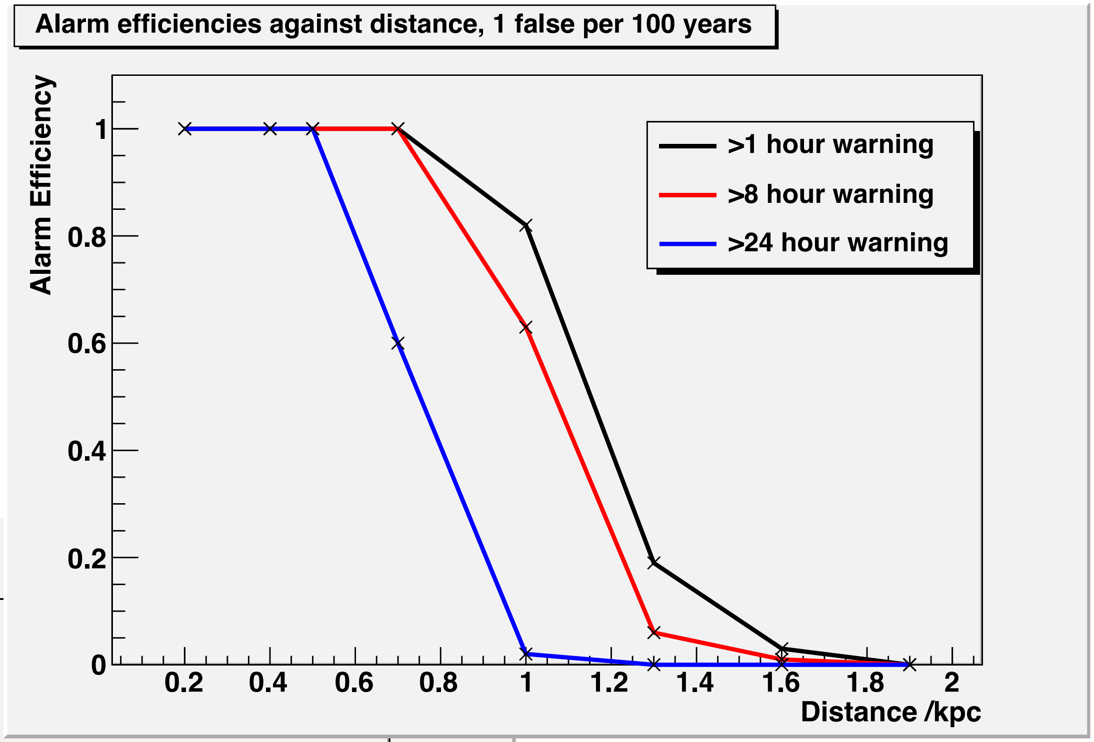
$$e^+ + e^- \rightarrow \bar{\nu}_e + \nu_e$$ (just above inverse beta threshold)

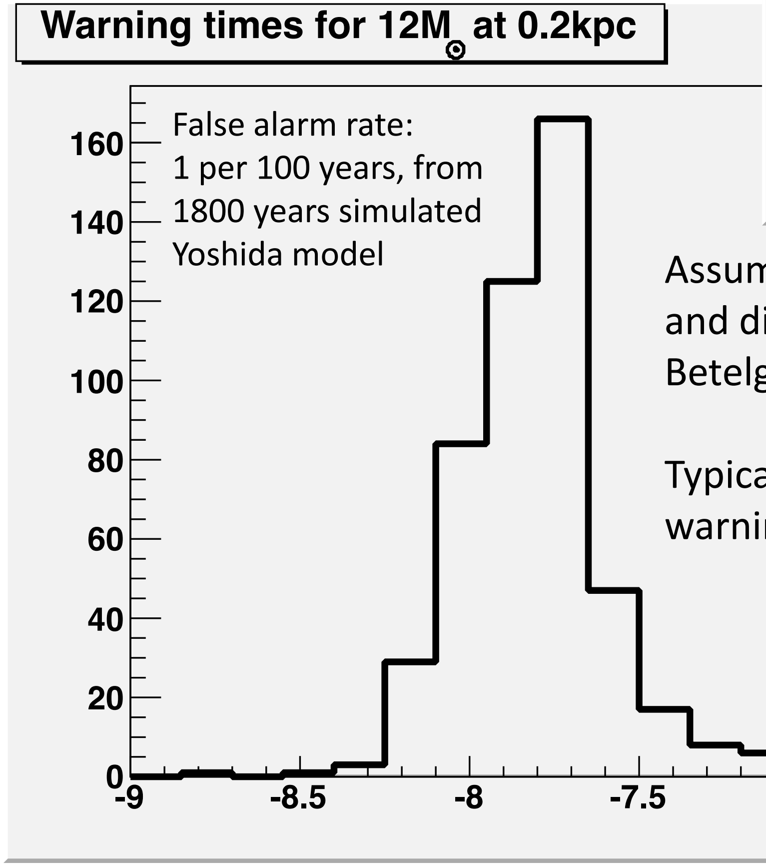
$$\bar{\nu}_e + p \rightarrow e^+ + n$$ (e^+ barely relativistic)

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

Gd-loaded Super-Kamiokande's Sensitivity to pre-SN ν's

(Super-K internal study)





Assuming reasonable mass and distance for Betelgeuse

Typical unambiguous warning time is 8 days

[C. Simpson]

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

[Snowbird photo by A. Kusenko]

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

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 continue Gd studies there.

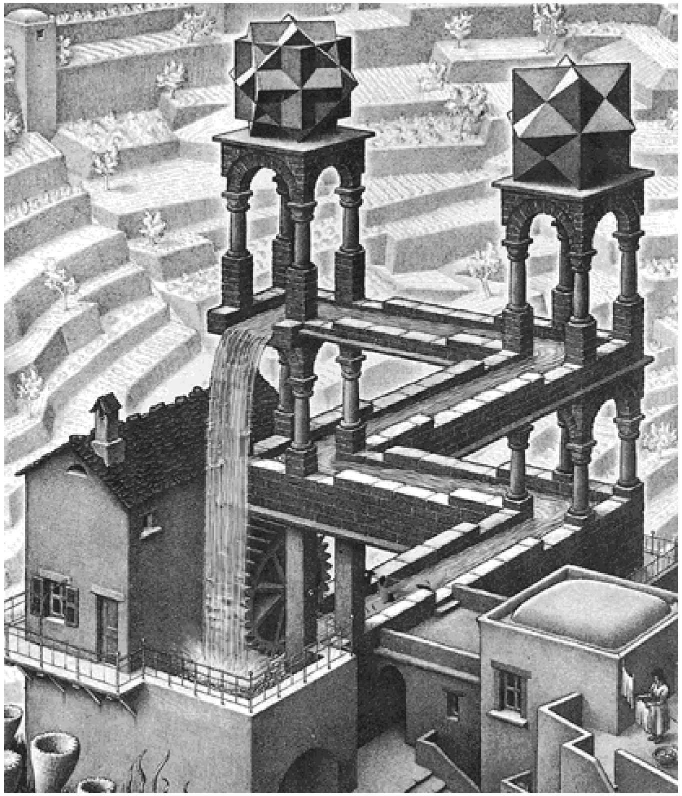
I was explicitly hired to make gadolinium work in water!

IPMU INSTITUTE FOR THE PHYSICS AND MATHEMATICS OF THE UNIVERSE

The Essential Magic Trick

→ We must keep the water in any Gd-loaded detector perfectly clean… *without removing the dissolved Gd.*

→ I've developed a new technology:
"Molecular Band-Pass Filtration"
Staged nanofiltration selectively retains Gd while removing impurities.



Amazingly, the darn thing works!

This technology will support a variety of applications, such as:

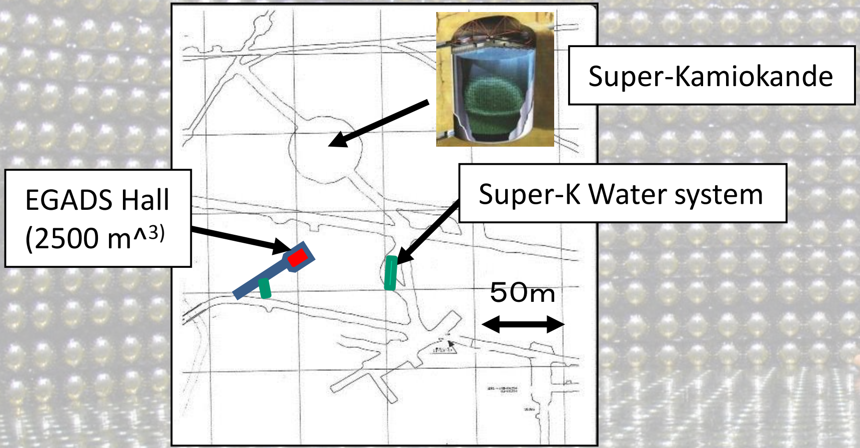
→ Supernova neutrino and proton decay searches

