Supernova Neutrinos in a Gadolinium-loaded Super-Kamiokande

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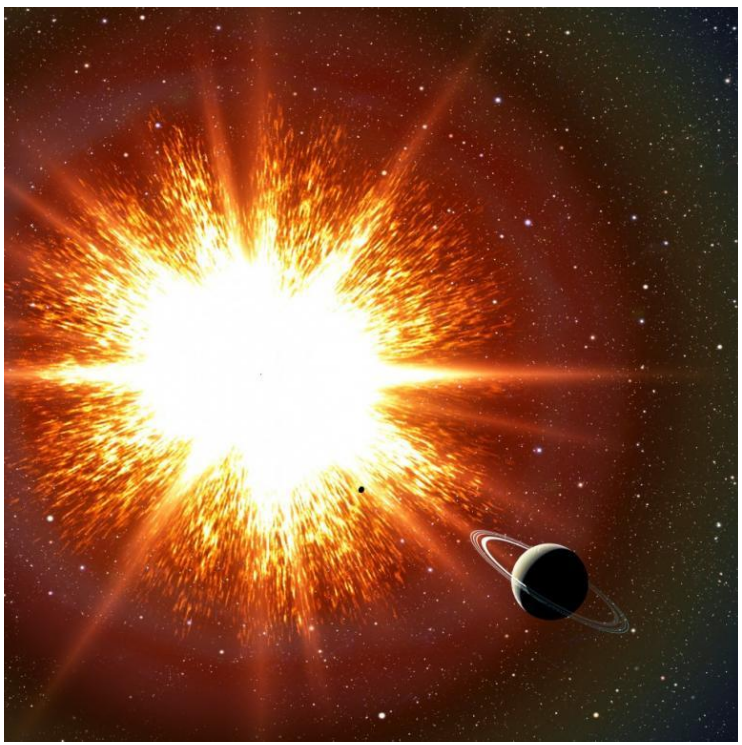
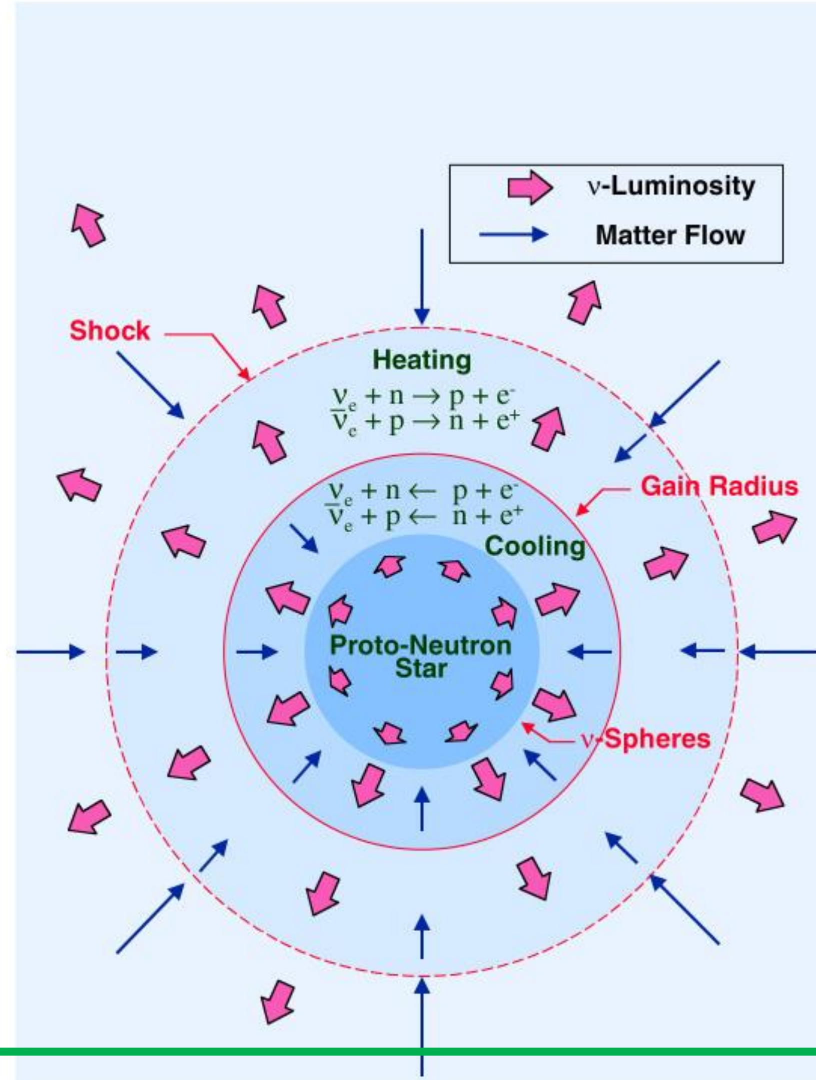
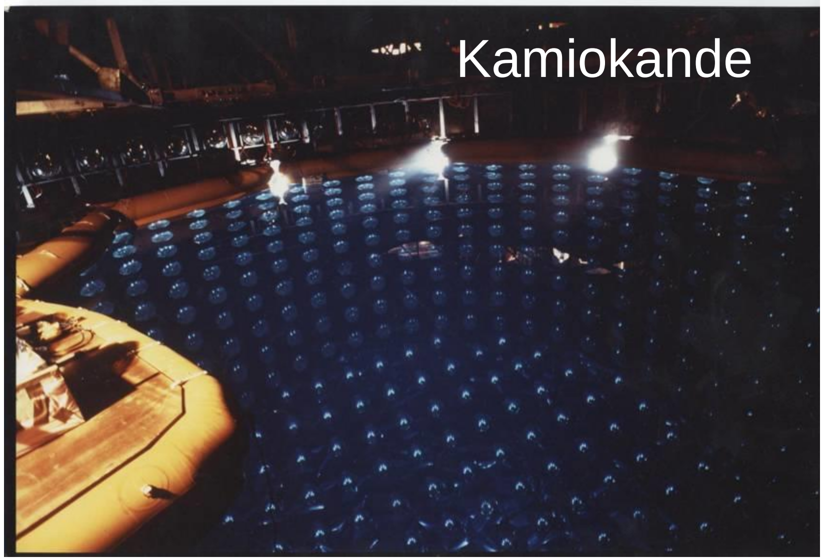
A core-collapse supernova is a nearly perfect “neutrino bomb”.

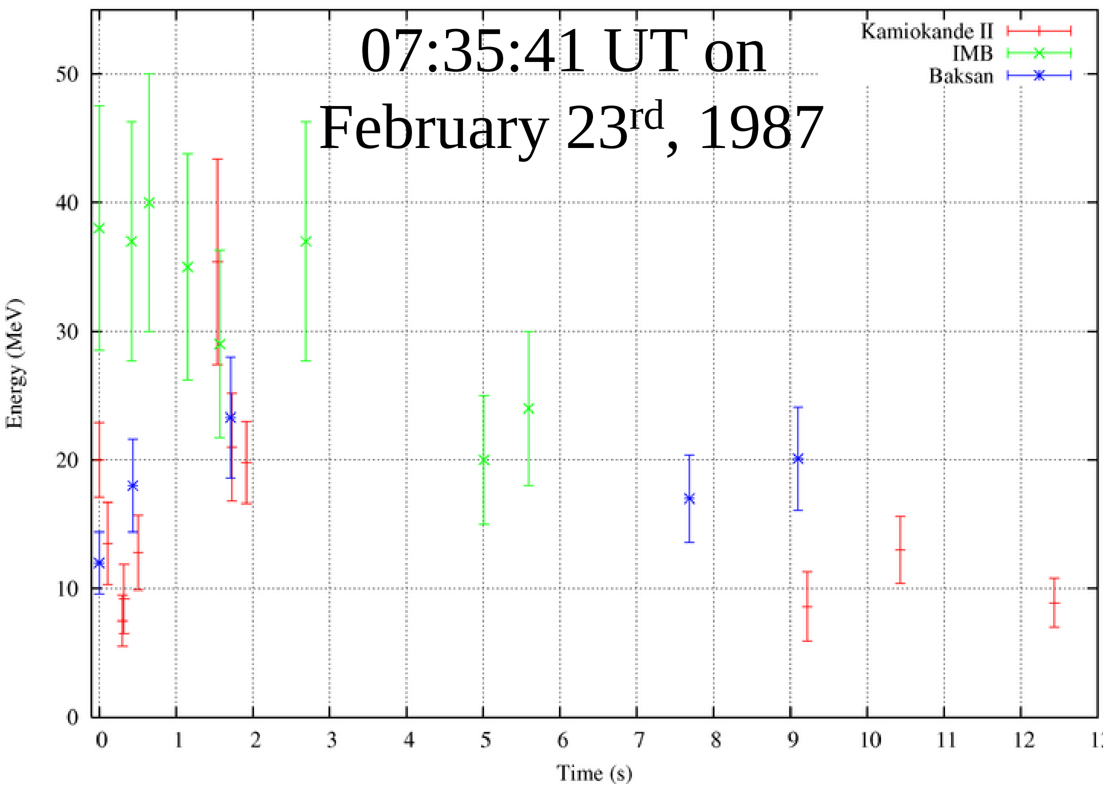
Within ten seconds of collapse it releases >98% of its huge energy (equal to 10^{12} hydrogen bombs exploding per second since the beginning of the universe!) as neutrinos.

