Prospects for a Gd-loaded Super-K

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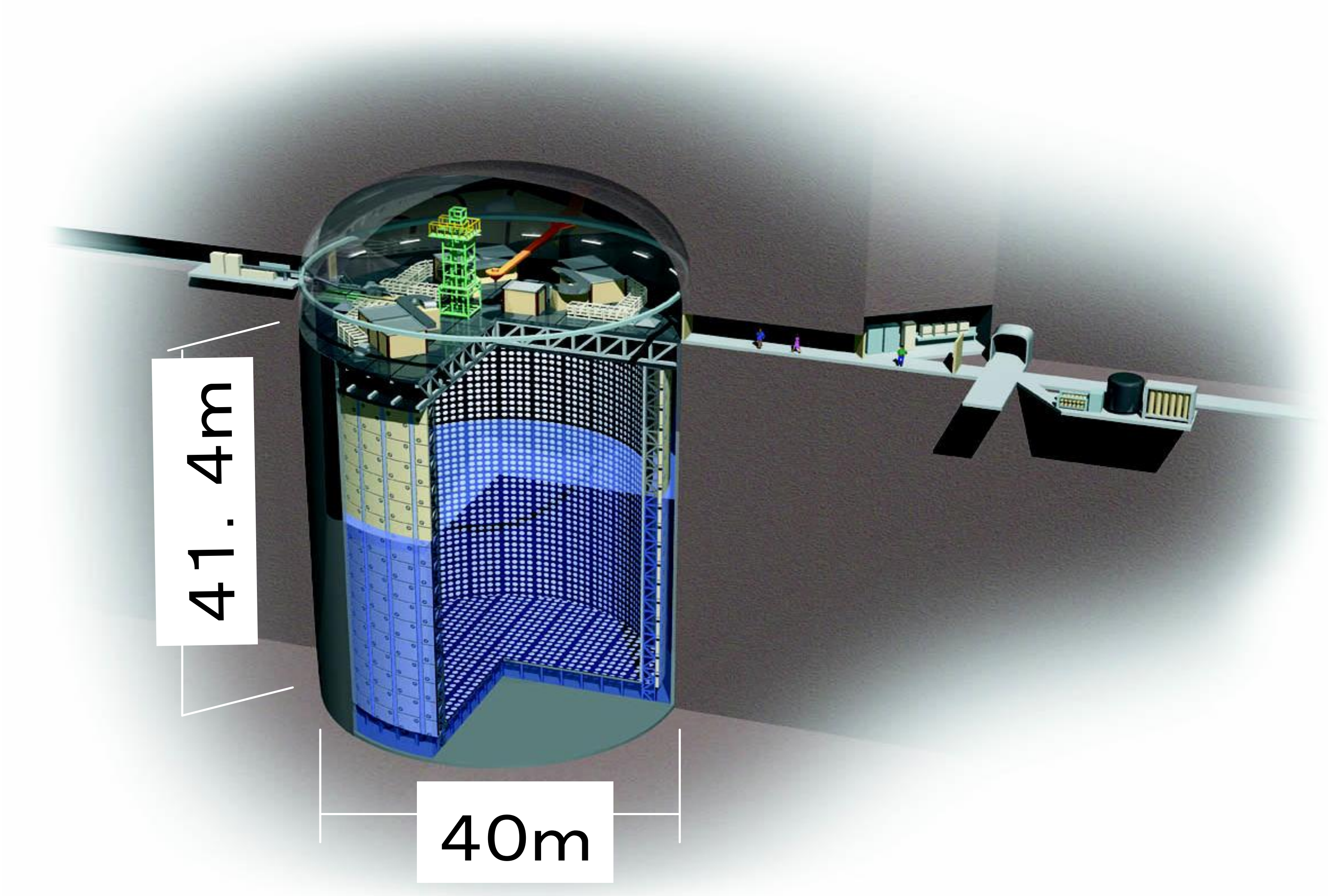
Prospects of Neutrino Physics

Kavli IPMU, Kashiwa April 8, 2019

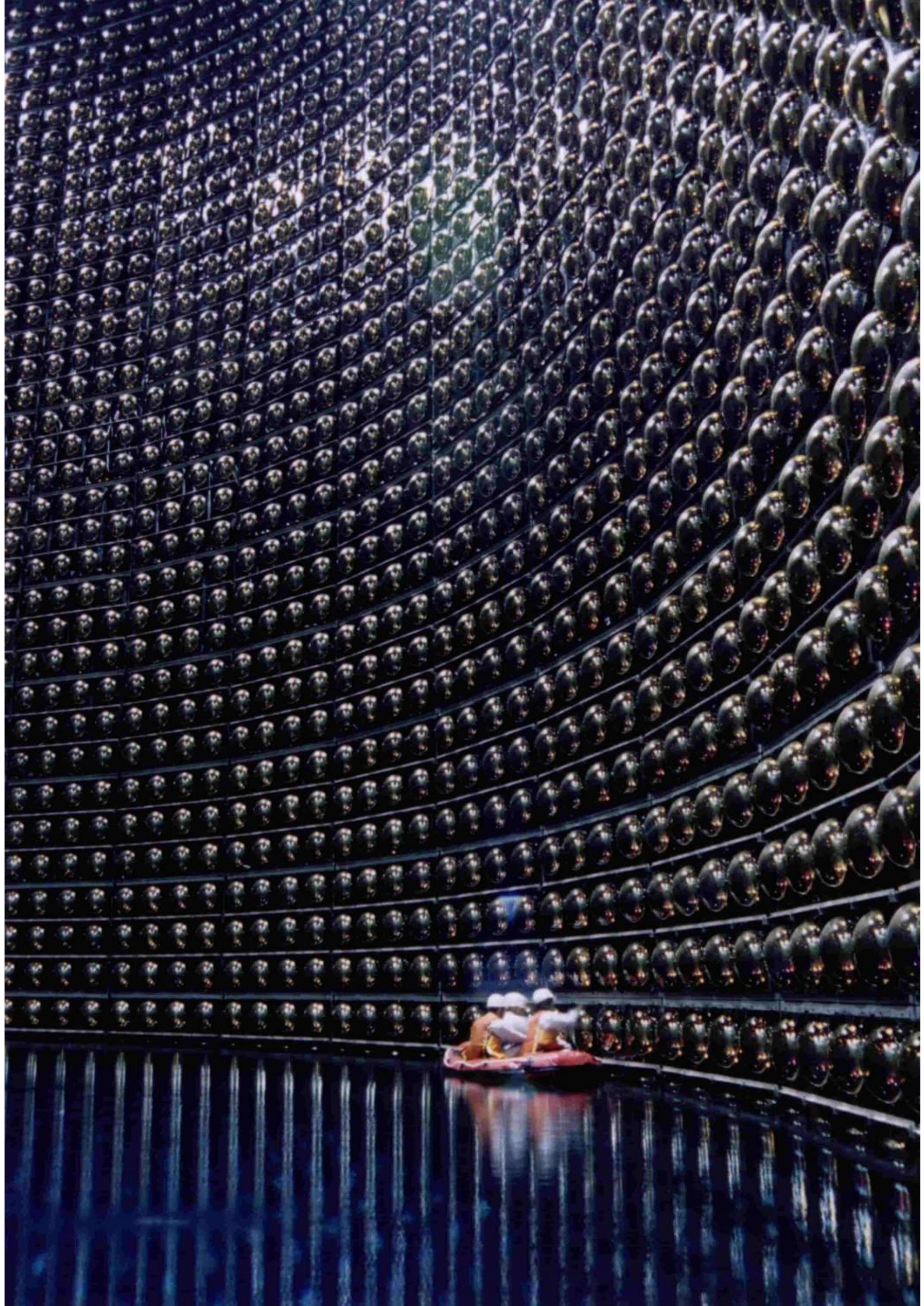


The Super-Kamiokande neutrino detector, in Mozumi, Japan.