→ Remote detection of clandestine fissile material production

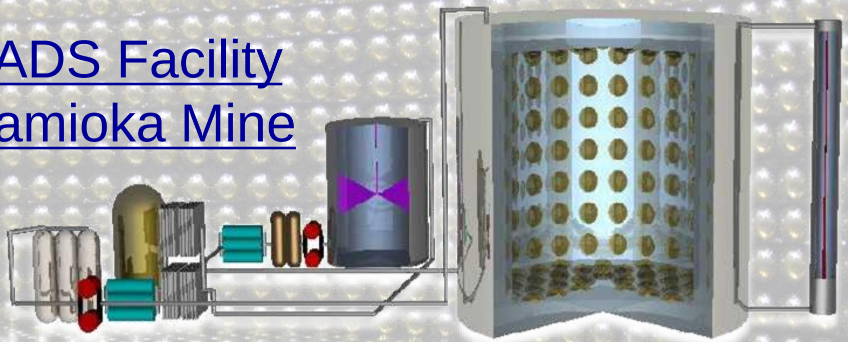
→ Efficient generation of clean drinking water without electricity

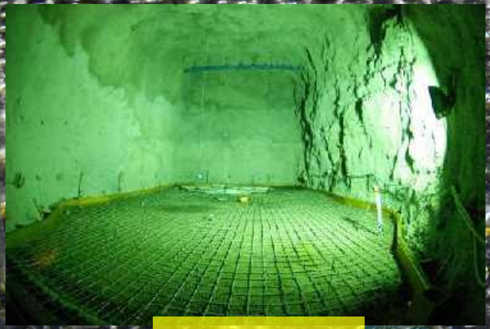
EGADS → Gd-loaded Super-K

To show everything was going to work as expected, we built **EGADS** (Evaluating Gadolinium's Action on Detector Systems), a dedicated Gd demonstrator which includes a working 200-ton scale model of SK.

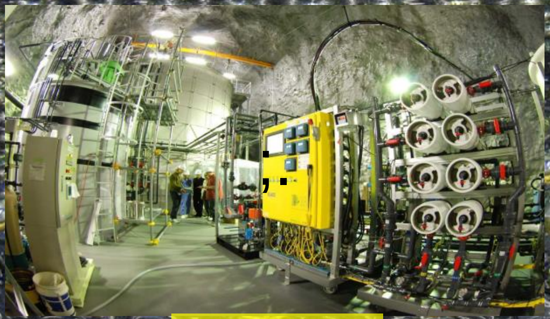


EGADS Facility in Kamioka Mine



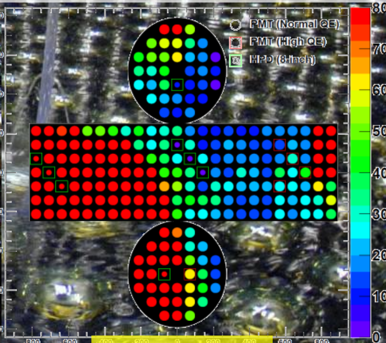


12/2009

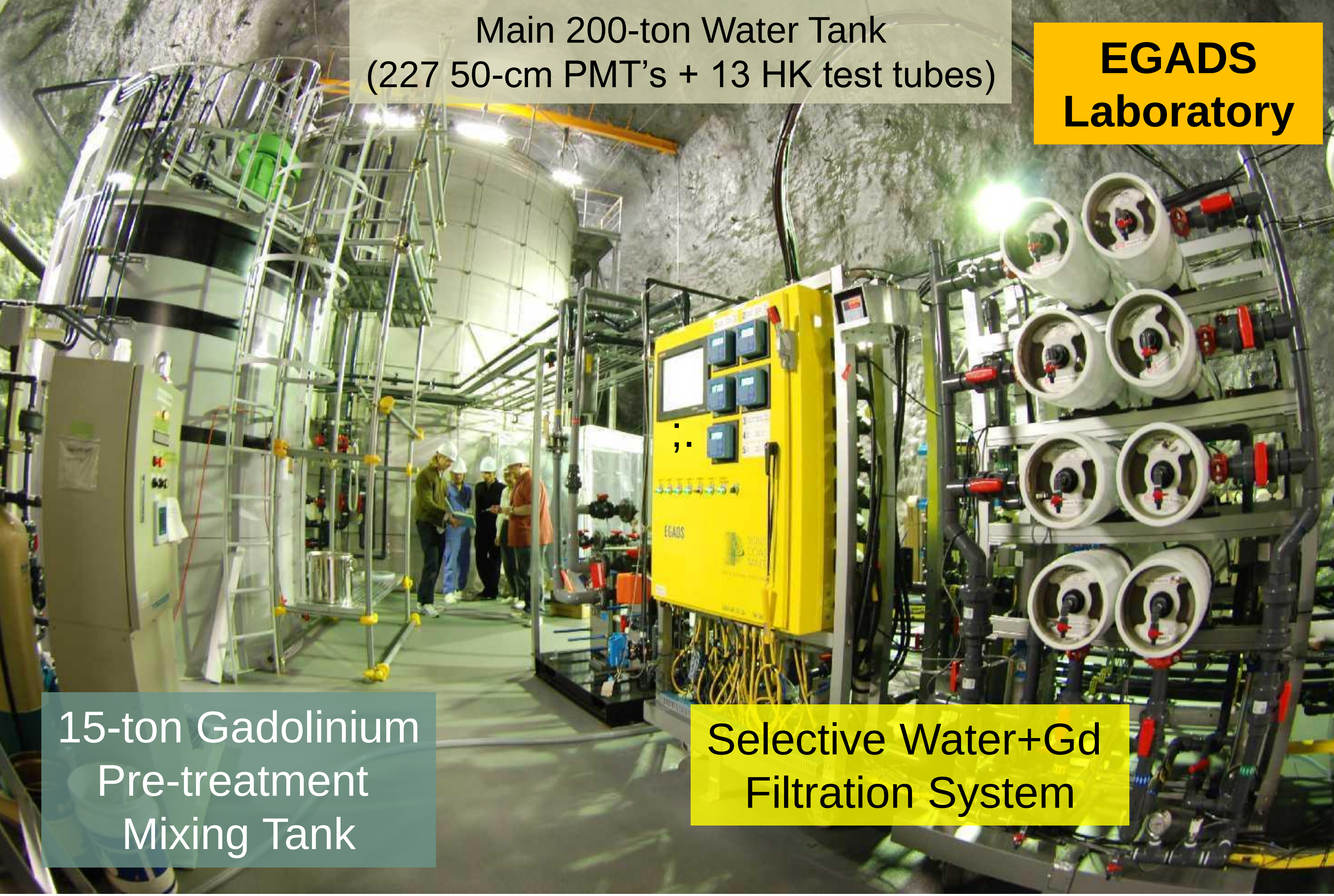


11/2011

8/2013



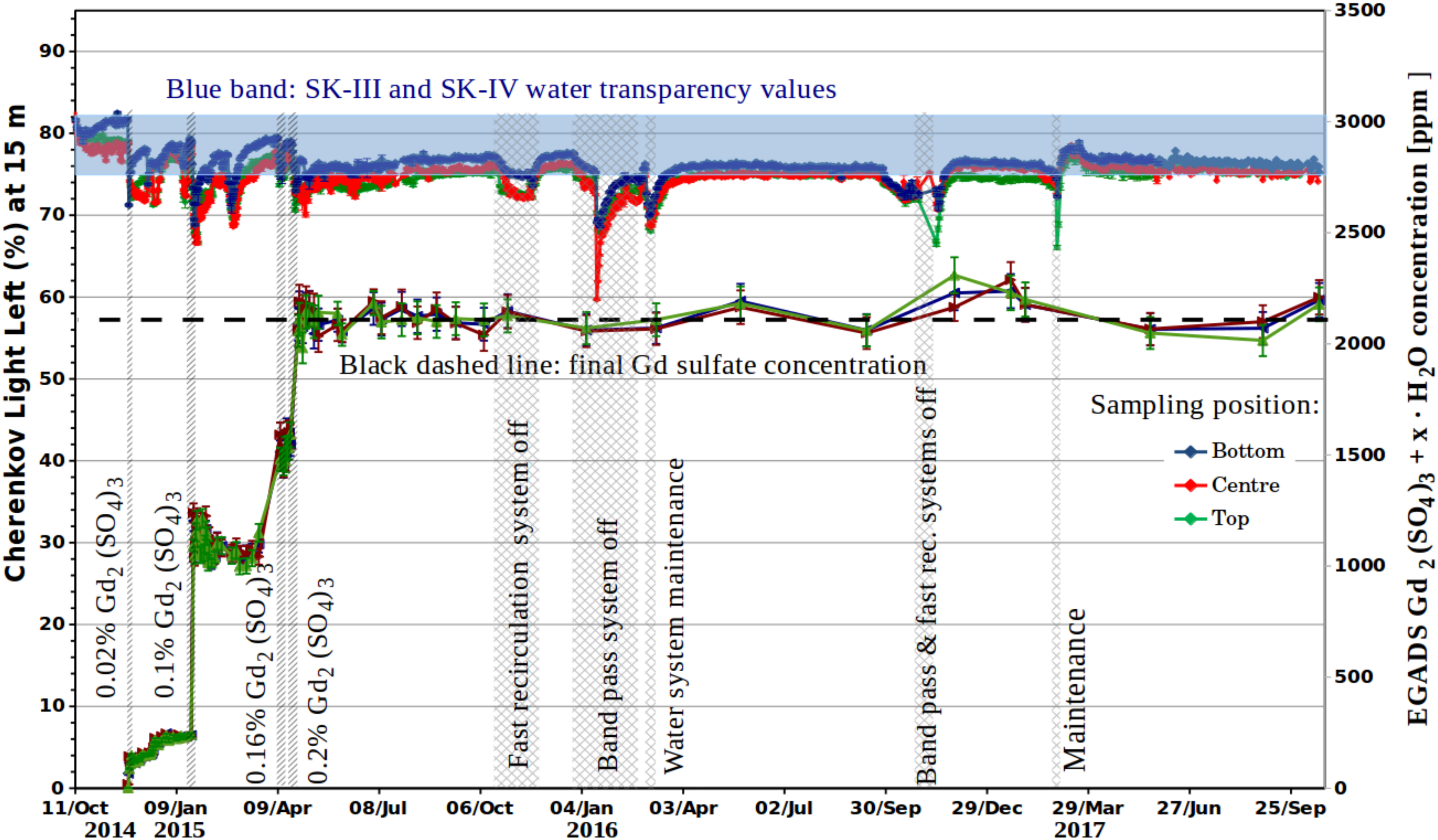
6/2015



Well over $10,000,000 (1.1B yen) - <u>not</u> counting salaries - has been spent developing and proving the viability of the Gd-in-water concept.