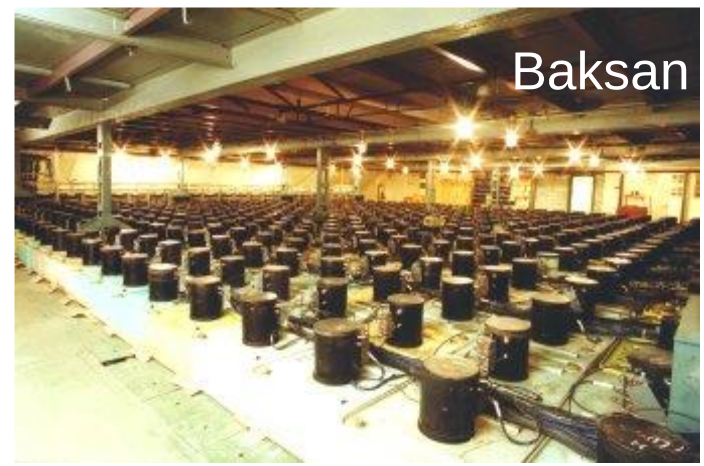




Neutrinos, and possibly gravitational waves, provide the only windows into core collapses’ inner dynamics.







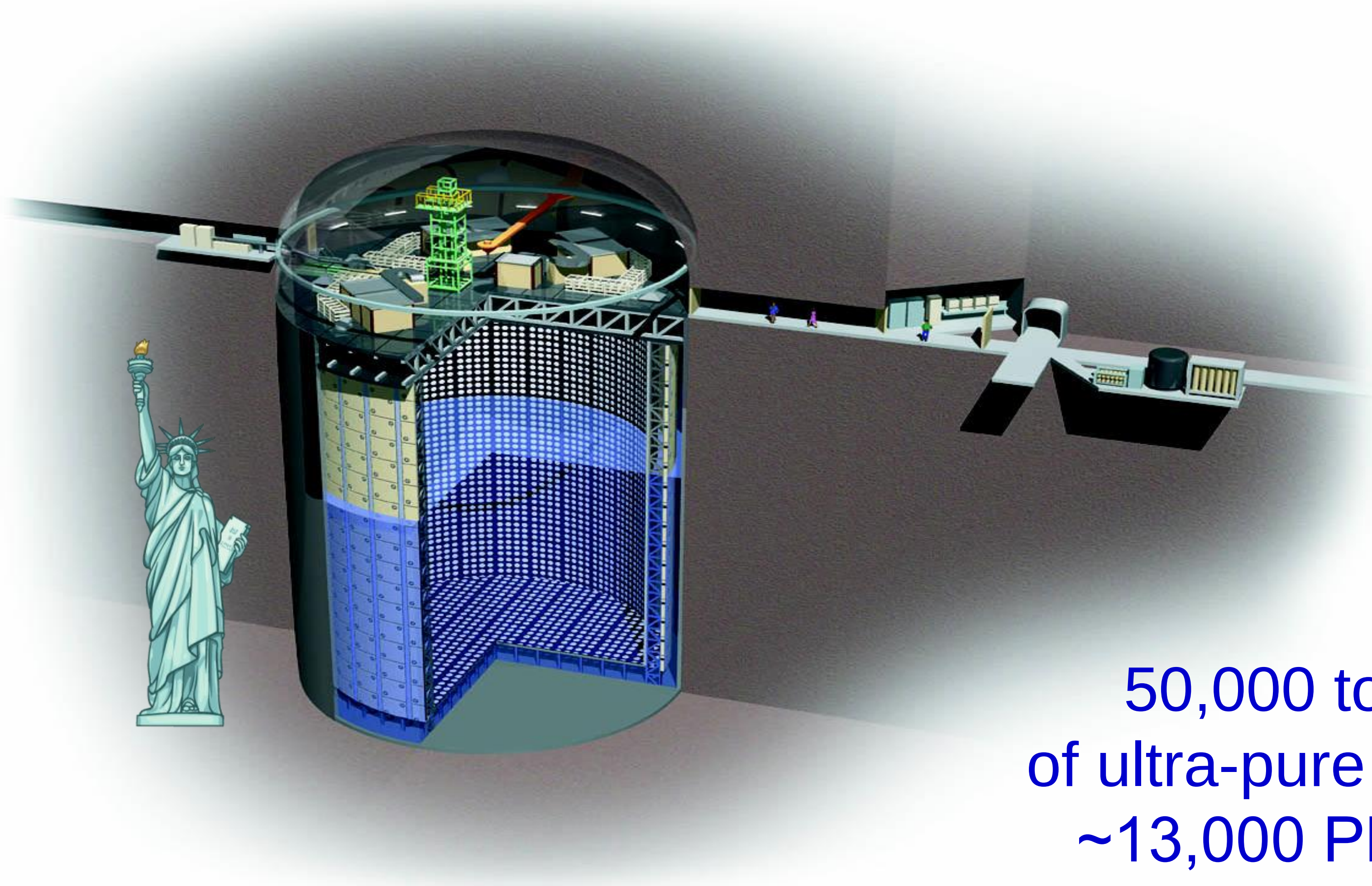
One paper every 10 days… for 32 years!

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!