50,000 tons of ultra-pure H_2O

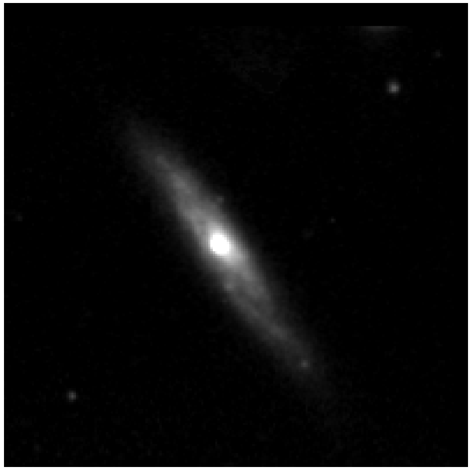
13,000 light detectors

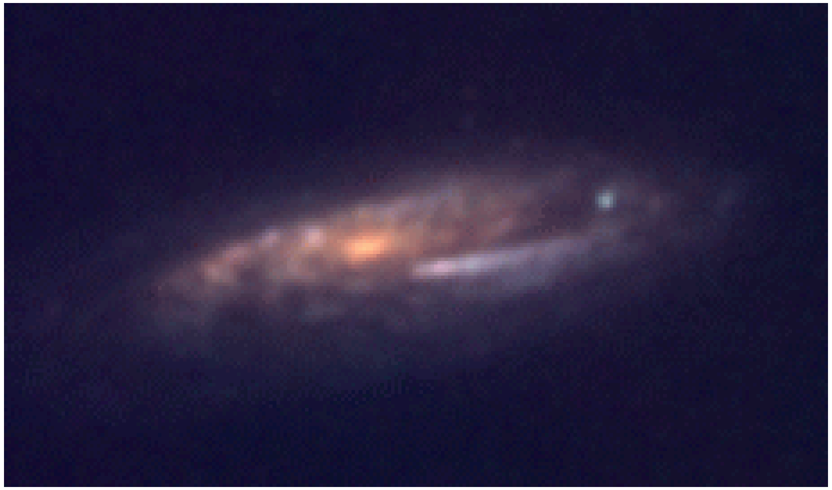
One kilometer underground



Since 1996, observes particles from the sun and cosmic rays

Also looks for proton decay and supernova neutrinos

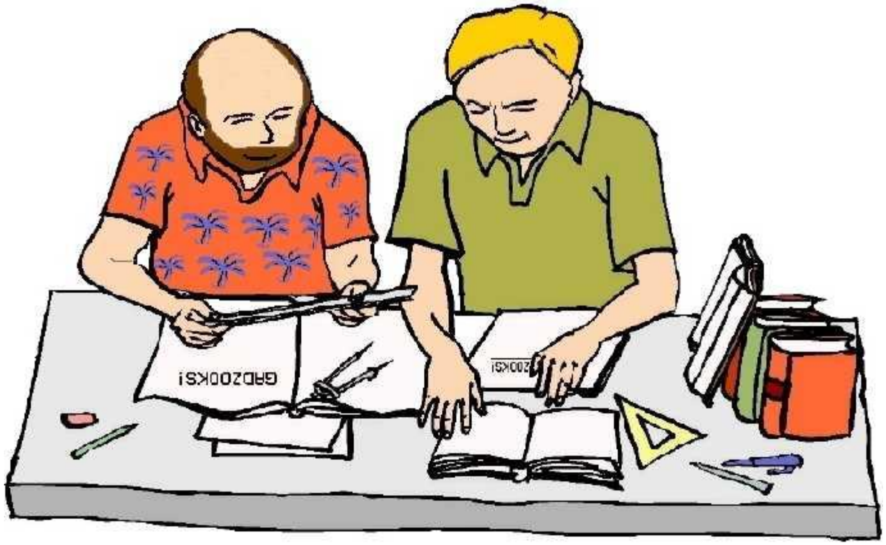




Here's how most supernovas look to us (video is looped).

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].



Motivated by detecting the DSNB, 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)

One of the very first papers to cite our GADZOOKS! paper:

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Reactor antineutrino oscillations and gadolinium loaded Super-Kamiokande detector

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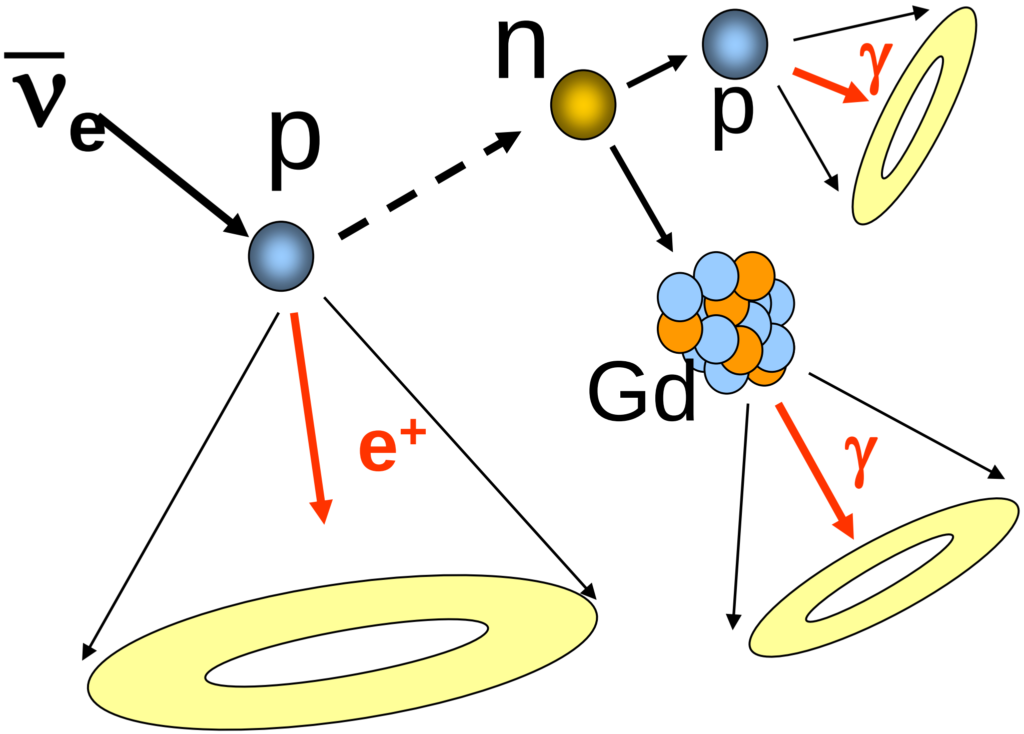
Abstract

We explore the potential of measuring the solar neutrino oscillation parameters in the proposed gadolinium loaded Super-Kamiokande (SK-Gd) detector. Gadolinium dissolved in water can detect neutrons much more efficiently than pure water. This imparts the detector the ability to observe electron type antineutrinos, transforming Super-Kamiokande into a huge reactor antineutrino detector with an event rate approximately 43 times higher than that observed in KamLAND. We simulate the reactor antineutrino data expected in this high statistics detector. We use these prospective data to study the precision with which the solar neutrino oscillation parameters, $\Delta m^2_\odot$ and $\sin^2\theta_\odot$, can be determined (i) with the SK-Gd detector, and (ii) by combining the SK-Gd data with the global data on solar neutrino oscillations. For comparison and completeness the allowed regions of $\Delta m^2_\odot$ and $\sin^2\theta_\odot$, expected to be obtained from the data of the solar neutrino and KamLAND experiments, are also presented. We find that the SK-Gd experiment could provide one of the most precise (if not the most precise) determination of the solar neutrino oscillation parameters $\Delta m^2_\odot$ and $\sin^2\theta_\odot$.