After gadolinium loading was completed on April 24th, 2015, the EGADS water filtration systems continuously recirculated the 0.2% $Gd_2(SO_4)_3$ water in the 200-ton tank.

Light @ 15 meters and Gd conc. in the 200-ton EGADS tank

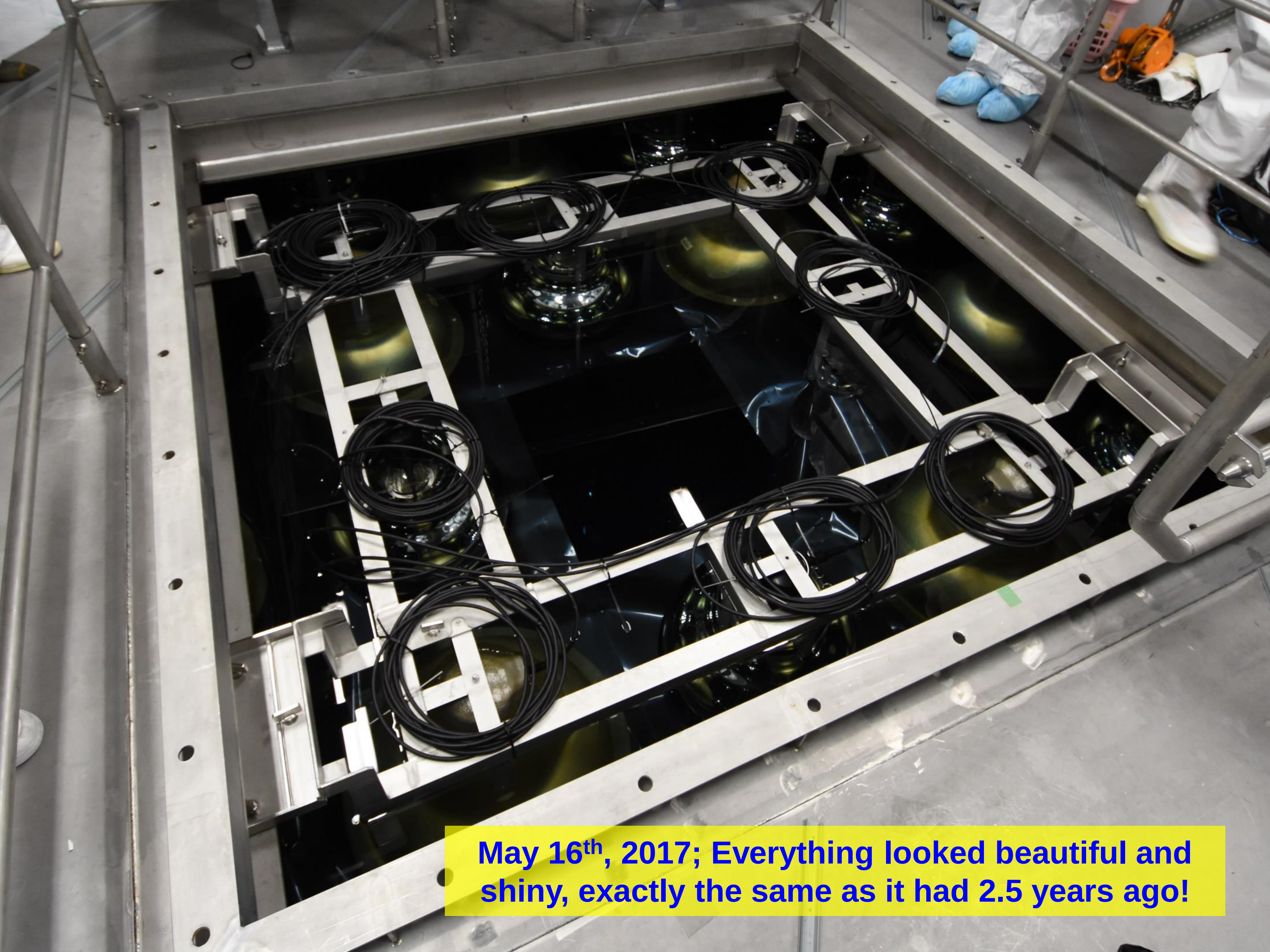


After two and a half years at full Gd loading, during stable operations <u>EGADS water transparency remains within the SK ultrapure range</u>.

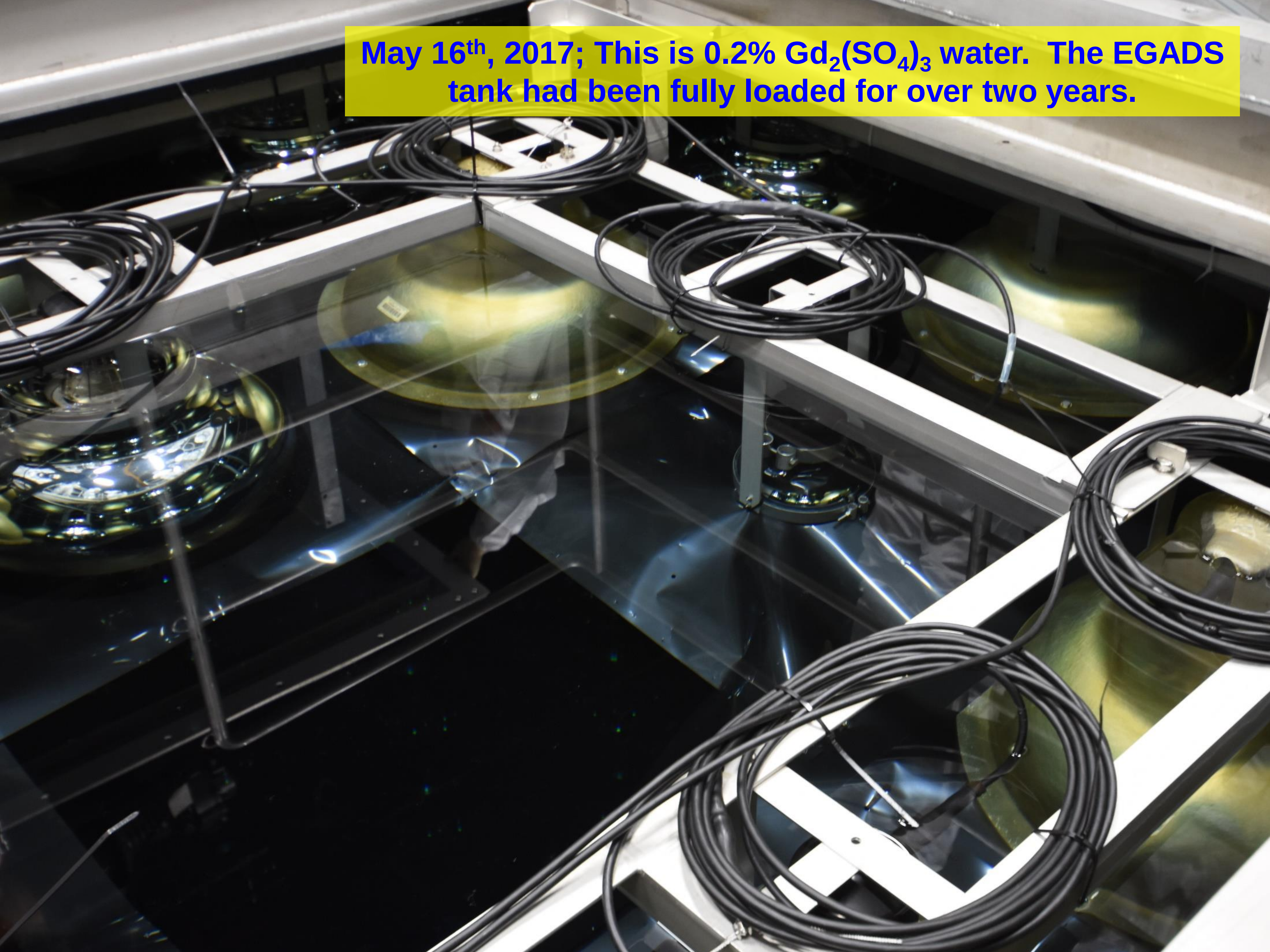
→ No detectable loss of Gd after more than 650 complete turnovers. ←

On May 16th, 2017, we opened the EGADS 200-ton tank, our first look inside since October 2014.