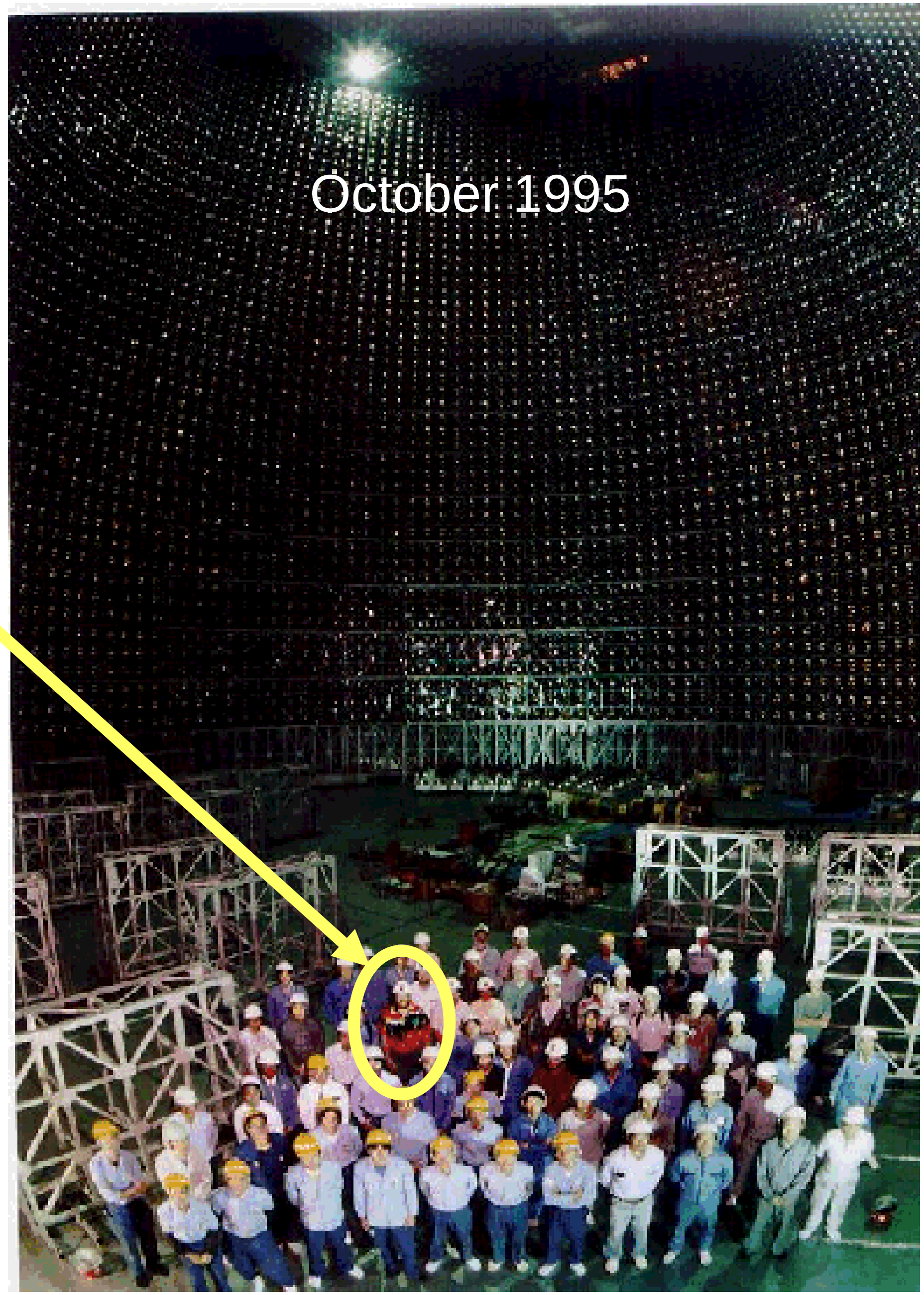
50,000 tons

of ultra-pure water,

~13,000 PMT's

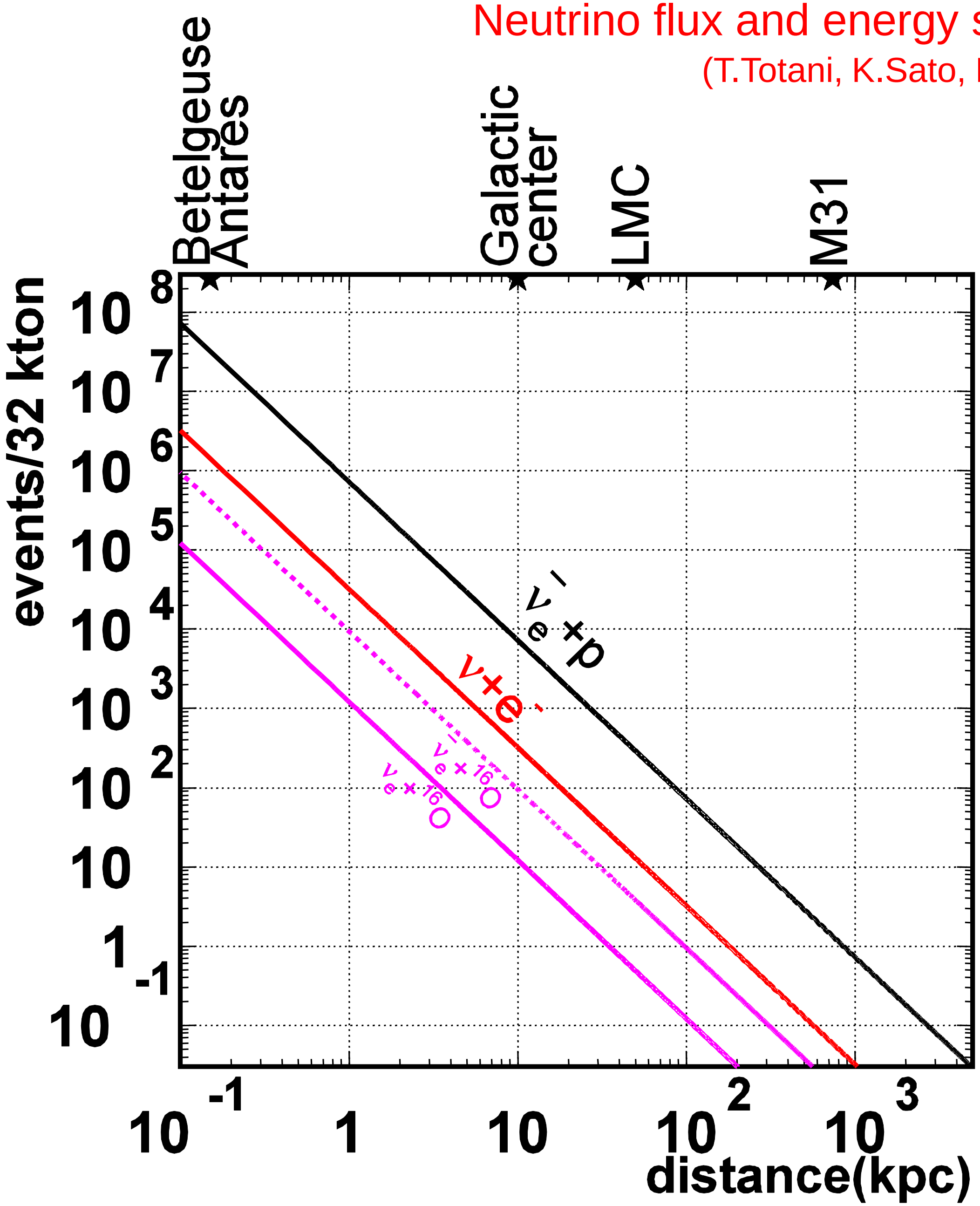
I've been a part of Super-K (and wearing brightly-colored shirts) from its very early days…

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

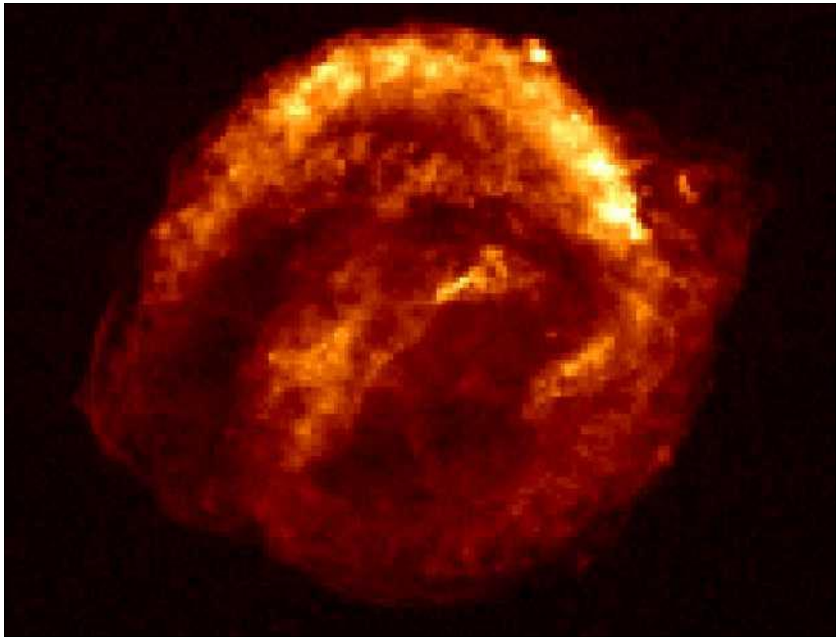
~5^o pointing from ν+e

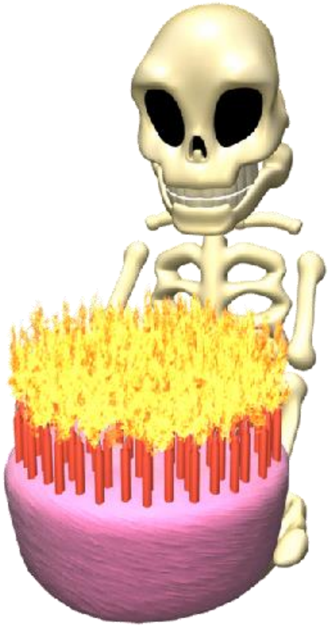
Nakazato simulation: ~50% less flux
(K.Nakazato, K.Sumiyoshi, H.Suzuki, T.Totani, H.Umeda,and S.Yamada, ApJ.Suppl. 205 (2013) 2)

Super-Kamiokande is ready (~99% SN uptime) 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.** ←

We would very much like to collect some more supernova neutrinos!





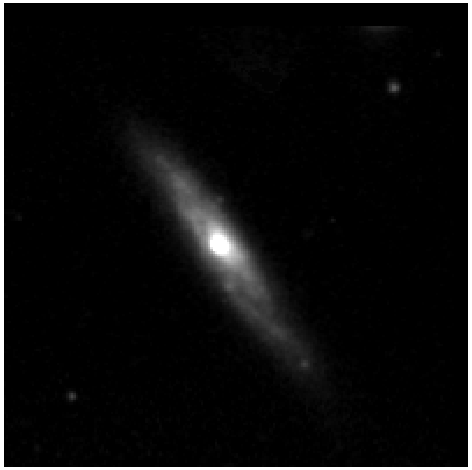
But it has already been nearly a third of a century since SN1987A, and exactly <u>415 years and 70 days</u> since a supernova was last definitely observed within our own galaxy.

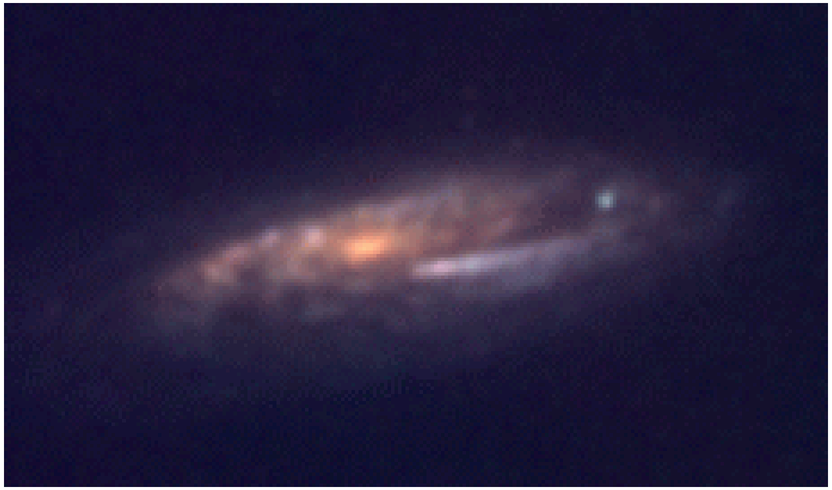
Yes, it's been a long, cold winter for SN neutrinos…
but there is hope!