It also contained the very first use of another name…

Inverse Beta Decay with Gadolinium



Possibility 1: 10% or less

$n+p \rightarrow d + \gamma$

2.2 MeV γ-ray

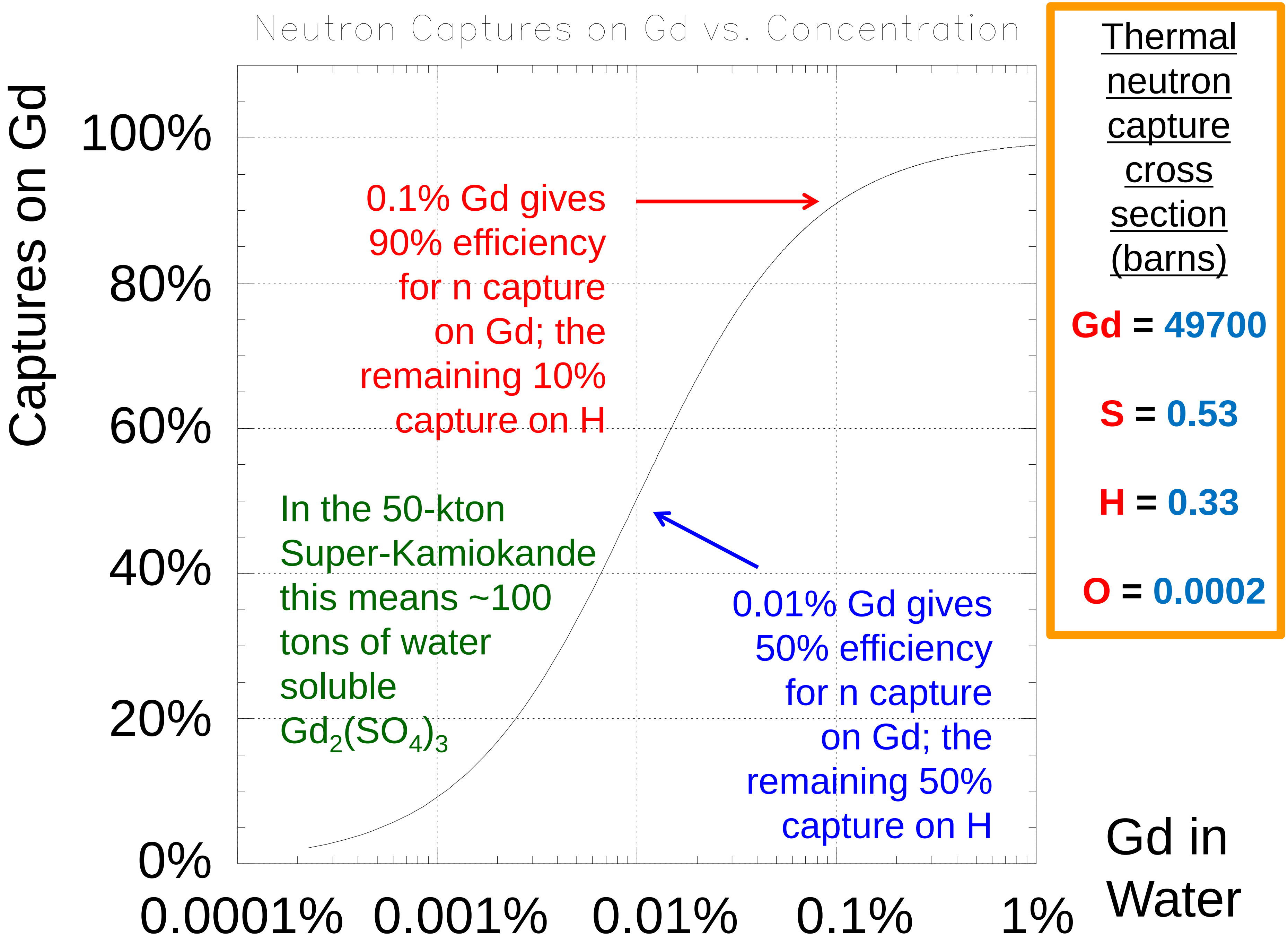
Possibility 2: 90% or more

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

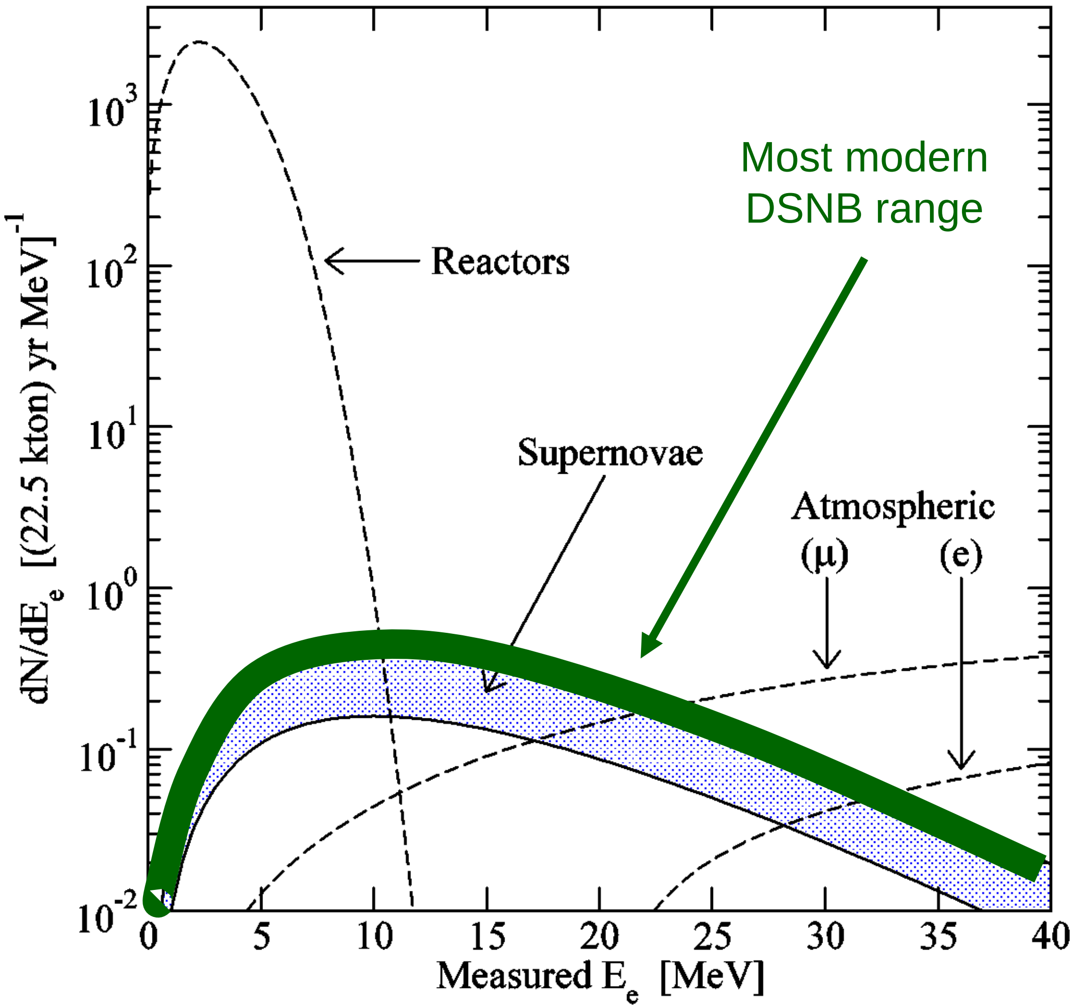
$\Delta T = \sim 30\ \mu sec$

Positron and gamma ray vertices are within ~50 cm.

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


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 $Gd_2(SO_4)_3$
0.01% Gd gives 50% efficiency for n capture on Gd; the remaining 50% capture on H
Thermal neutron capture cross section (barns)
Gd = 49700
S = 0.53
H = 0.33
O = 0.0002

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



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

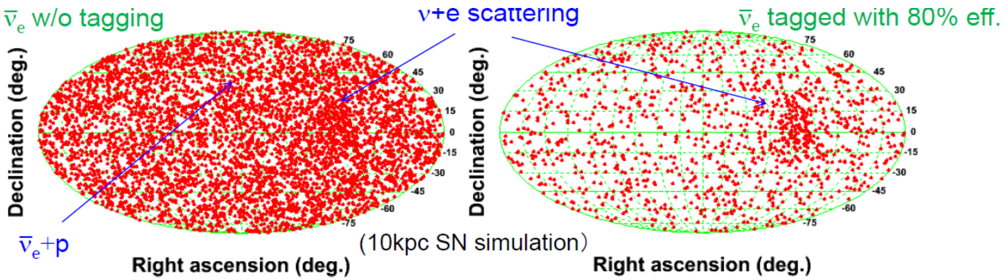
spatial and temporal separation between prompt e^+ Cherenkov light and delayed Gd neutron capture gamma cascade:

$\lambda = \sim 4cm$, $\tau = \sim 30\mu s$

→ 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:

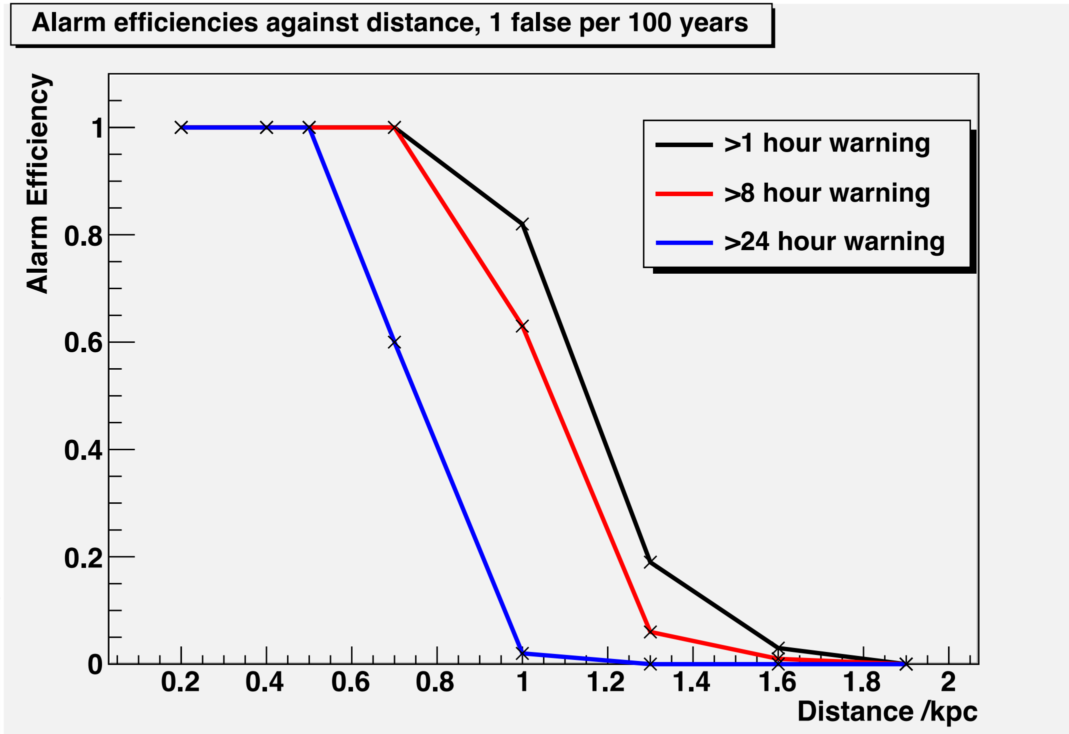
- Allows the exact $\bar{\nu}_e$ flux, energy spectrum, and time profile to be determined via the extraction of a tagged, pure sample of inverse beta events.
- Instantly identifies a burst as genuine via “Gd heartbeat”.
- Doubles the ES pointing accuracy. Error circle cut by 75%.