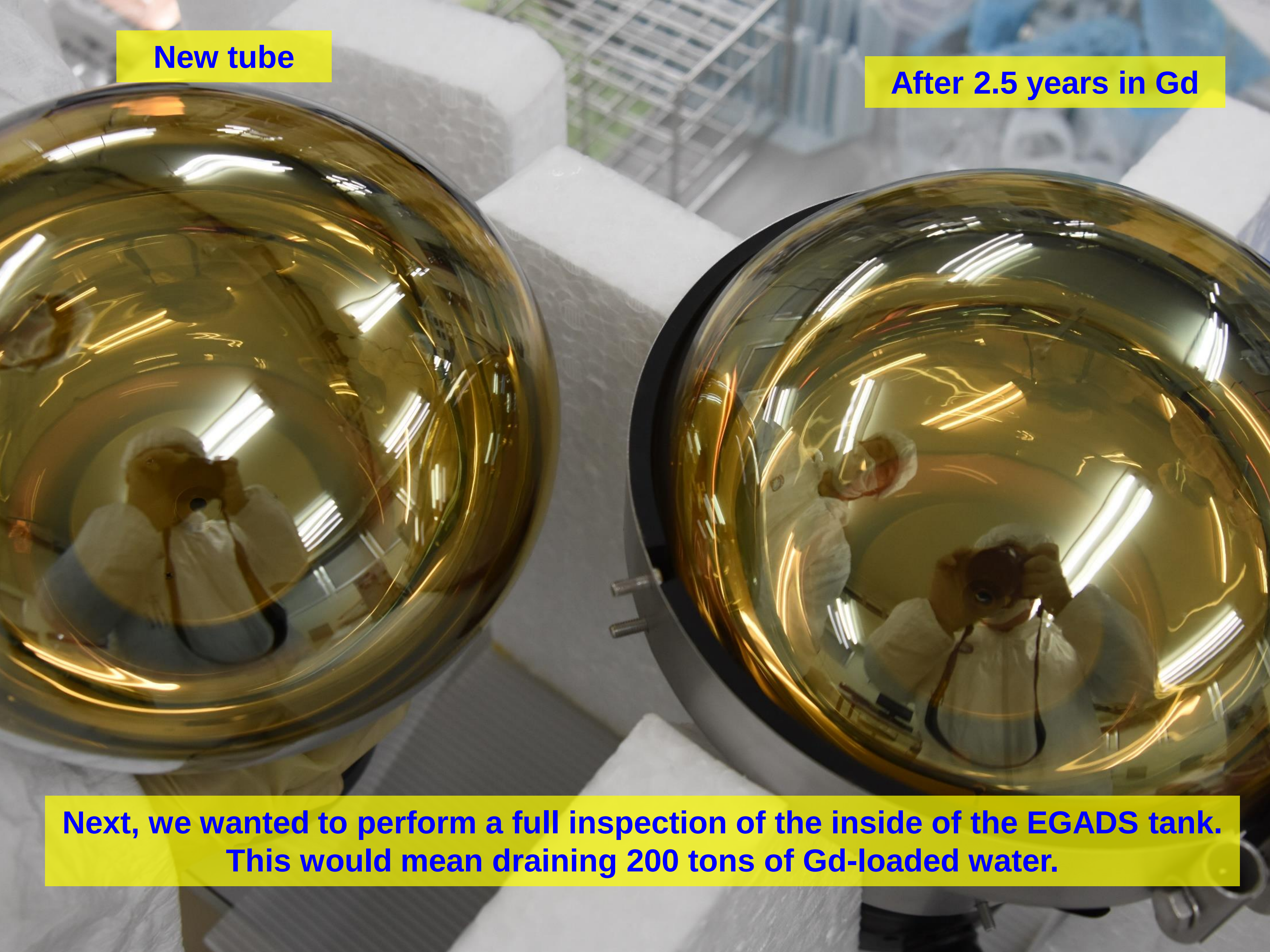

The big reveal - opening the square hatch; May 16th, 2017



May 16th, 2017; Everything looked beautiful and shiny, exactly the same as it had 2.5 years ago!



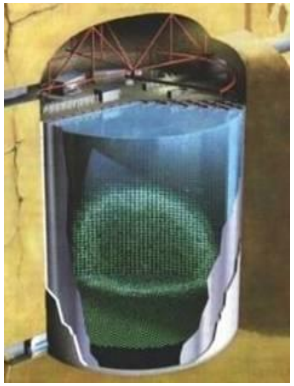
May 16th, 2017; This is 0.2% $Gd_2(SO_4)_3$ water. The EGADS tank had been fully loaded for over two years.


New tube
After 2.5 years in Gd
Next, we wanted to perform a full inspection of the inside of the EGADS tank.
This would mean draining 200 tons of Gd-loaded water.

November 6th, 2017; This view is directed up the side wall from the bottom of the 200-ton tank. Looks great after 2.5 years of exposure to 0.2% $Gd_2(SO_4)_3$ water!

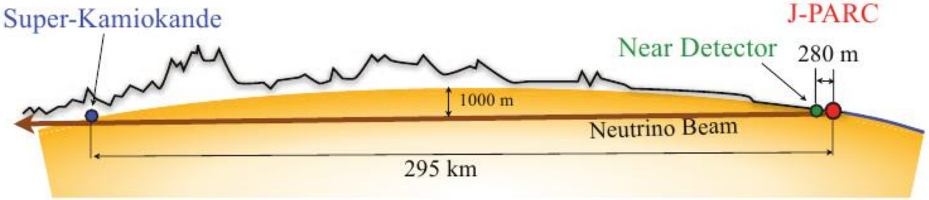
November 6th, 2017; This view is into the access manhole at the bottom of the 200-ton tank, near the bottom of the wall of inward-facing PMTs.
Nice and clean!

After years of testing and study
– culminating in these powerful EGADS results –
no technical showstoppers have been encountered. And so…