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, nearby supernova explosions may be rare, but supernova explosions are extremely common.



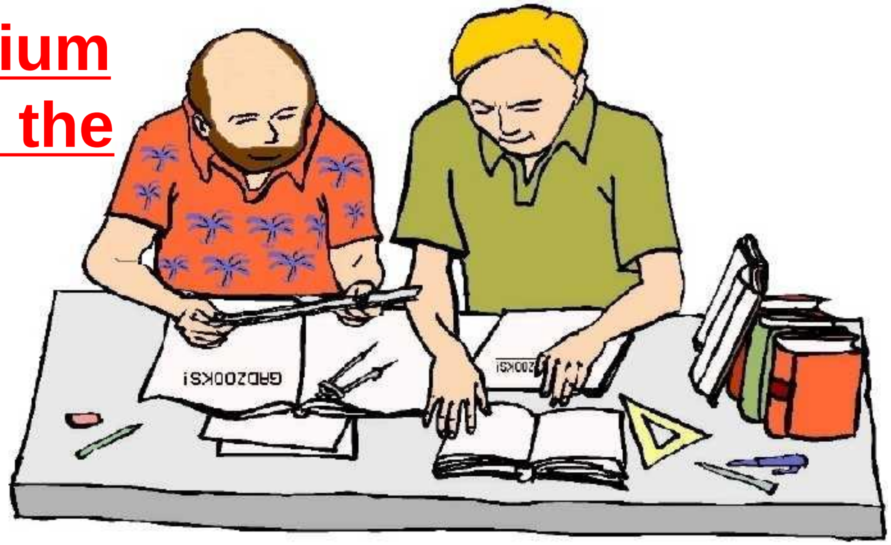


Here's how most supernovas look to us (video is looped).

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].

Adding gadolinium to SK will make the DSNB visible!



Motivated by detecting the DSNB, theorist John Beacom and I wrote the original GADZOOKS!

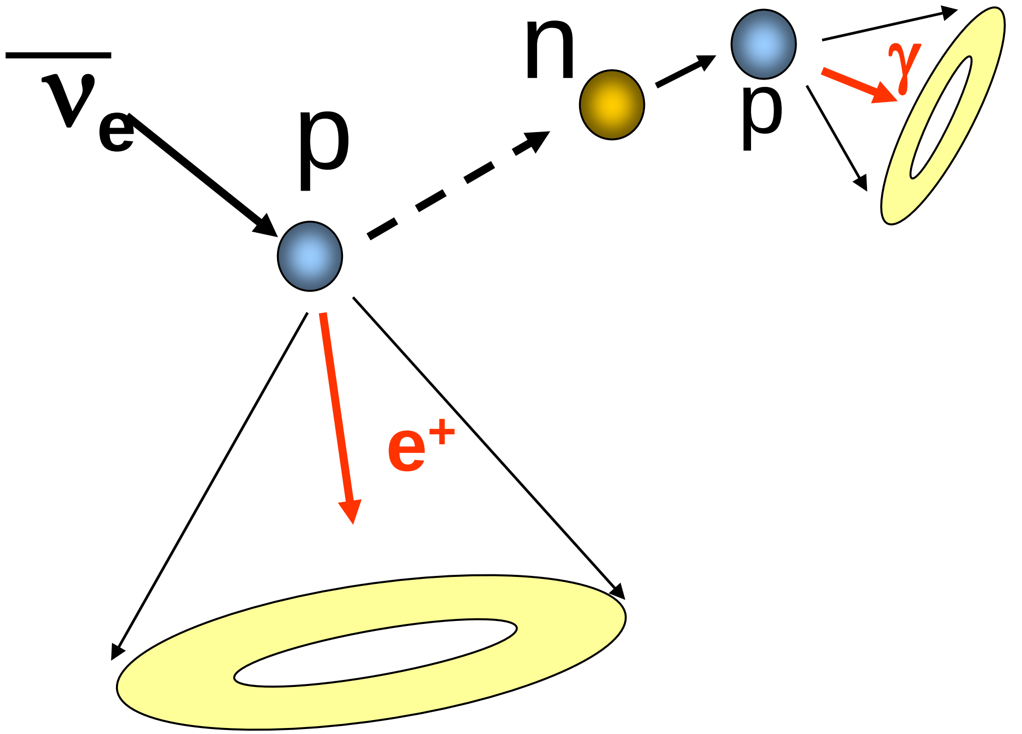
(Gadolinium Antineutrino Detector Zealously Outperforming Old Kamiokande, Super!) paper.

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]

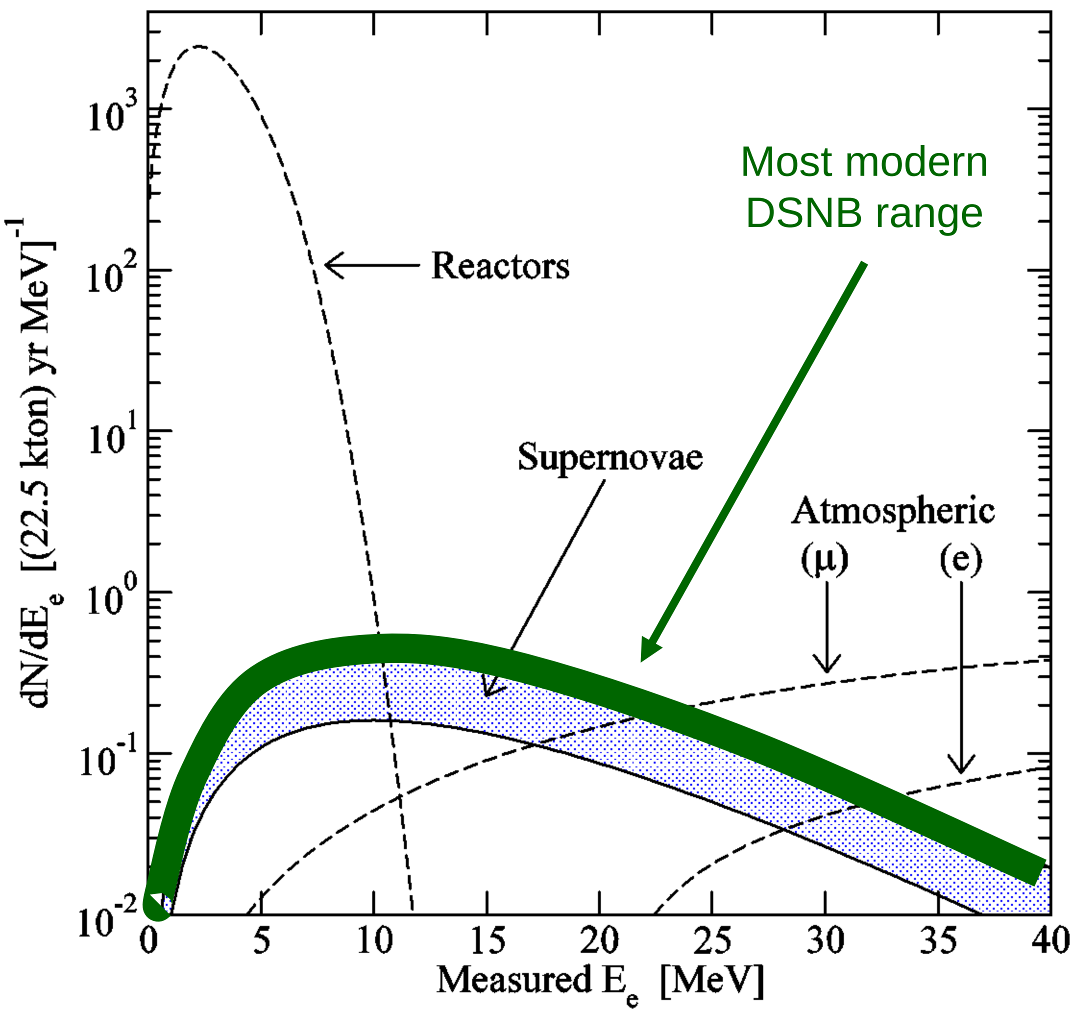
(391 citations → one every 15 days for fifteen years)

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



Positron and gamma ray vertices are within ~50cm.

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:

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

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

In the case of a Milky Way 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.