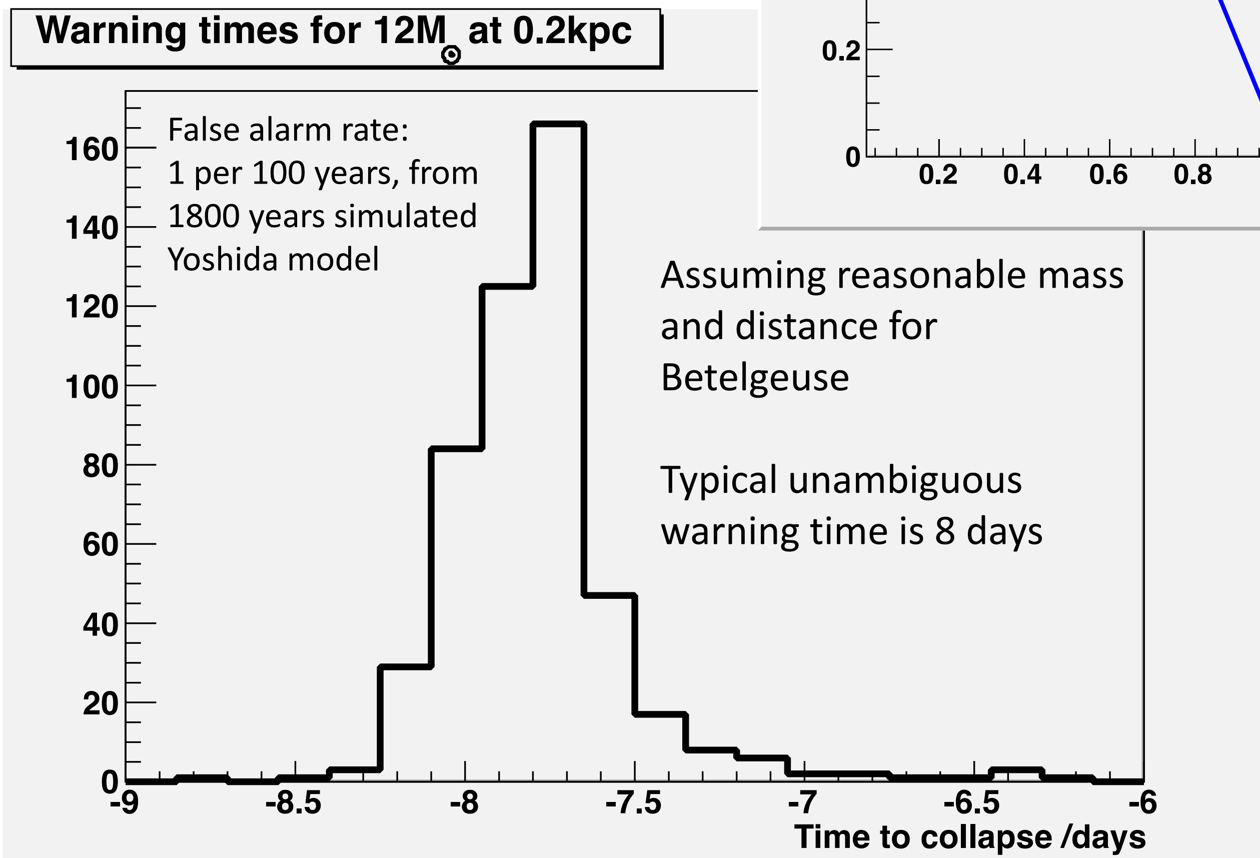


- Helps to identify the other neutrino signals, especially the weak neutronization burst of ν_e.
- Enables a search for very late time black hole formation.
- Provides for very early warning of the most spectacular, nearby explosions so we can be sure not to miss them.

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

(Super-K internal study)

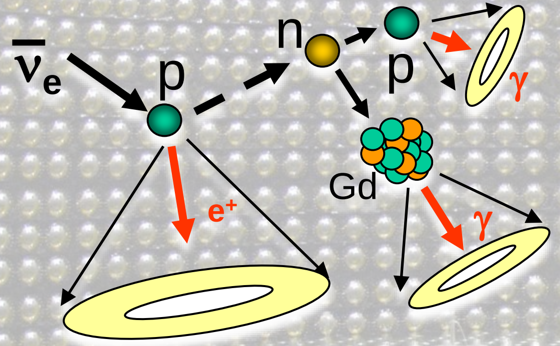




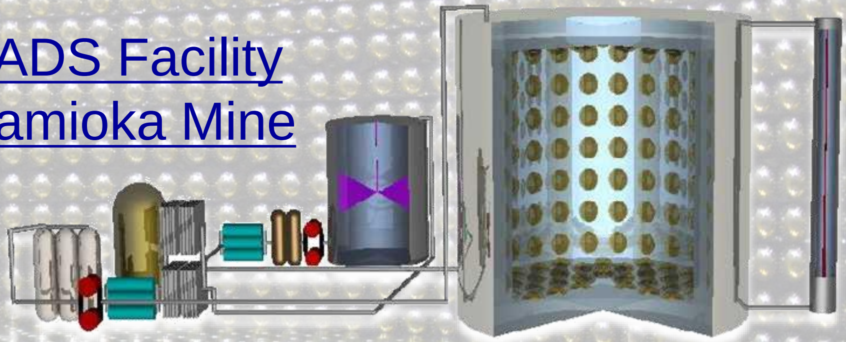
[C. Simpson]

EGADS → Gd-loaded Super-K

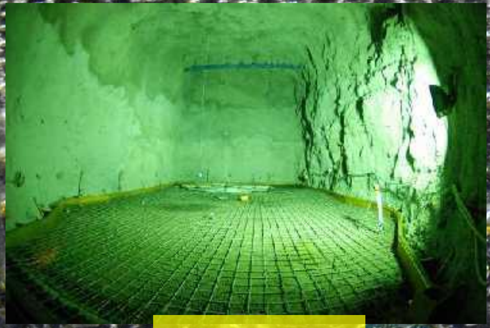
Adding **water soluble gadolinium** to **Super-K** will greatly enhance its ability to detect **supernova neutrinos** (and help with many other physics topics like **proton decay**). **EGADS** is a dedicated gadolinium demonstrator which includes a working 200 ton scale model of SK.



EGADS Facility
in Kamioka Mine



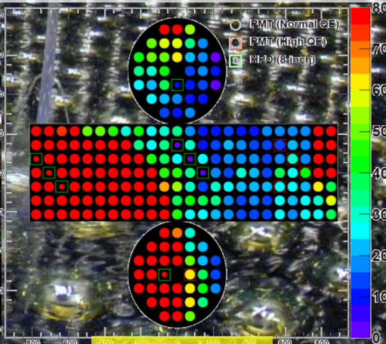
Beacom and Vagins, *Phys. Rev. Lett.*, 93:171101, 2004 [359 citations]