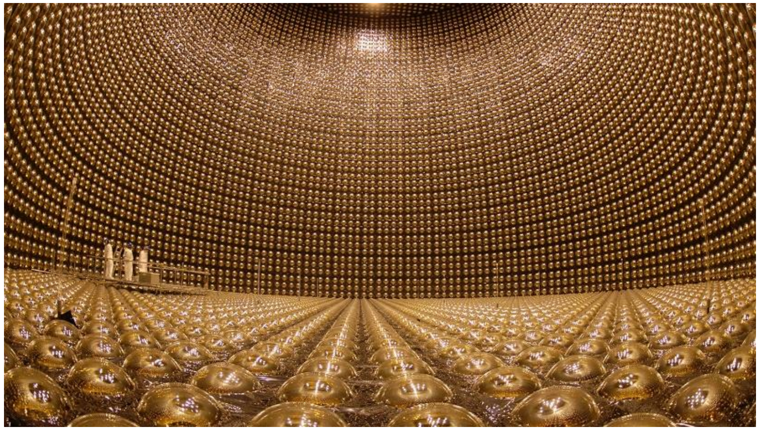


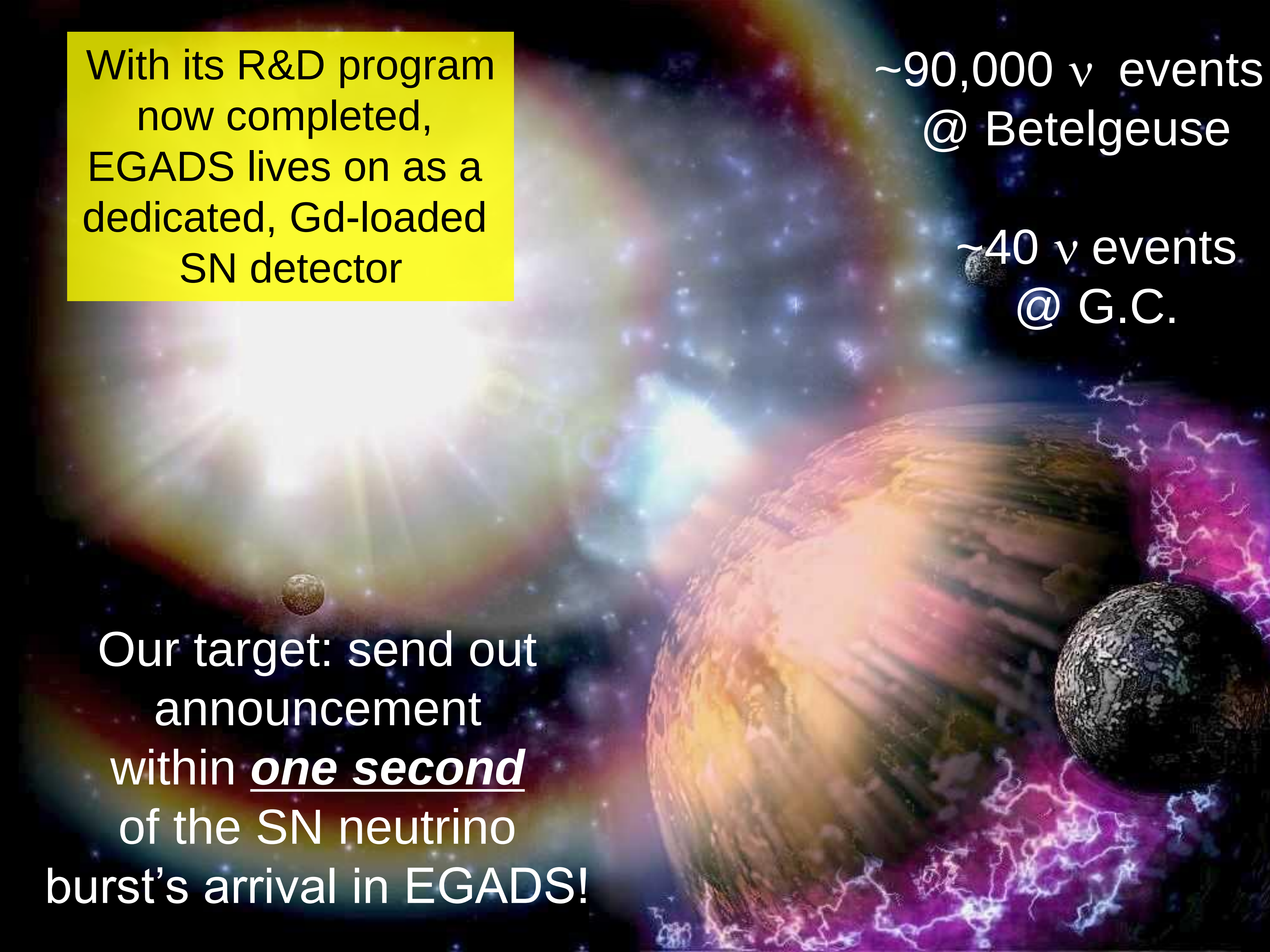
June 27, 2015: The Super-Kamiokande Collaboration approved the addition of gadolinium to the detector, pending discussions with T2K.

January 30, 2016: The T2K Collaboration approved addition of gadolinium to Super-Kamiokande, with the precise timing to be jointly determined based on the needs of both projects.



July 26, 2017: The official start time of draining the SK tank to prepare for Gd loading was decided → June 1, 2018.



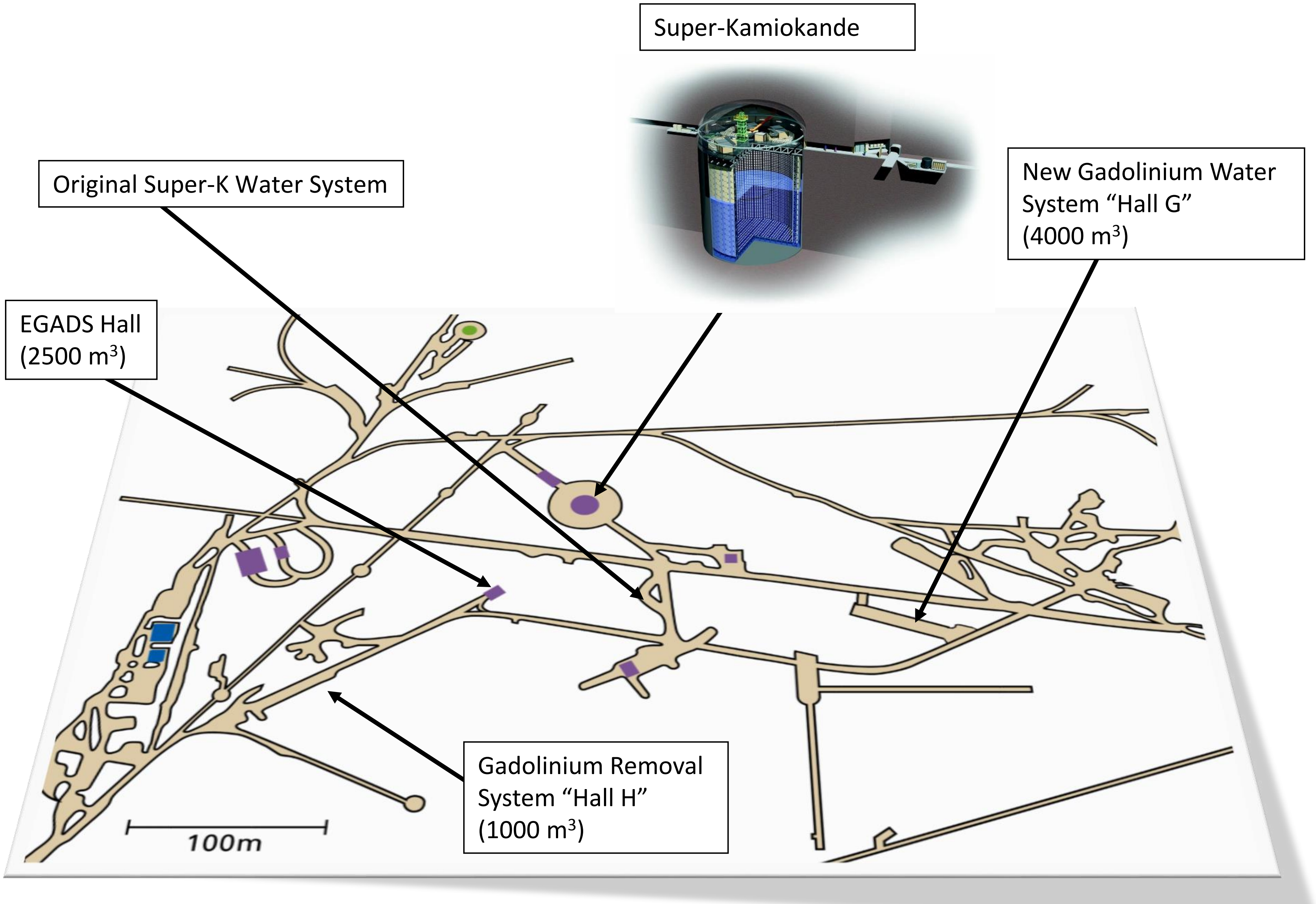


With its R&D program now completed, EGADS lives on as a dedicated, Gd-loaded SN detector

~90,000 ν events @ Betelgeuse

~40 ν events @ G.C.

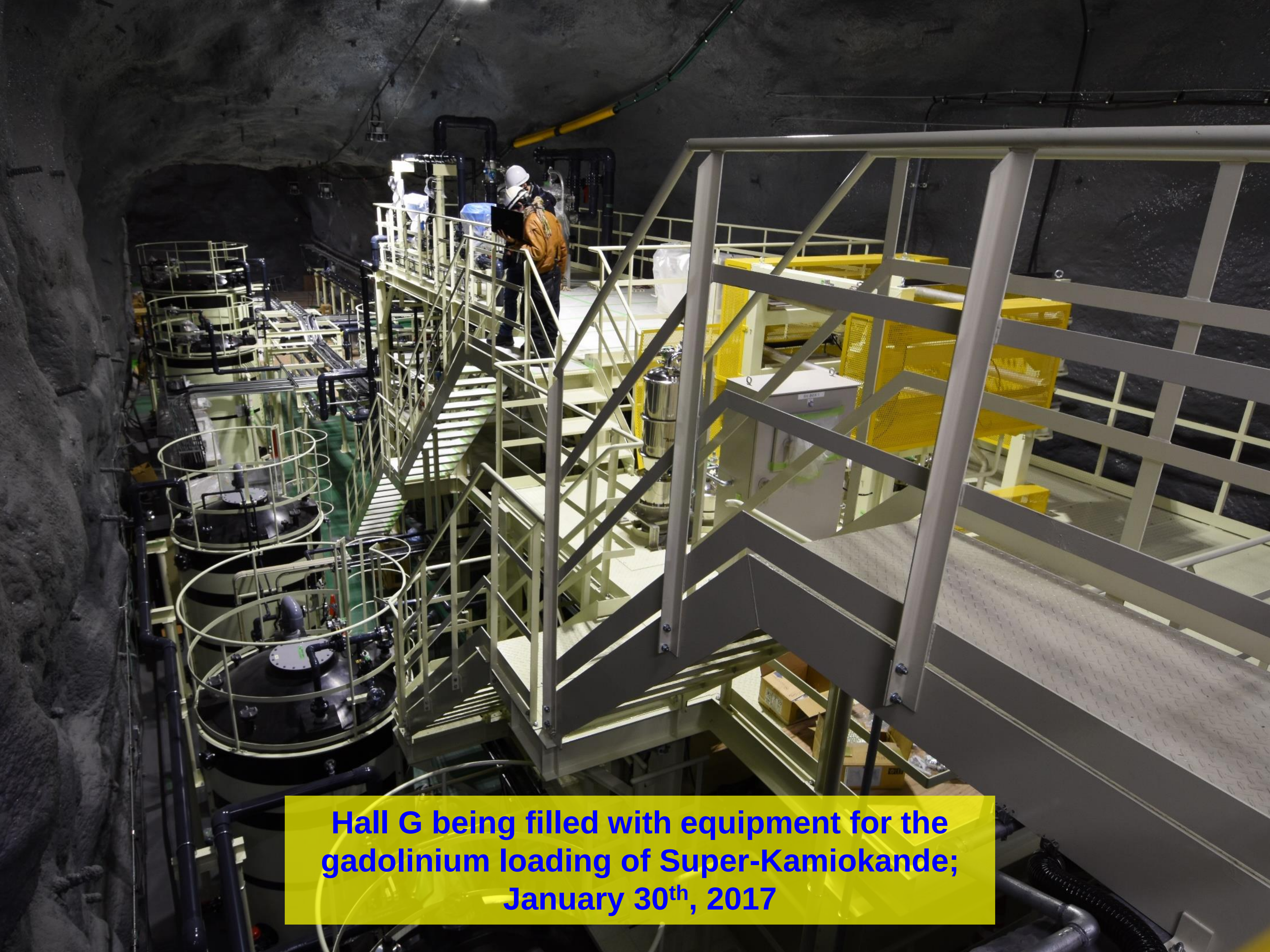
Our target: send out announcement within ***<u>one second</u>*** of the SN neutrino burst's arrival in EGADS!