In 2008 I underwent a significant transformation…

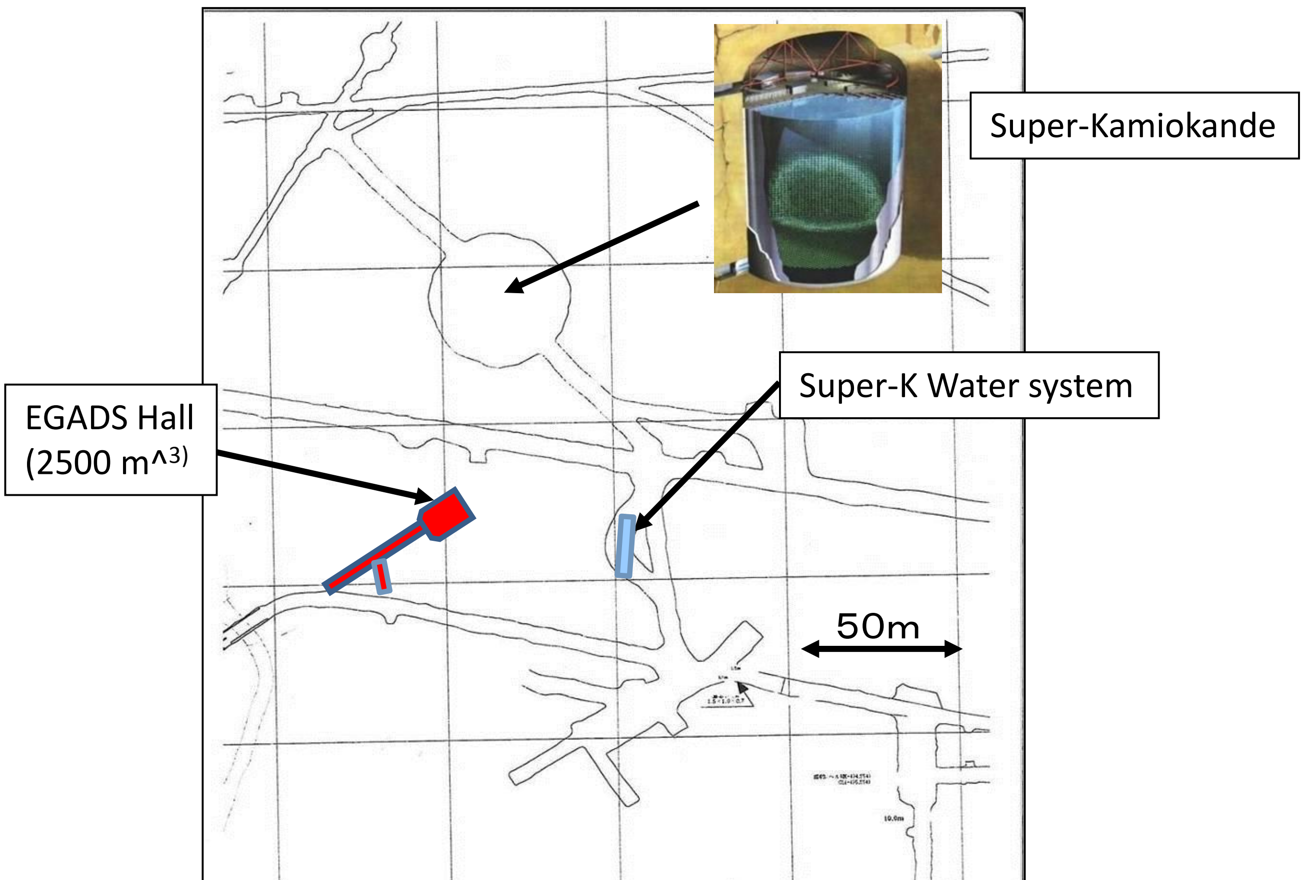
I joined UTokyo's newly-formed IPMU as their first full-time *gaijin* professor.

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

IPMU INSTITUTE FOR THE PHYSICS AND MATHEMATICS OF THE UNIVERSE

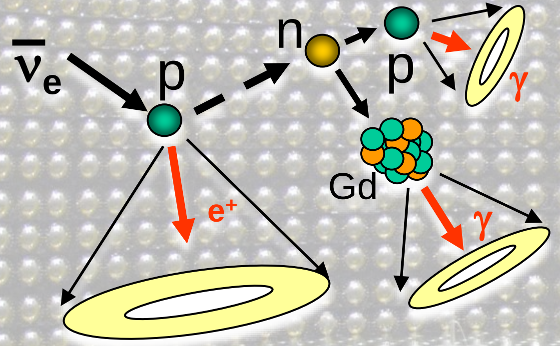
Starting in 2009, a dedicated Gd test facility was built in the Kamioka mine under my direction, complete with its own water filtration system, 50-cm PMT's, and DAQ electronics.

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

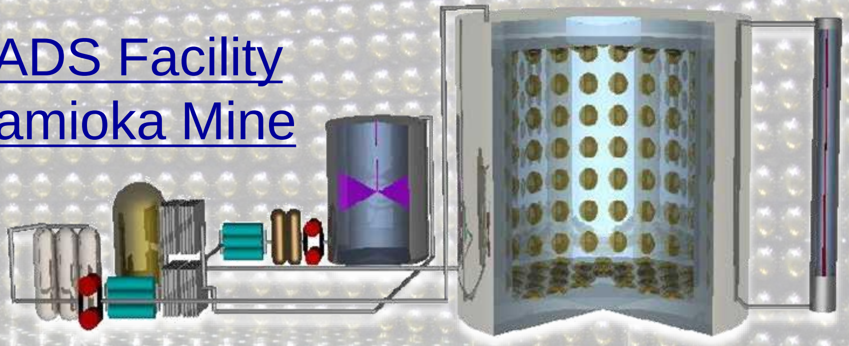


EGADS → Gd-loaded Super-K

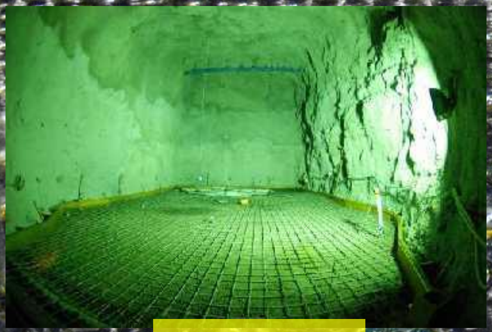
Adding **water soluble gadolinium** to **Super-K** will greatly enhance its ability to detect **supernova neutrinos** (and help with many other physics topics like **proton decay**). **EGADS** is a dedicated gadolinium demonstrator which includes a working 200 ton scale model of SK.



EGADS Facility in Kamioka Mine



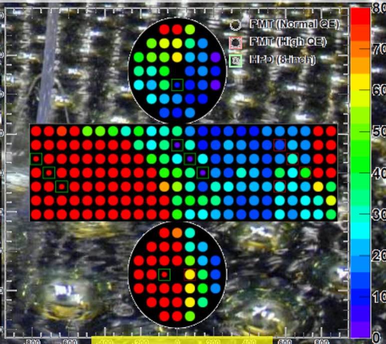
Beacom and Vagins, *Phys. Rev. Lett.*, 93:171101, 2004 [391 citations]