12/2009

11/2011

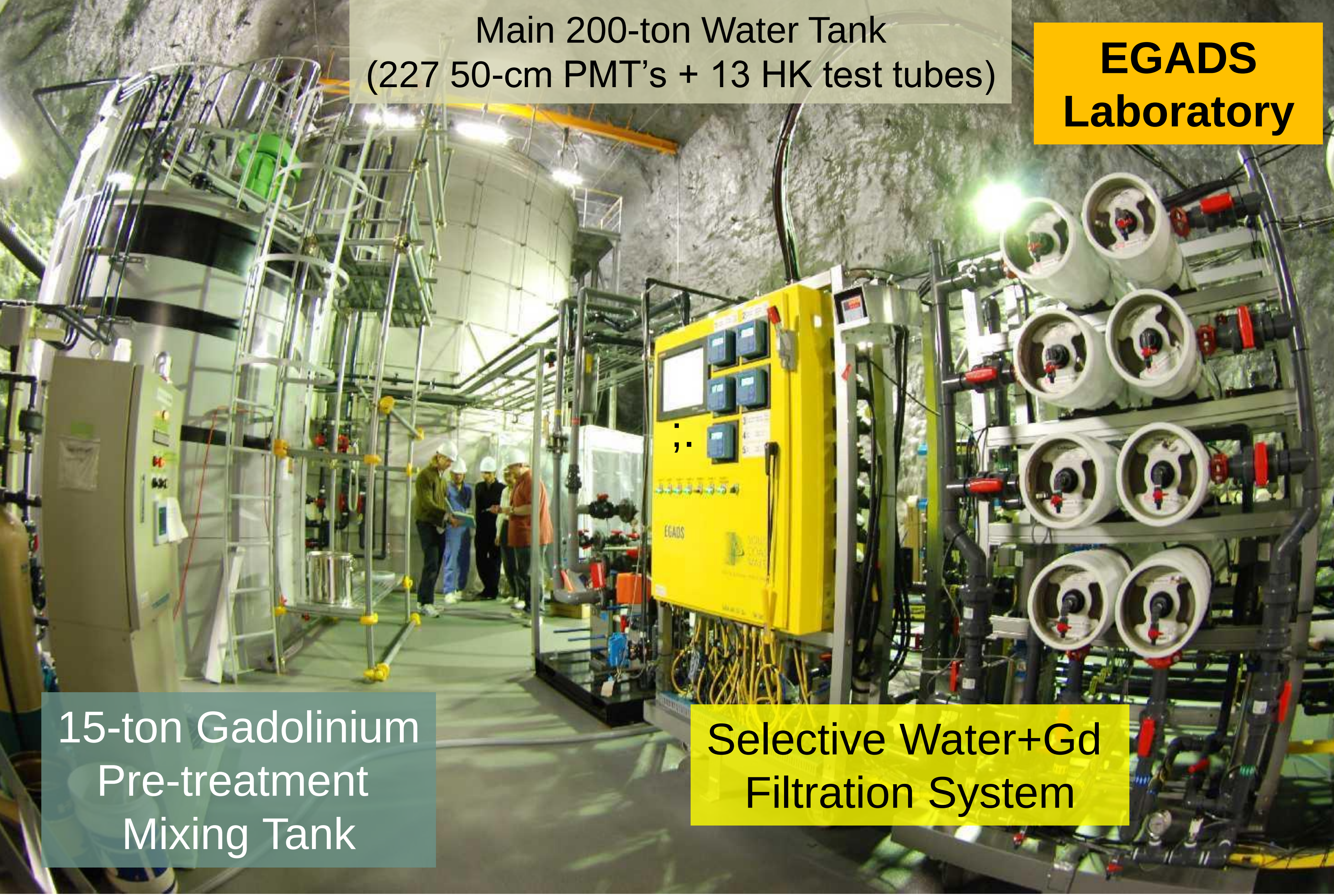
8/2013



6/2015

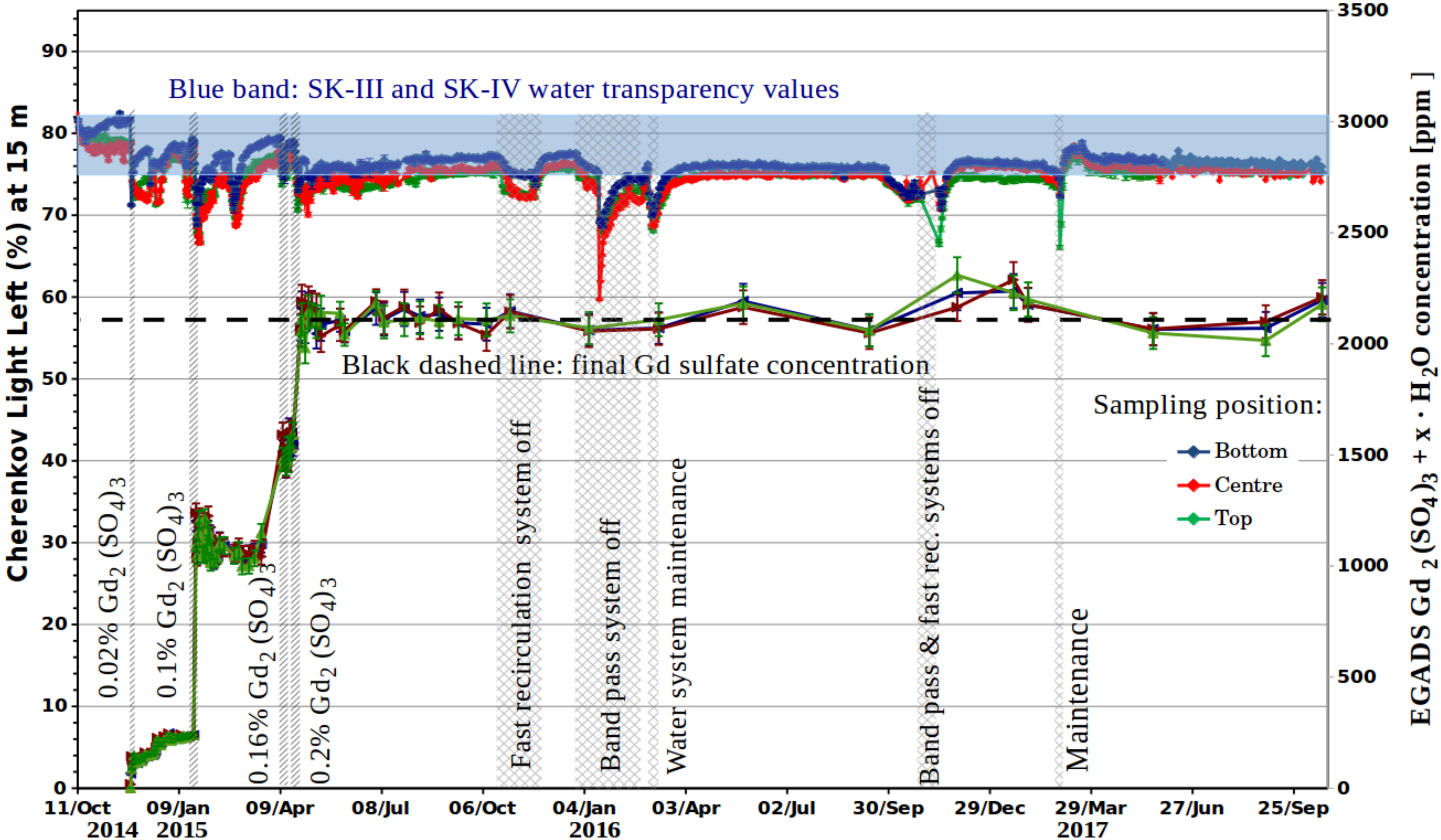
Maintaining good water quality in the presence of dissolved gadolinium required the development of an entirely new technology: true selective filtration. I call my resulting system a "molecular band-pass" filter.

This electro-mechanical system continuously circulates the Gd-loaded water and removes every impurity *except* $Gd_2(SO_4)_3$.



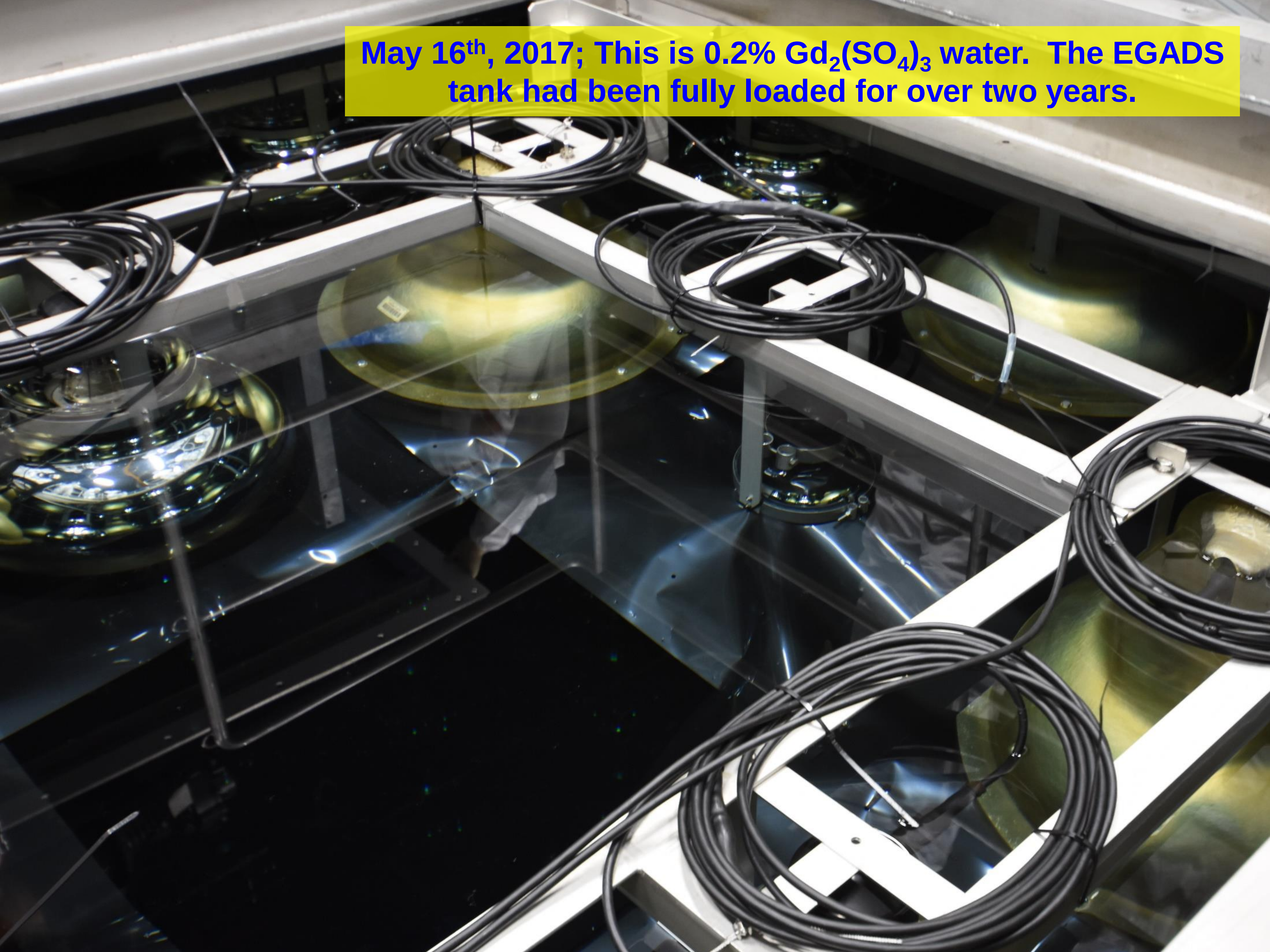
Worldwide, over ¥1.1B (<u>not</u> counting salaries) has been spent developing and proving the viability of the Gd-in-water concept.

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



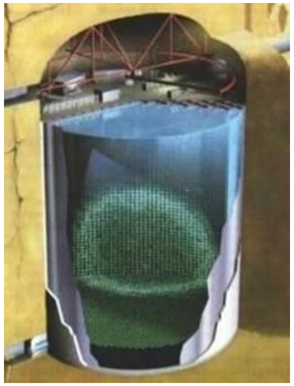
After two and a half years at full Gd loading, during stable operations **<u>EGADS water transparency remains within the SK ultrapure range</u>.**

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


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

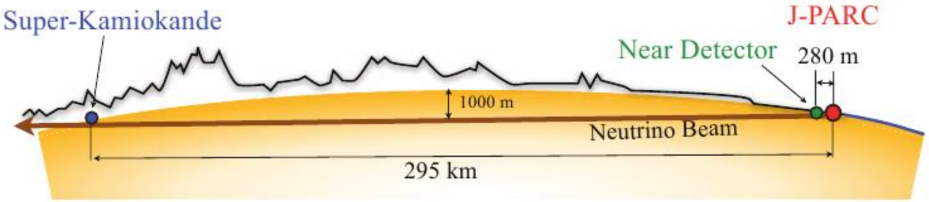
November 6th, 2017; This view is directed up the side wall from the bottom of the 200-ton tank. Looks great after 2.5 years of exposure to 0.2% $Gd_2(SO_4)_3$ water!