The Kamioka Observatory in the Mozumi Mine

New gadolinium water system hall (“Hall G”); September 10st, 2015


Hall G ready for occupancy;
April 22nd, 2016



Hall G being filled with equipment for the gadolinium loading of Super-Kamiokande; January 30^{th}, 2017

Prior to Gd loading we must be prepared to completely remove and capture the Gd
→ New system needed

In Hall H; March 24th, 2018

In Hall H; March 30th, 2018

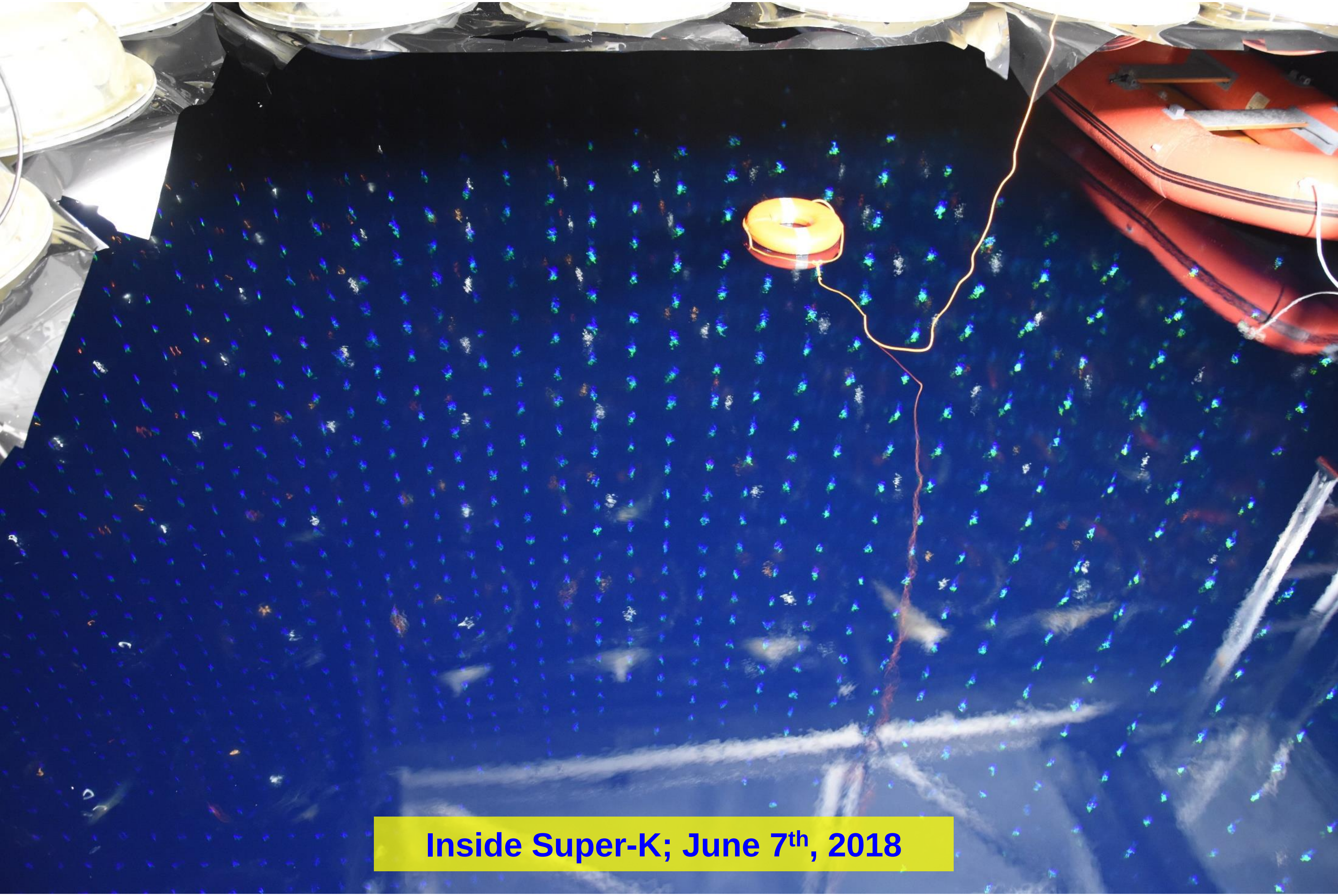
Completed gadolinium removal system (62 tons of ion exchange resin) in Hall H; April 1st, 2018


Main jobs to get ready for Gd loading:
1) Fix SK leak
2) Clean up interior
3) Replace dead PMTs
4) Augment internal plumbing
Entering Super-K for the first time since 2006; June 1st, 2018

From March 2018 → October 2018,
2683 person-days of work were required!

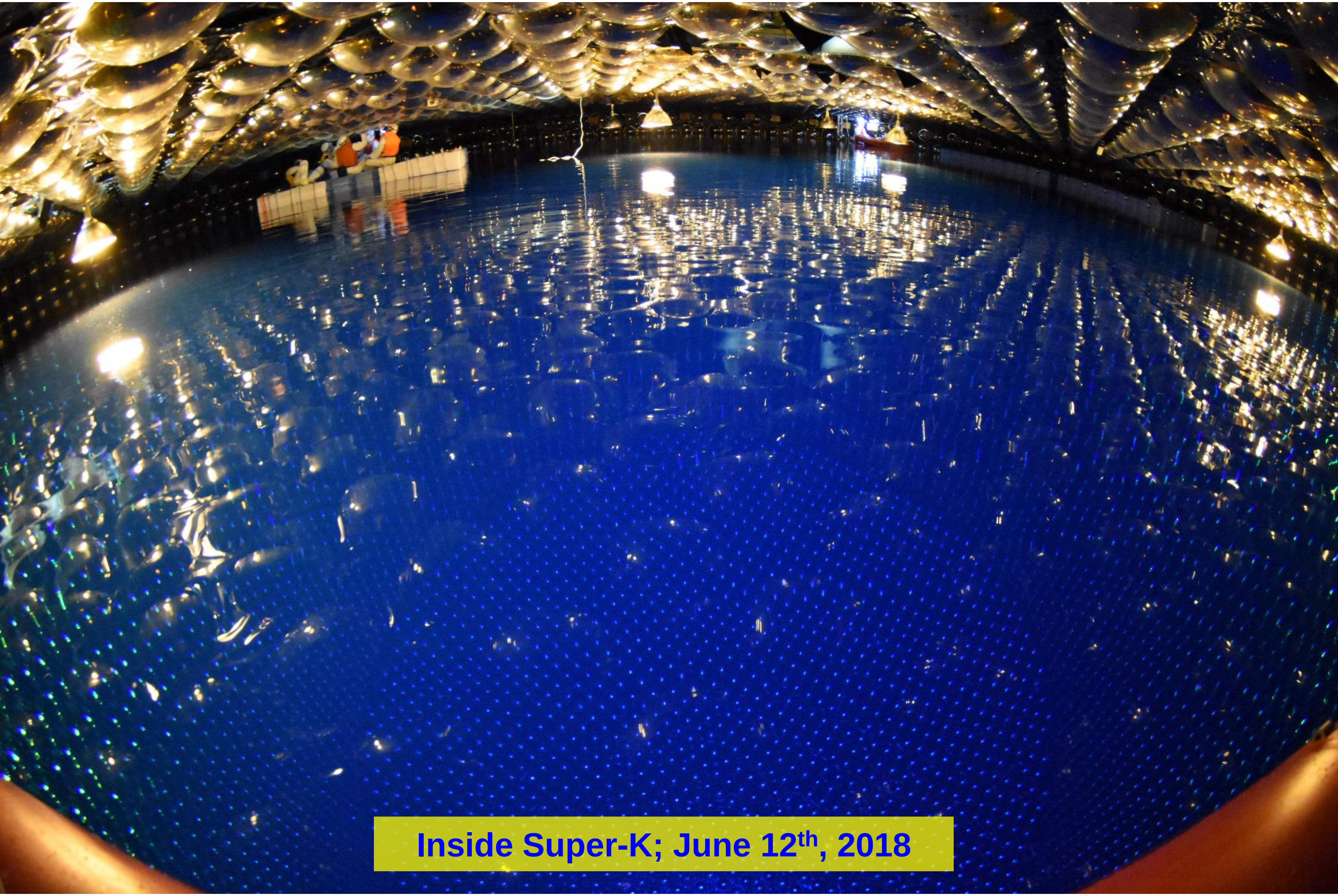
Inside Super-K veto region (top); June 6th, 2018