12/2009

11/2011

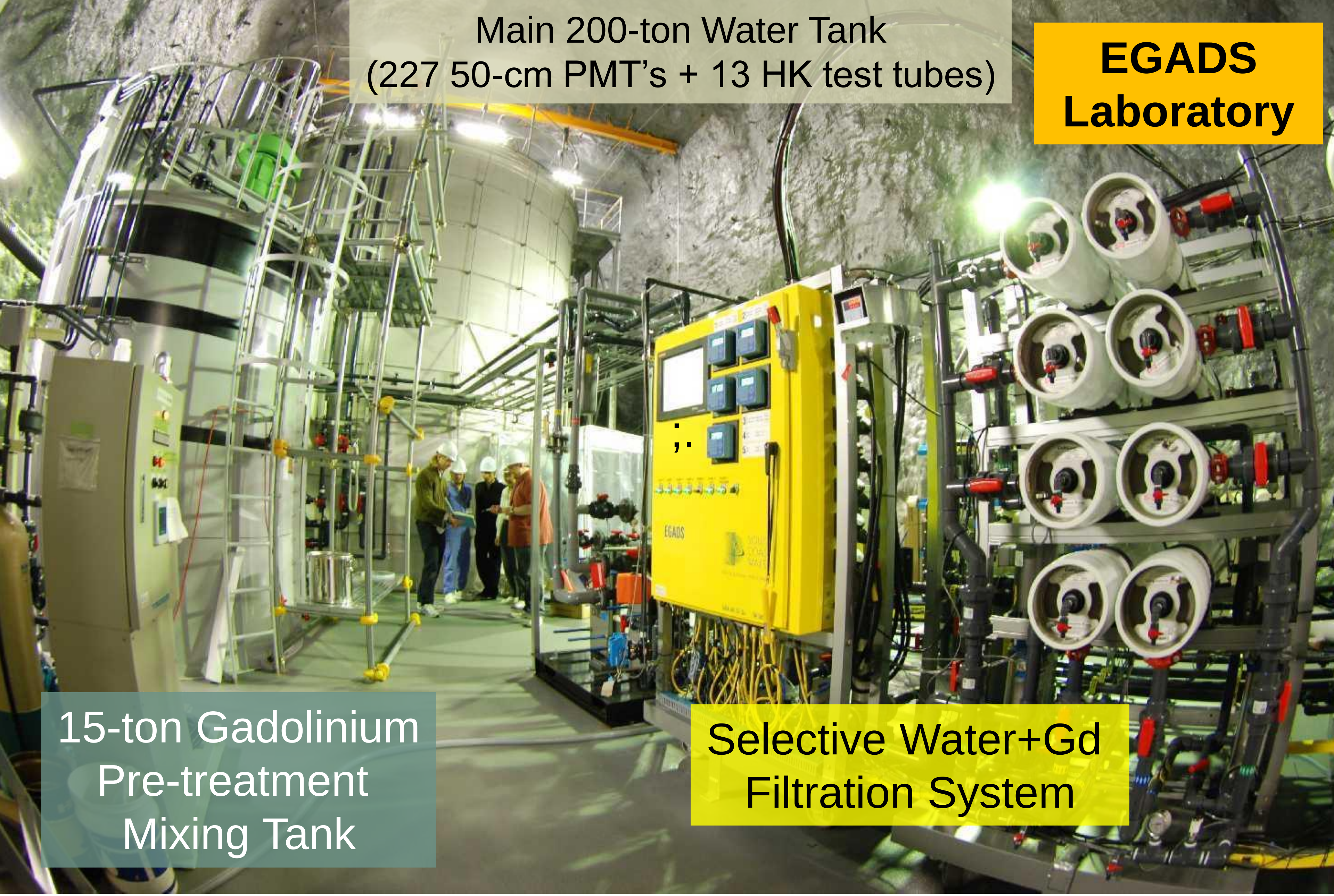
8/2013



6/2015

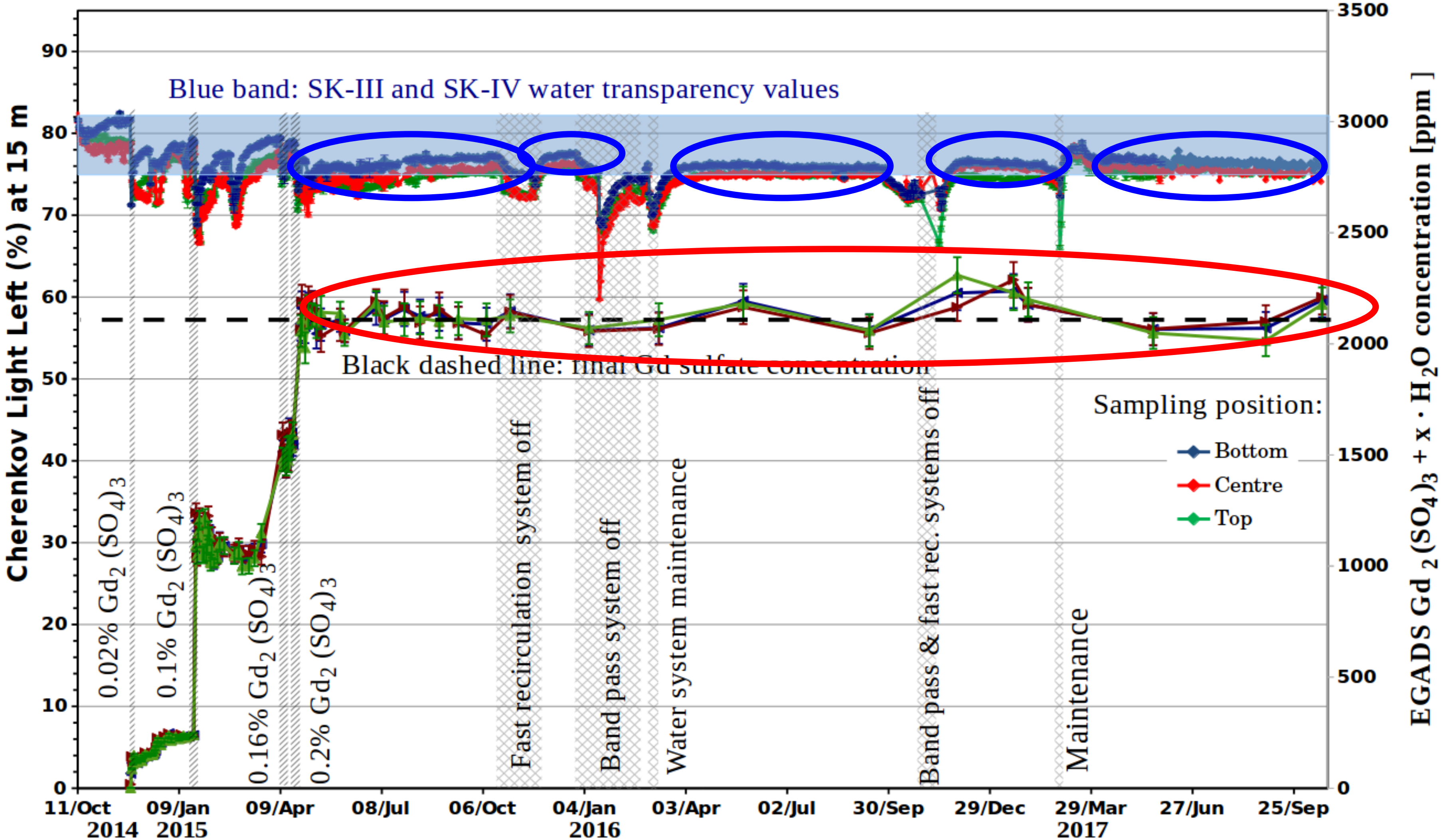
Maintaining good water quality in the presence of dissolved gadolinium required the development of an entirely new technology: true selective filtration. I call my resulting system a <u>“molecular band-pass”</u> filter.

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



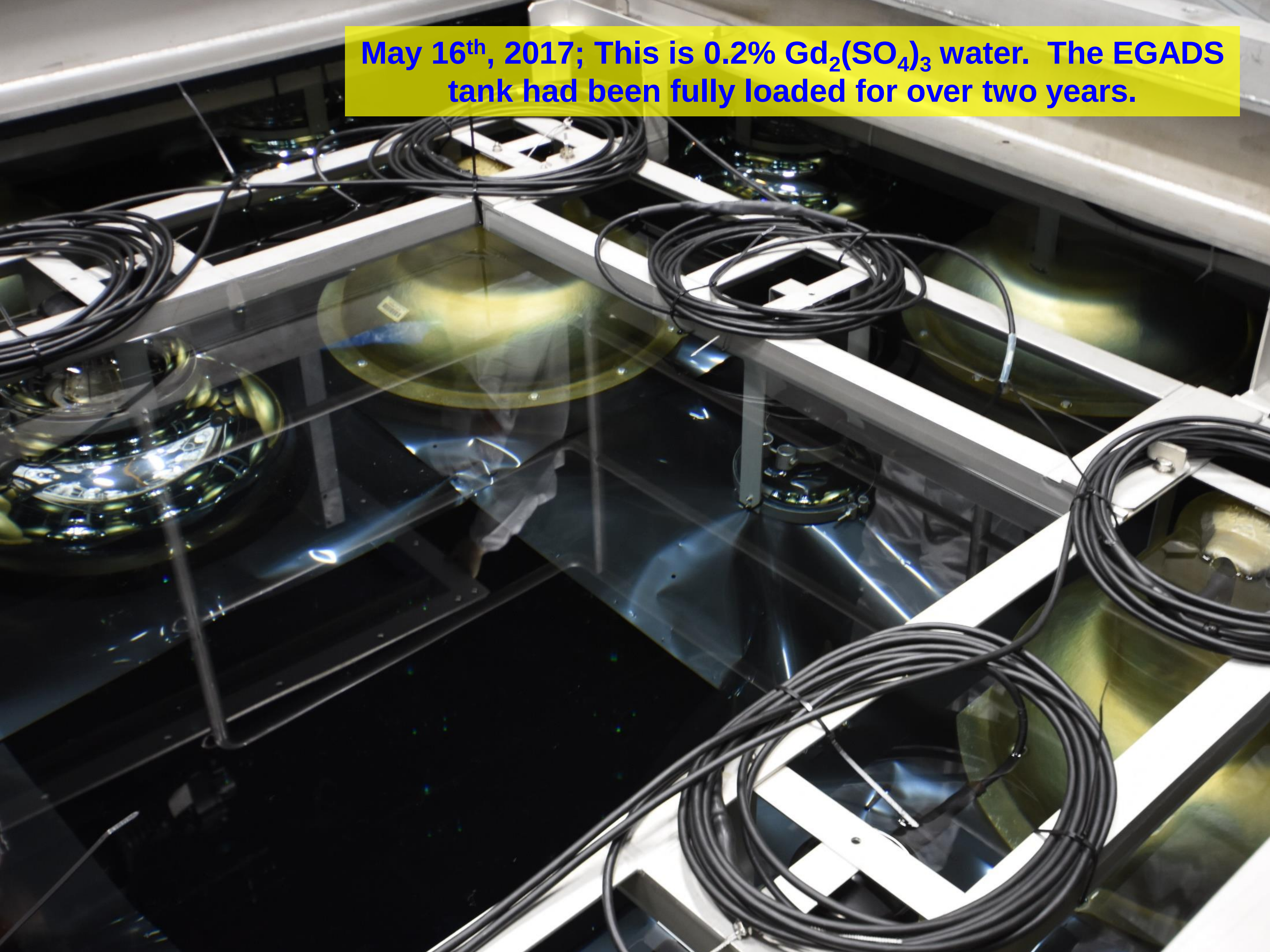
Worldwide, over £7.6M (not counting salaries) has been spent developing and proving the viability of the Gd-in-water concept.