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

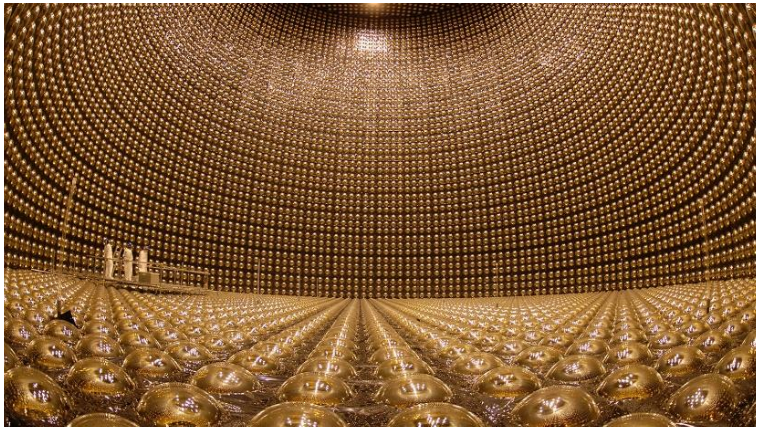


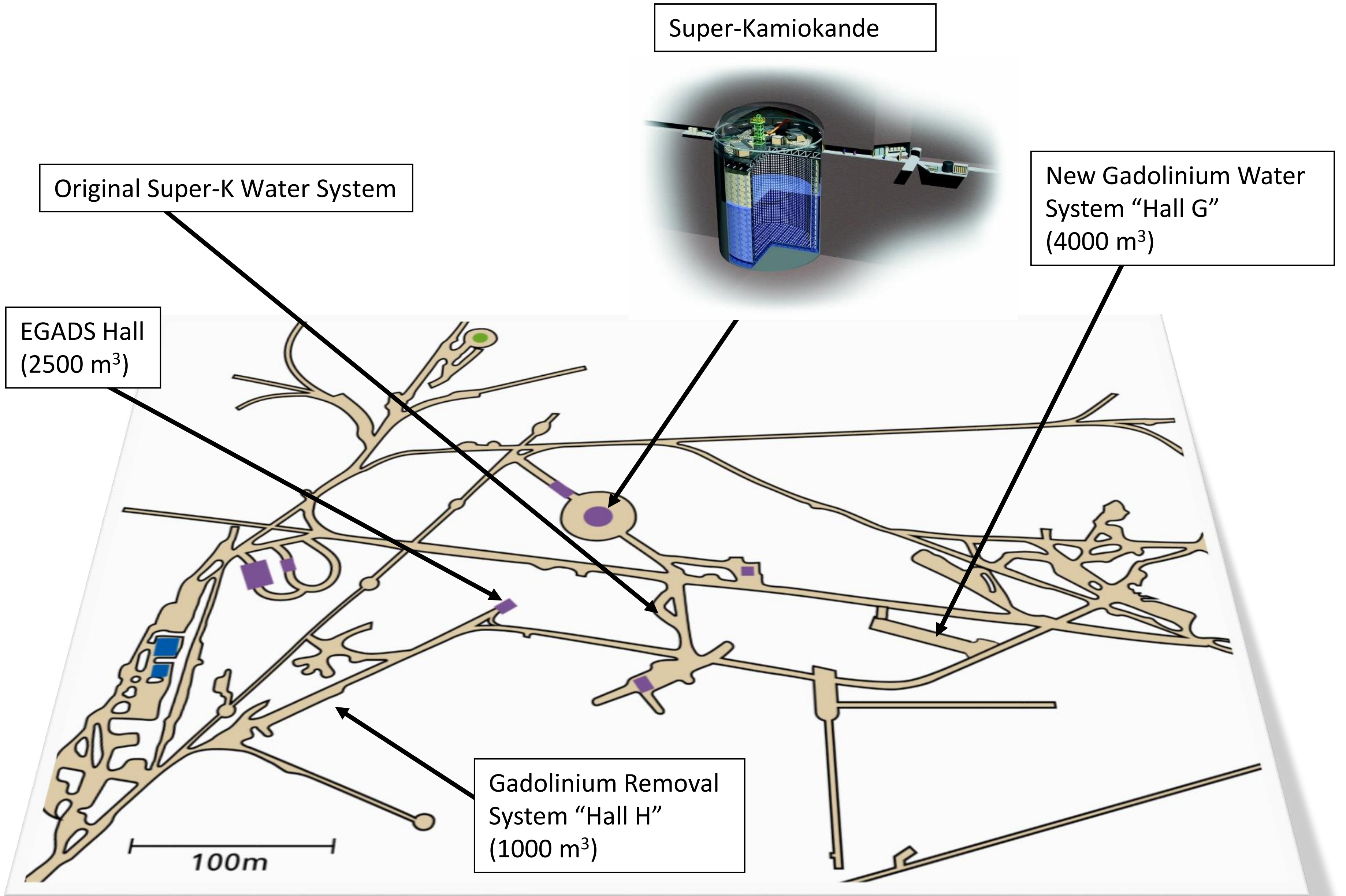
June 27, 2015: The Super-Kamiokande Collaboration approved the addition of gadolinium to the detector, pending discussions with T2K.

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.

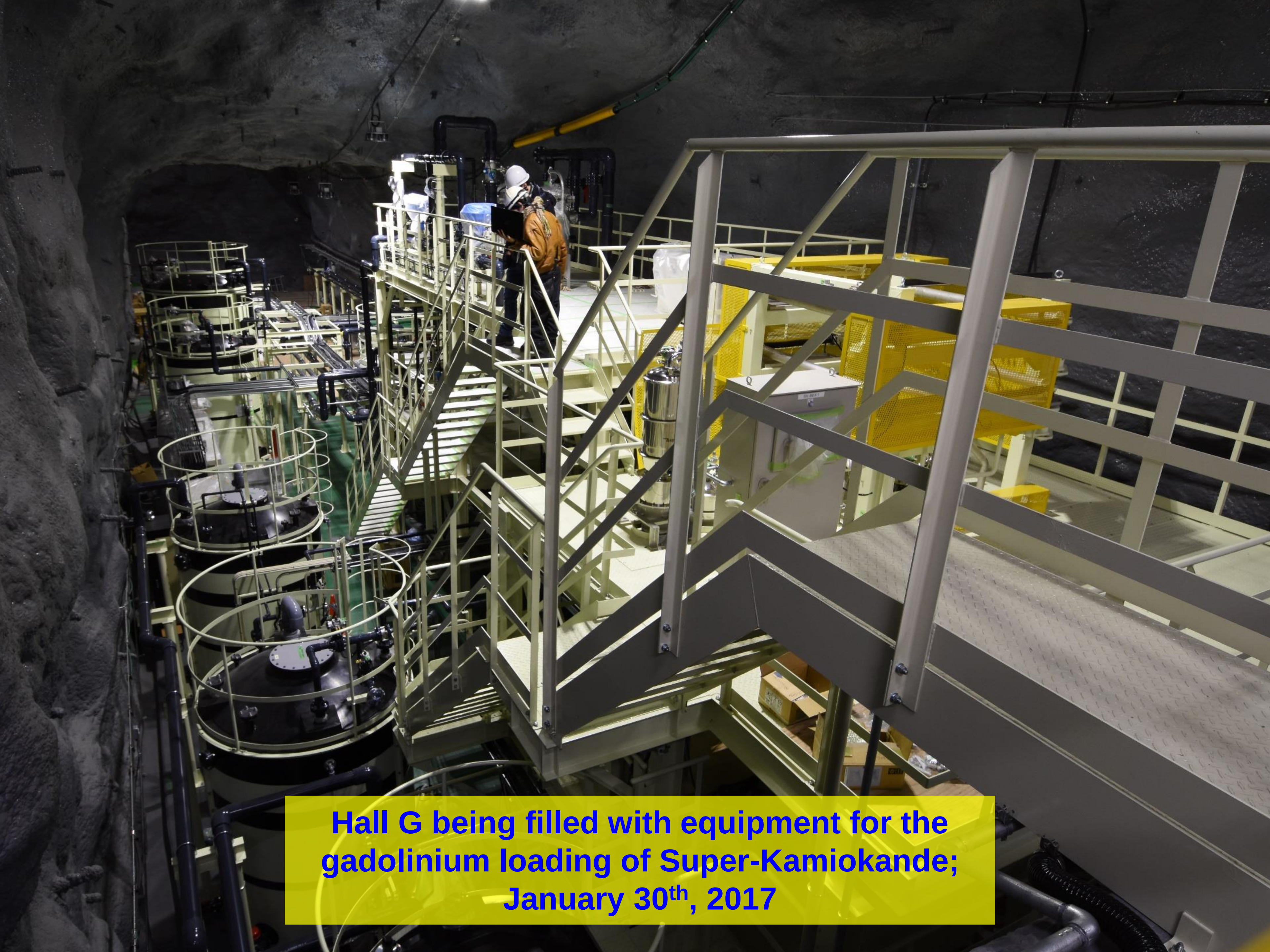




The Kamioka Observatory in the Mozumi Mine

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 30th, 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