Super-K veto region (side) with floating floor; June 6th, 2018



Inside Super-K; June 7th, 2018

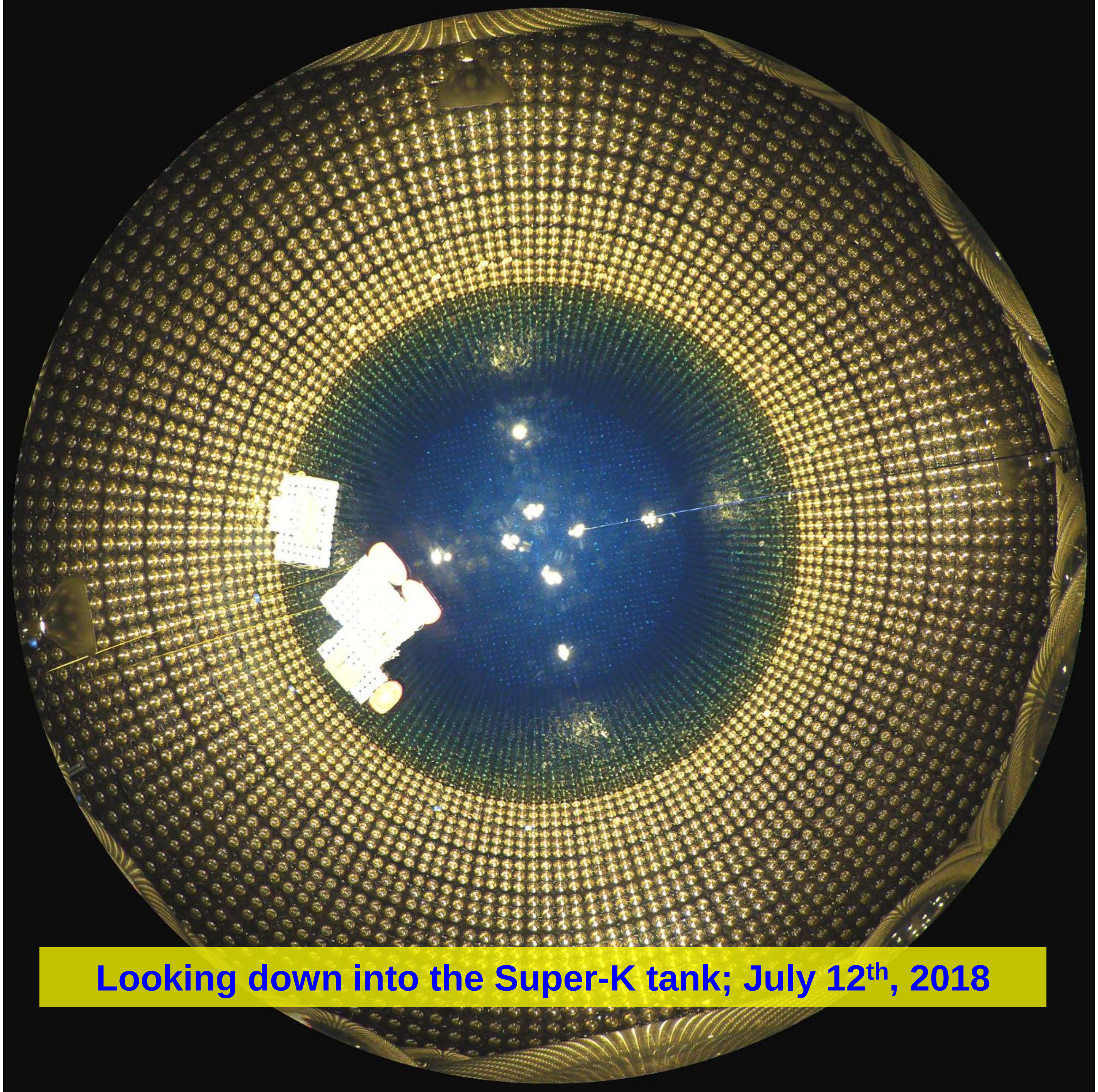
Inside Super-K; June 10th, 2018



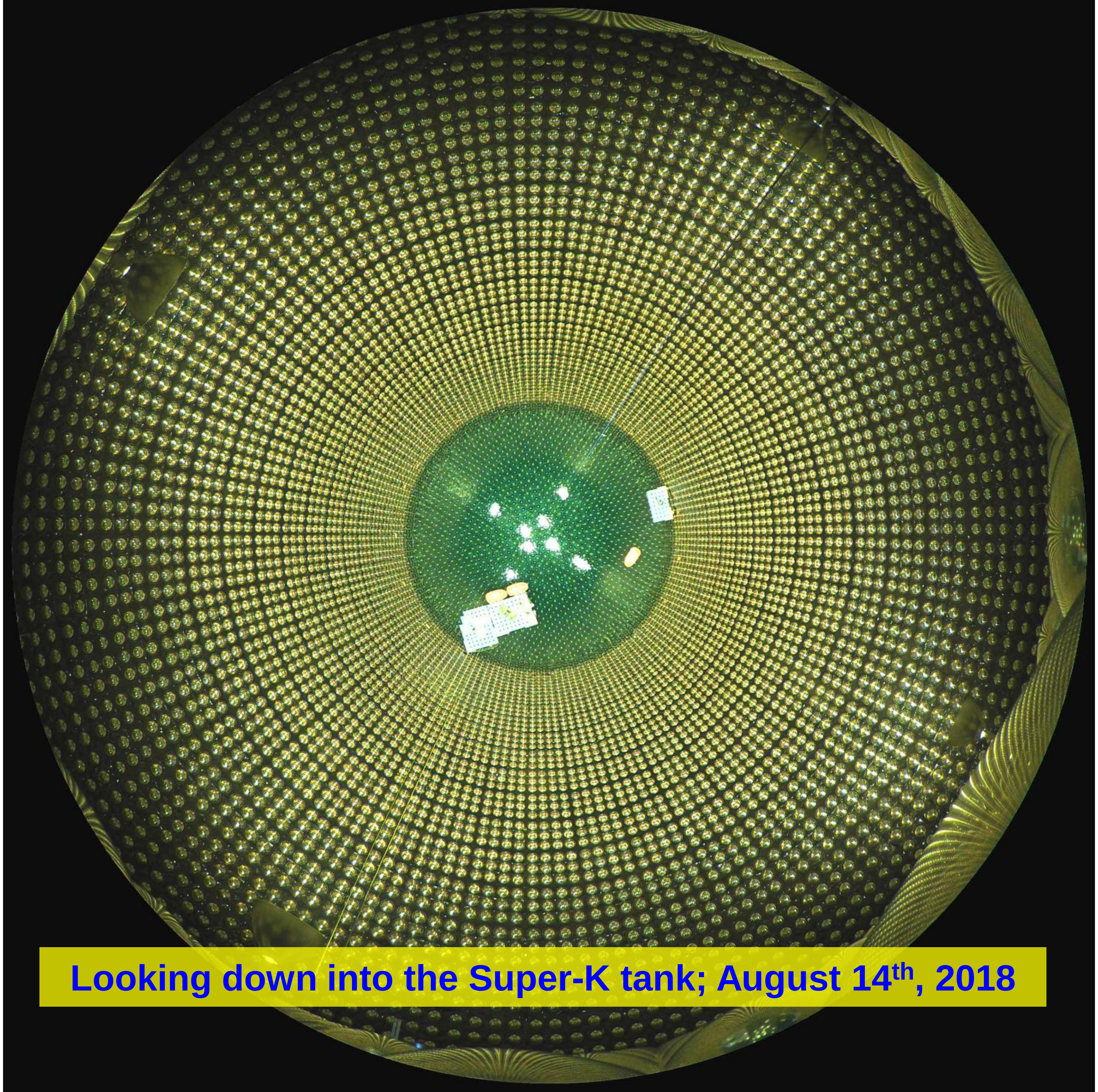
Inside Super-K; June 12th, 2018

Applying special low-background MineGuard sealant

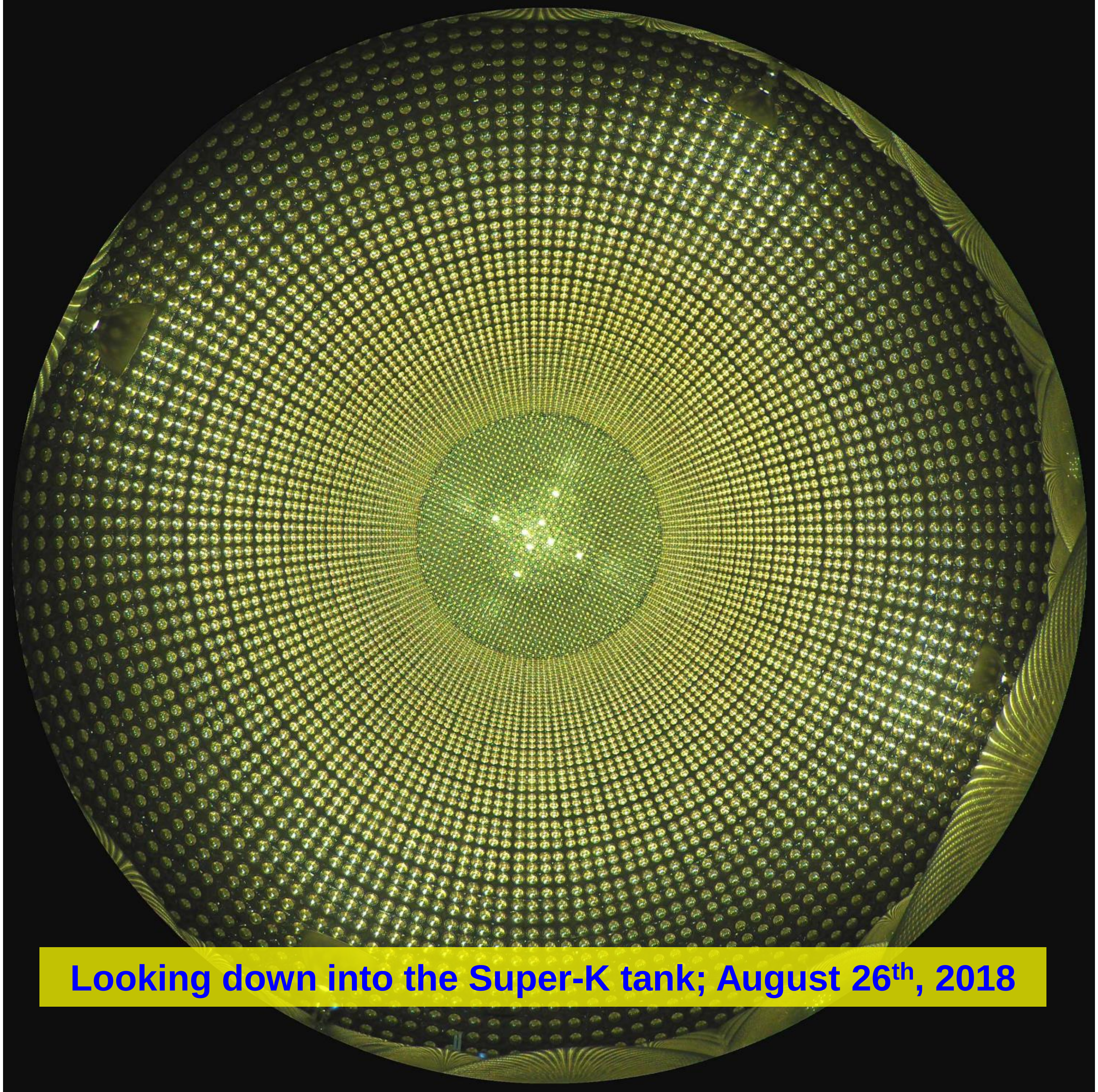
Super-K veto region (side) with floating floor; June 23rd, 2018



Looking down into the Super-K tank; July 12th, 2018



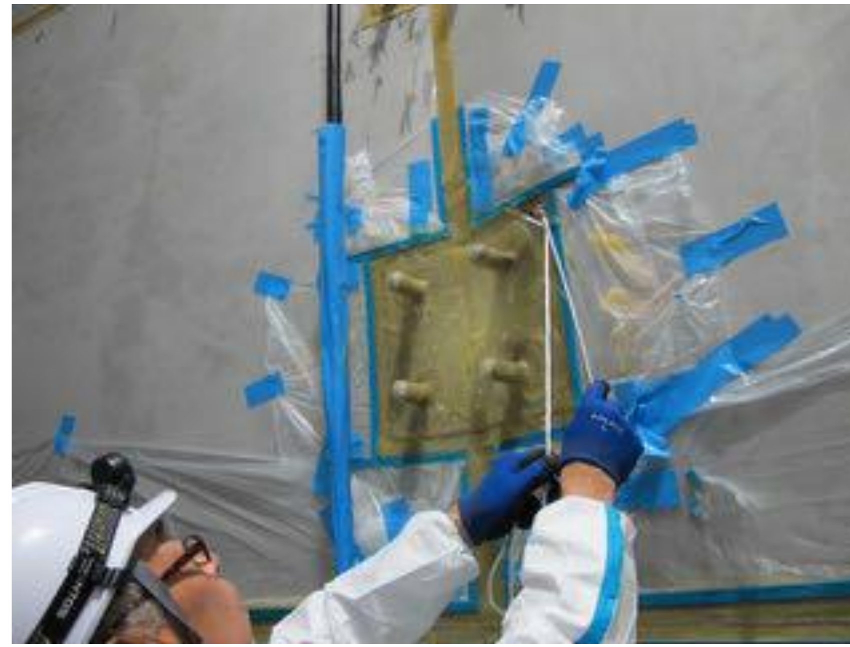
Looking down into the Super-K tank; August 14th, 2018



Looking down into the Super-K tank; August 26th, 2018

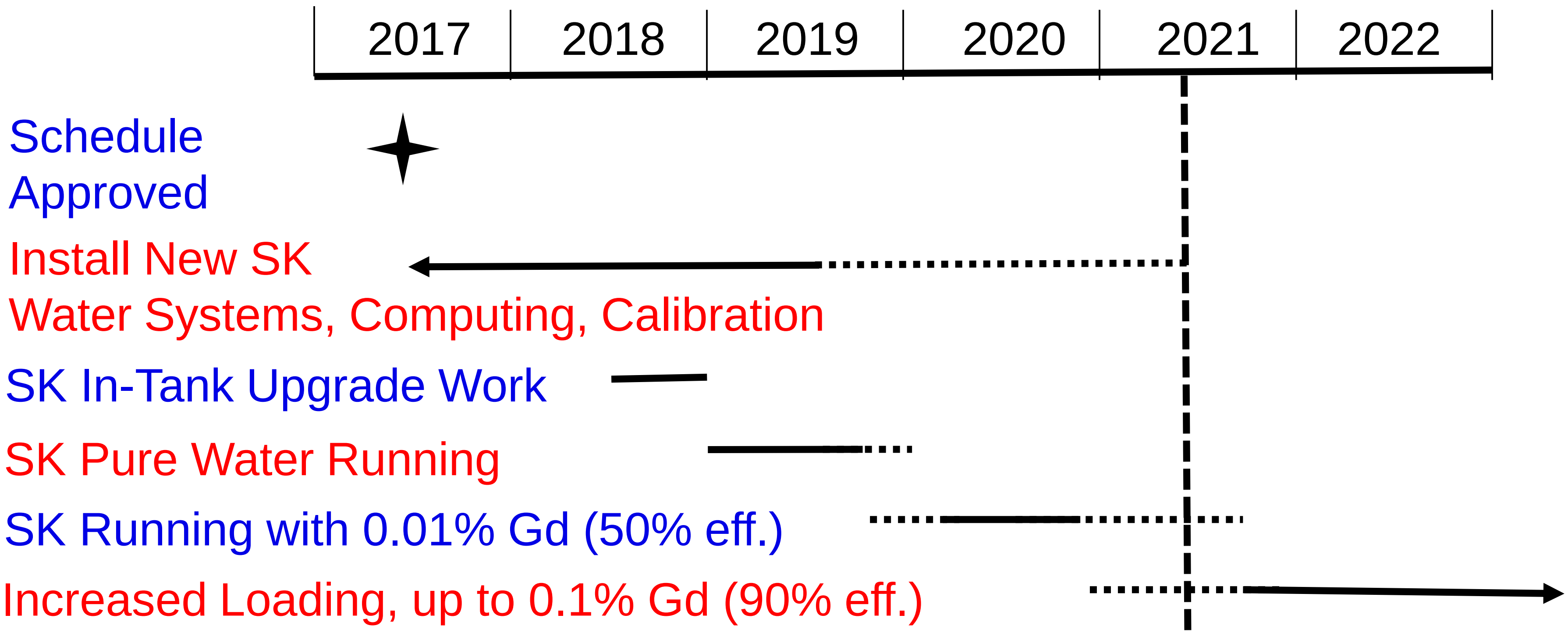
Following ~3000 person-days of refurbishment work, as of Feb. 2019 the detector is now refilled with pure water and taking data, ready for the addition of gadolinium!

"Currently we do not observe any water leakage from the SK tank within the accuracy of our measurement, which is less than 0.017 tons per day. This is less than 1/200th of the leak rate observed before the 2018/2019 tank refurbishment."



Leak sealing work is a success!

Expected timeline for SK-Gd



We expect to have collected the world's first diffuse supernova neutrinos before 2022!

While Super-Kamiokande is waiting for the next galactic supernova explosion, adding gadolinium will allow us to continuously collect supernova neutrinos from explosions halfway across the universe.

<u>After 17 years of study and planning, the first Gd is expected to go into Super-K late this year or early in 2020!</u>