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



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

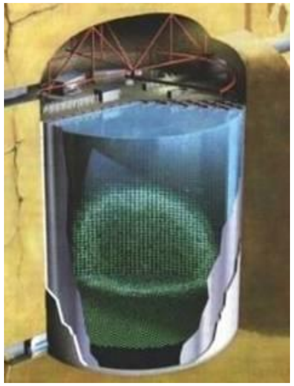
<u>No detectable loss of Gd after more than 650 complete turnovers.</u>



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

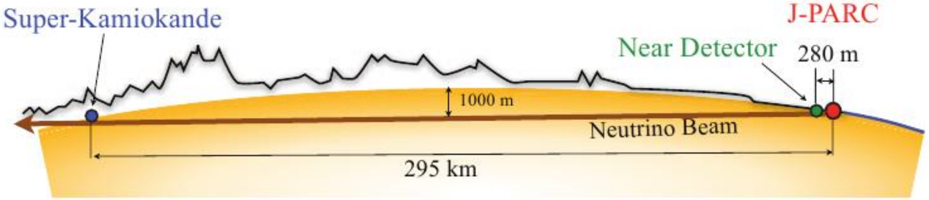
November 6th, 2017; This view is directed up the side wall from the bottom of the 200-ton tank. Looks great after 2.5 years of exposure to 0.2% $Gd_2(SO_4)_3$ water!

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

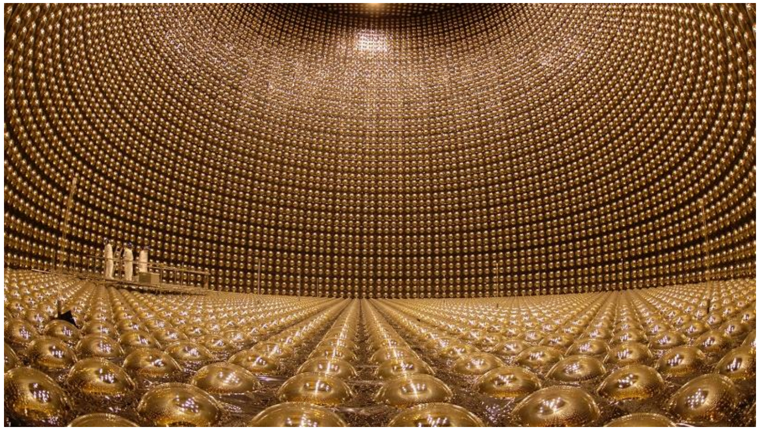


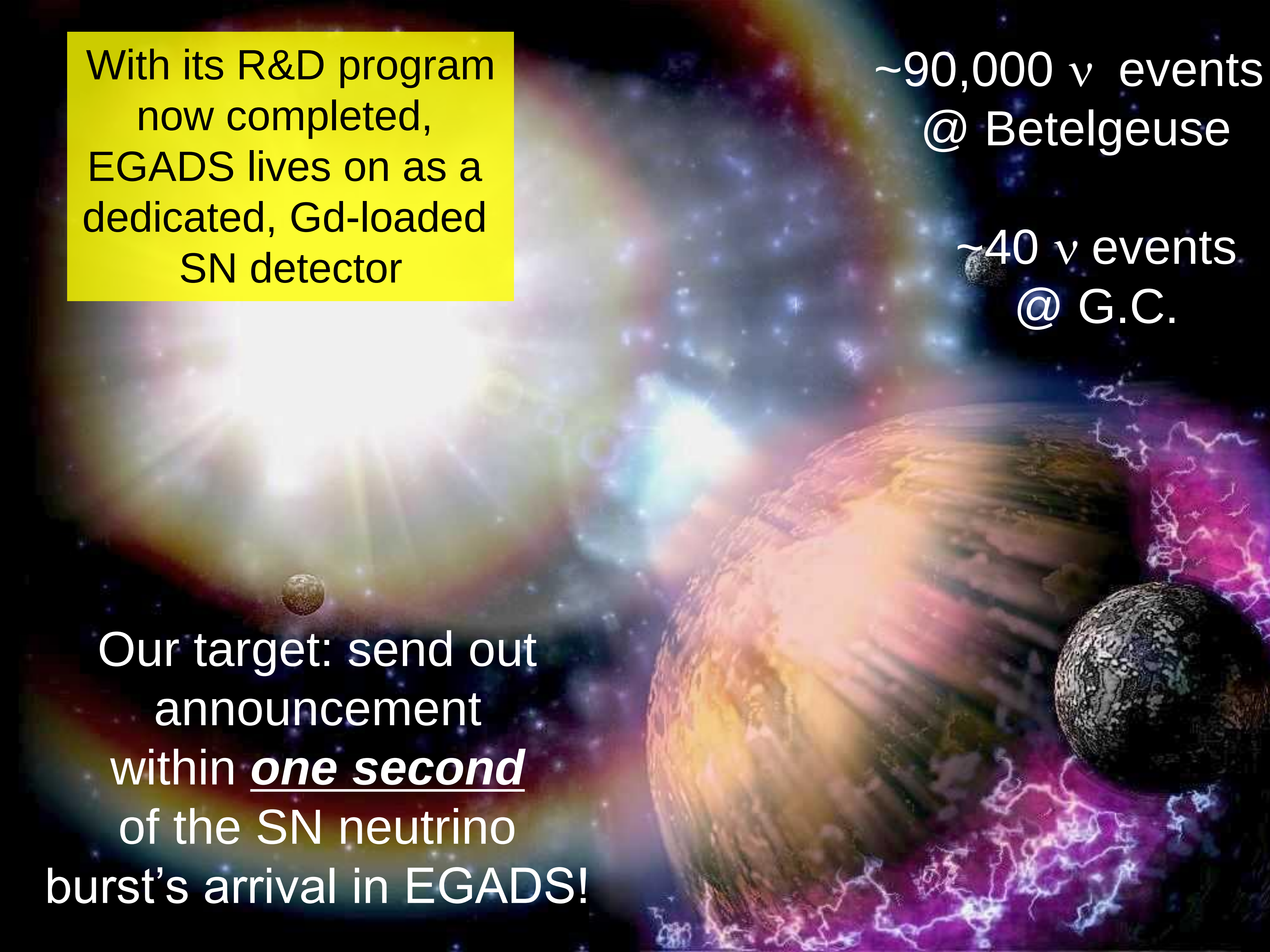
June 27, 2015: The Super-Kamiokande Collaboration approved the addition of gadolinium to the detector, pending discussions with T2K.

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.



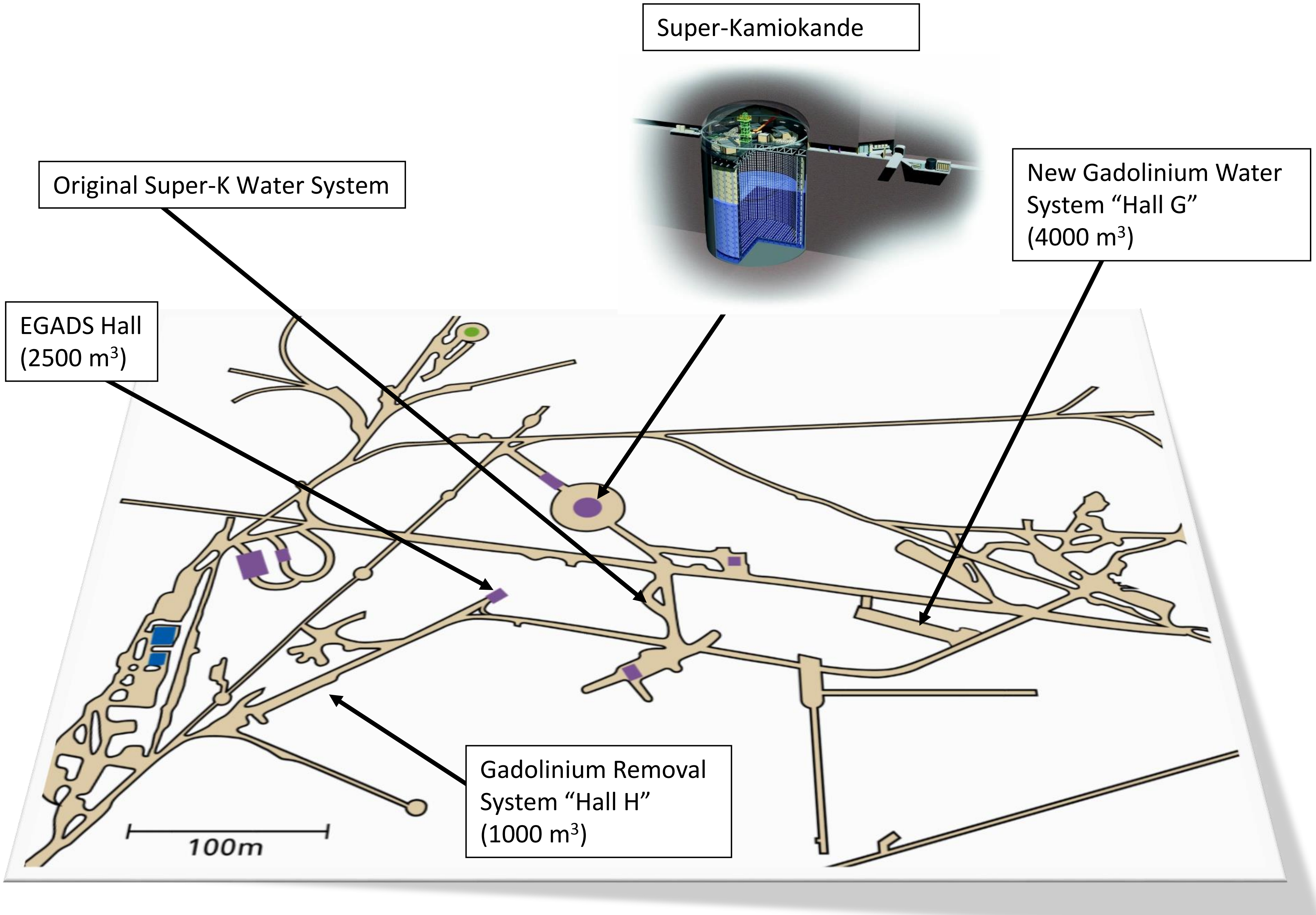


With its R&D program now completed, EGADS lives on as a dedicated, Gd-loaded SN detector