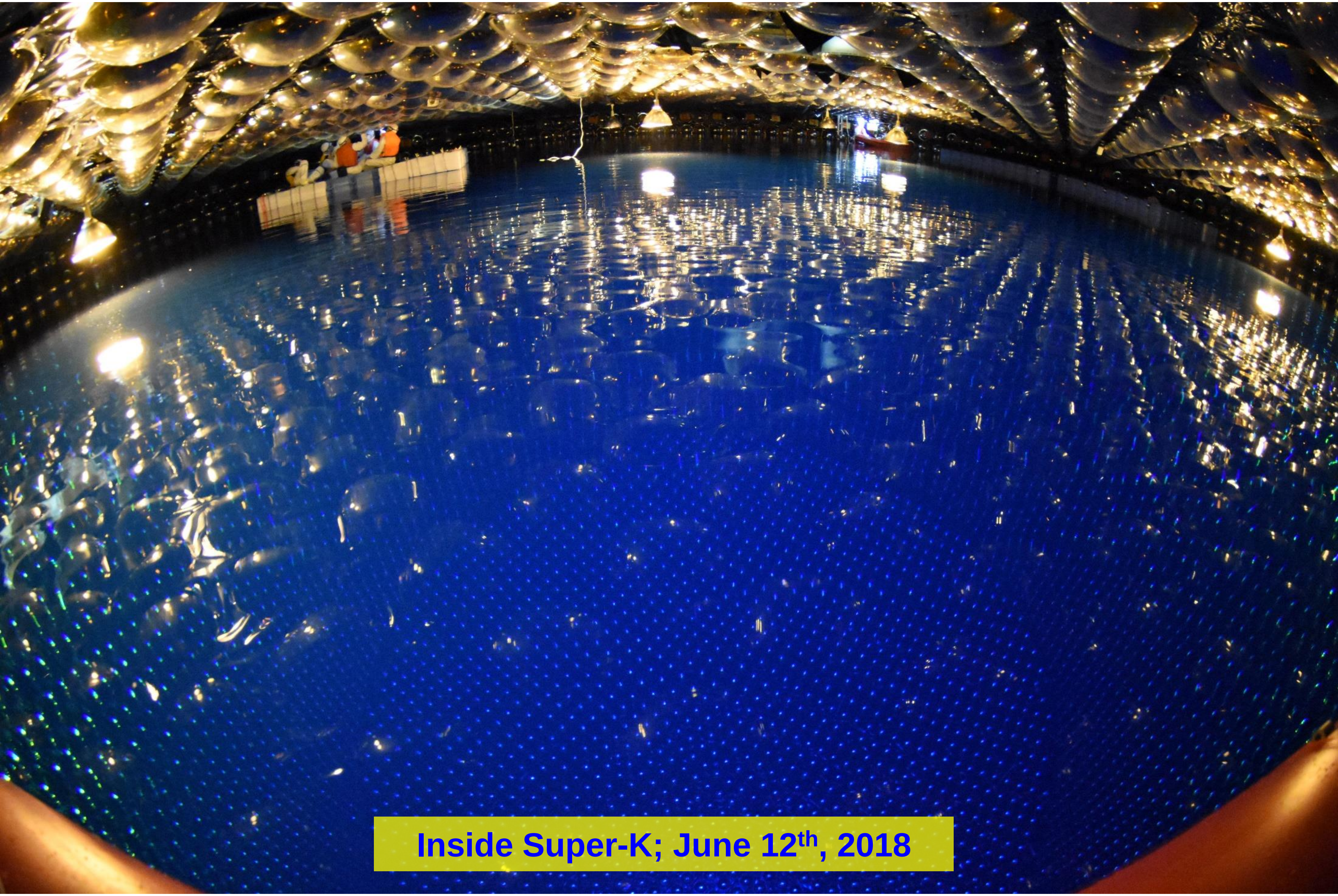
Completed gadolinium removal system (62 tons of ion exchange resin) in Hall H; April 1st, 2018


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

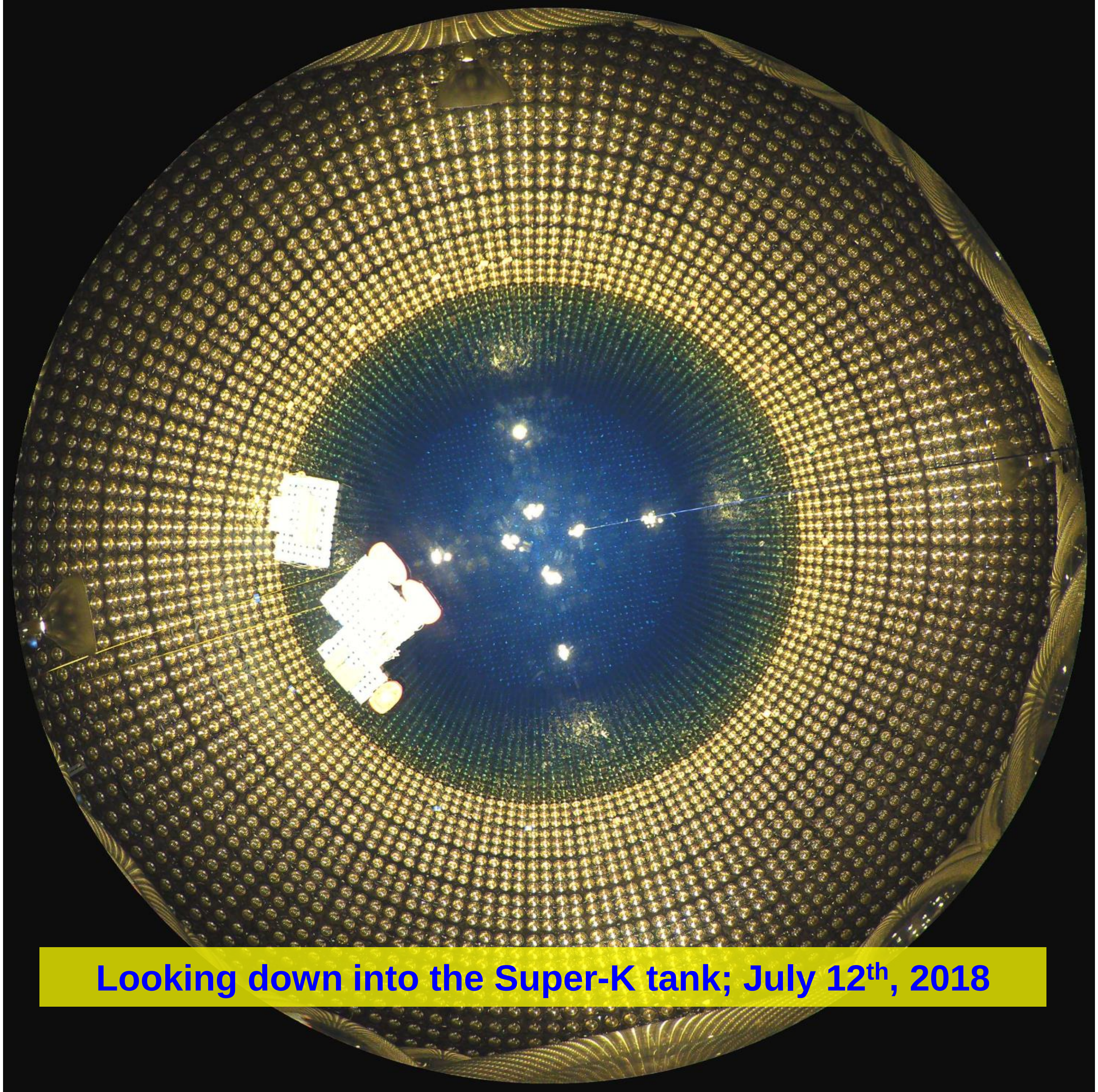
Super-K veto region (side) with floating floor; June 6th, 2018



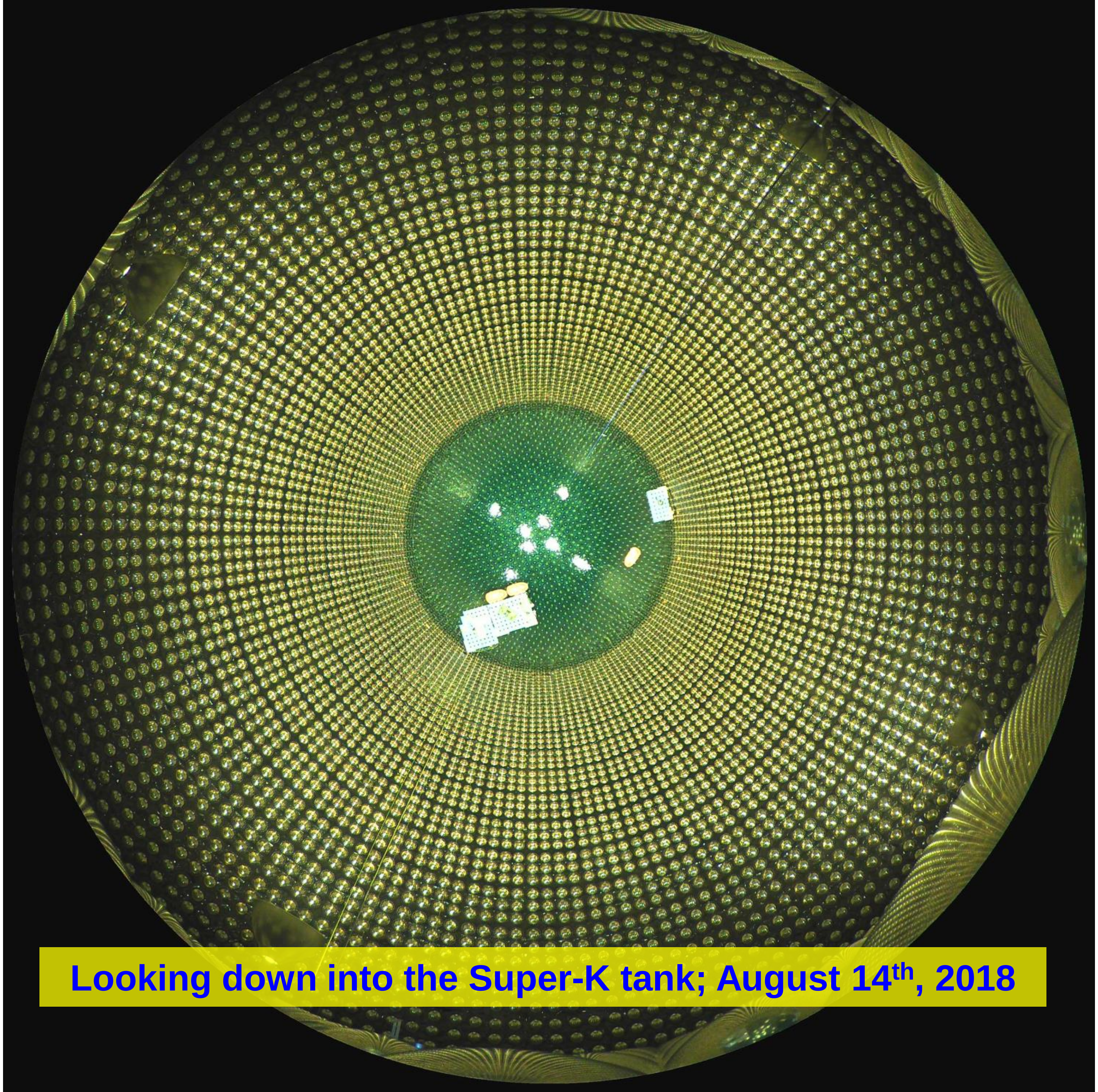
Inside Super-K; June 12th, 2018

Applying special low-background MineGuard sealant

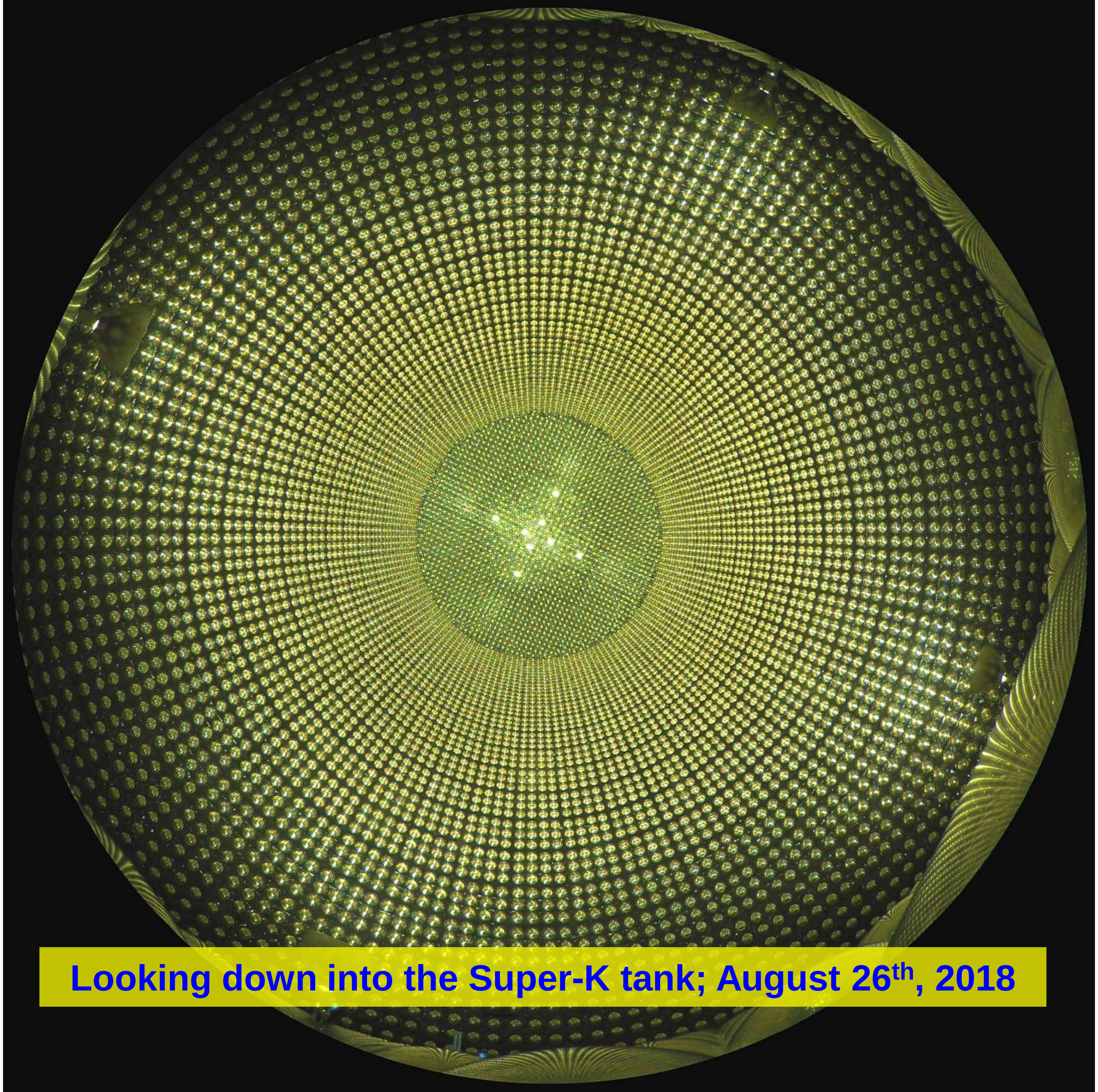
Super-K veto region (side) with floating floor; June 23rd, 2018



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



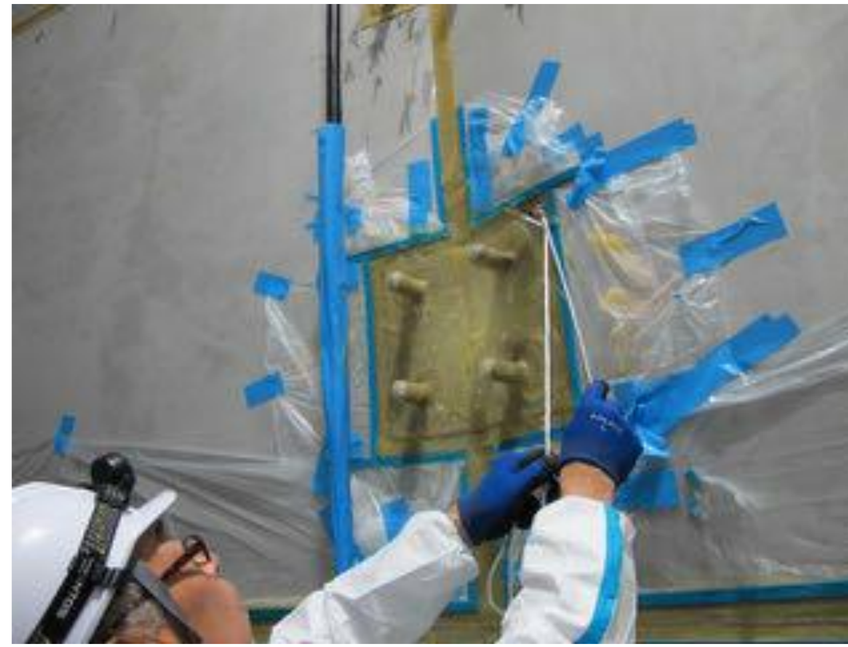
Looking down into the Super-K tank; August 14th, 2018



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!

Developing special low-background $Gd_2(SO_4)_3$

Radioactive chain	Part of the chain	mBq/kg
^{238}U	^{238}U	50
	^{226}Ra	5
^{232}Th	^{228}Ra	10
	^{228}Th	100
^{235}U	^{235}U	32
	^{227}Ac / ^{227}Th	300

Radio isotopes in "typical" off-the-shelf gadolinium sulfate

Radioactive chain	Part of the chain	SRN (mBq/kg)	Solar ν (mBq/kg)
^{238}U	^{238}U	< 5	-
	^{226}Ra	-	< 0.5
^{232}Th	^{228}Ra	-	< 0.05
	^{228}Th	-	< 0.05
^{235}U	^{235}U	-	< 3
	^{227}Ac / ^{227}Th	-	< 3

We need from 1-4 orders of magnitude reduction in RI

↑

What the physics requires

Low background Ge counters at Canfranc underground laboratory (Spain)

Kamioka Ge counter (Japan)

Boulby Underground Germanium Suite (UK)

Low background Ge counters at Canfranc underground laboratory (Spain)

Kamioka Ge counter (Japan)

Boulby Underground Germanium Suite (UK)

Low background Ge counters at Canfranc underground laboratory (Spain)

Kamioka Ge counter (Japan)

Boulby Underground Germanium Suite (UK)

After this iterative purification campaign, one company was able to produce gadolinium sulfate with the required radiopurity.

We recently ordered three 0.5 ton batches from them and tested samples from these batches at Kamioka to be sure everything was okay:

Goal (mBq/kg)		Batch 1	Batch 2	Batch 3
238U < 5	ICPMS	< 0.02	0.02	0.04
	Ge	<9.45	<9.89	<28.4
232Th< 0.05	ICPMS	0.04	0.02	0.04
	Ge	<0.20	<0.21	0.16
226Ra< 0.5	Ge	0.46 ± 0.24	<0.33	<0.20

In 2019 we will purchase ~13 tons of ultrapure gadolinium sulfate, enough for the first step in loading Super-Kamiokande.

→ *It will be the largest order of gadolinium in human history!* ←

Expected timeline for SK-Gd