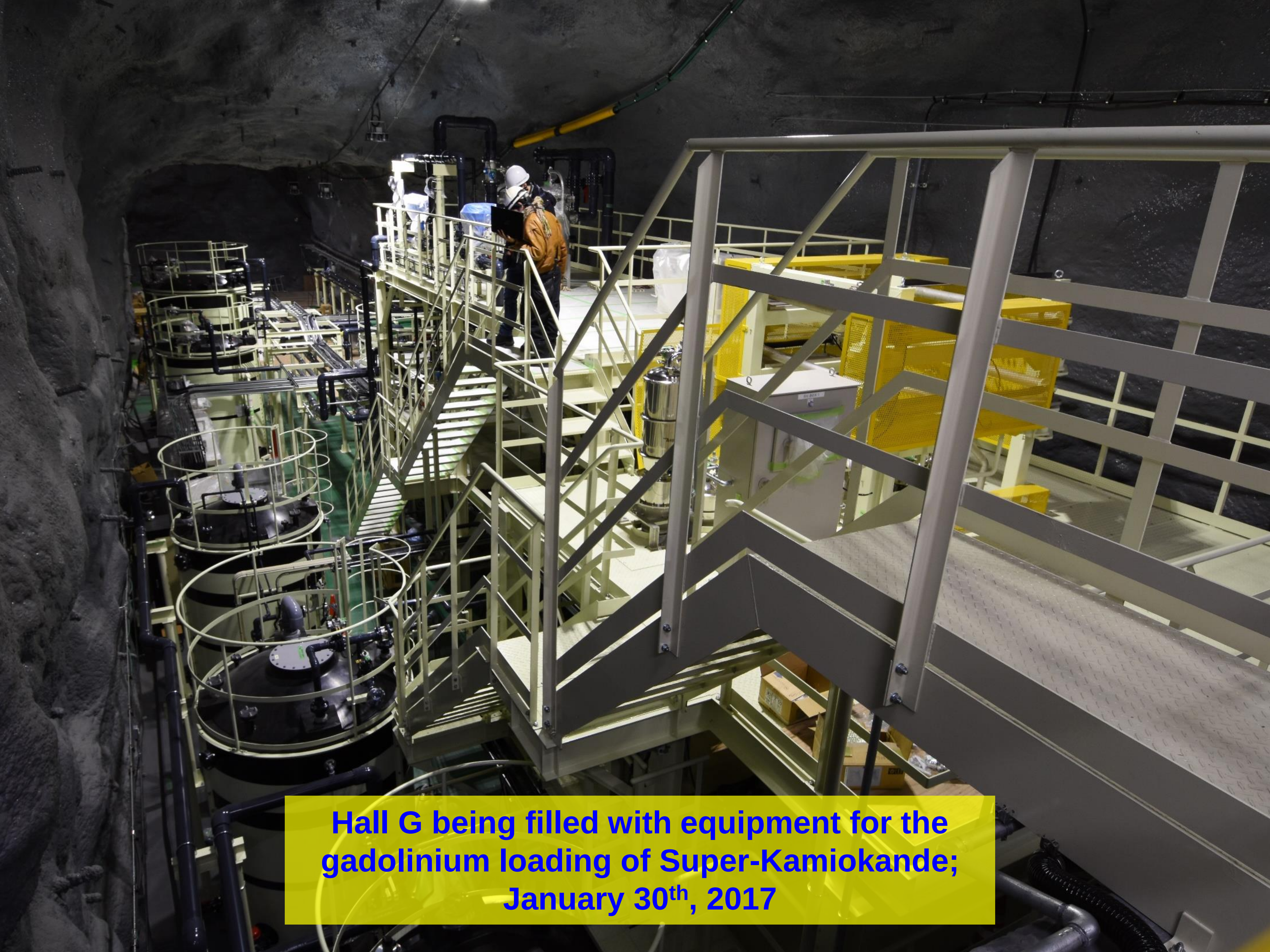
~90,000 ν events @ Betelgeuse

~40 ν events @ G.C.

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



The Kamioka Observatory in the Mozumi Mine

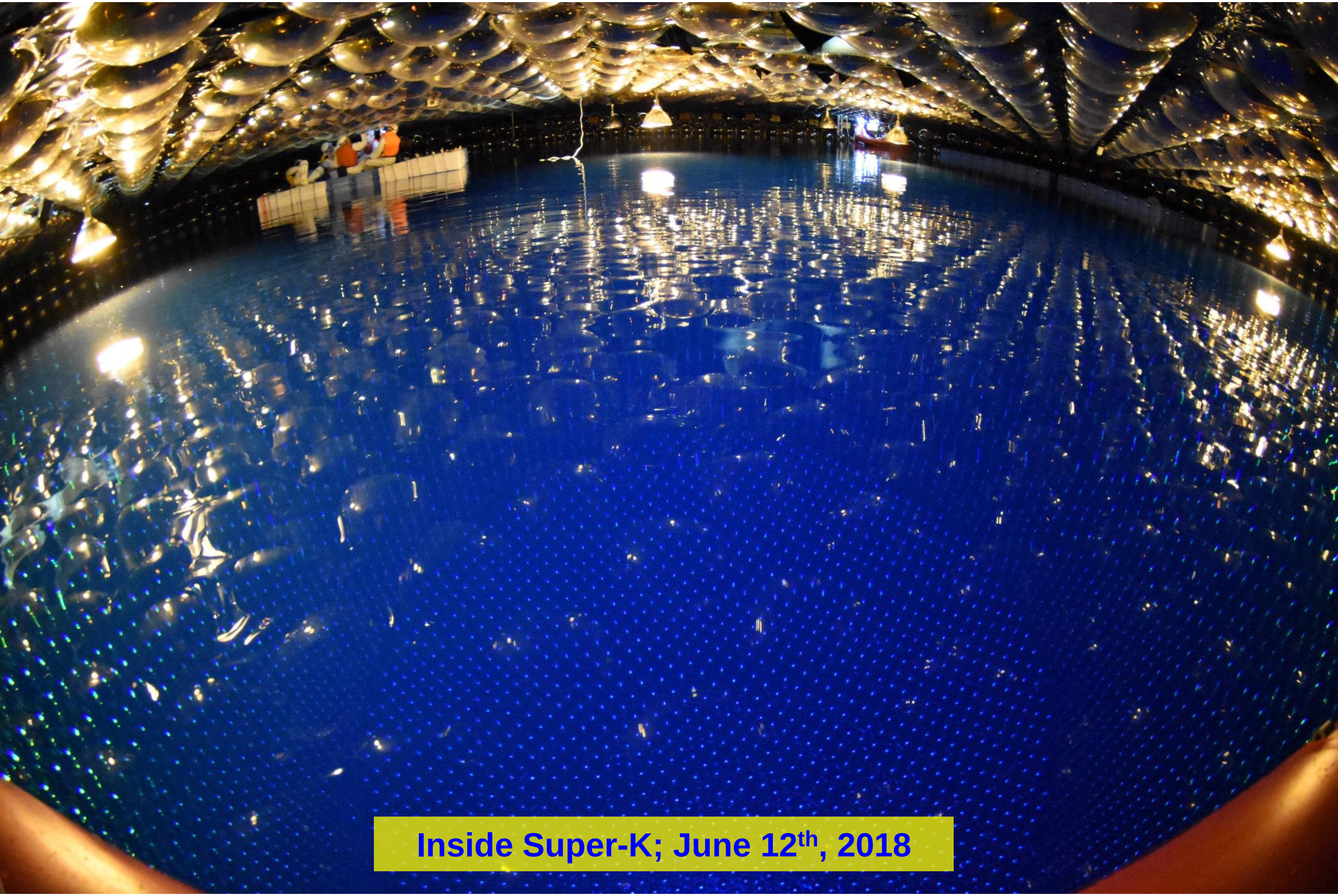


Hall G being filled with equipment for the gadolinium loading of Super-Kamiokande; January 30th, 2017

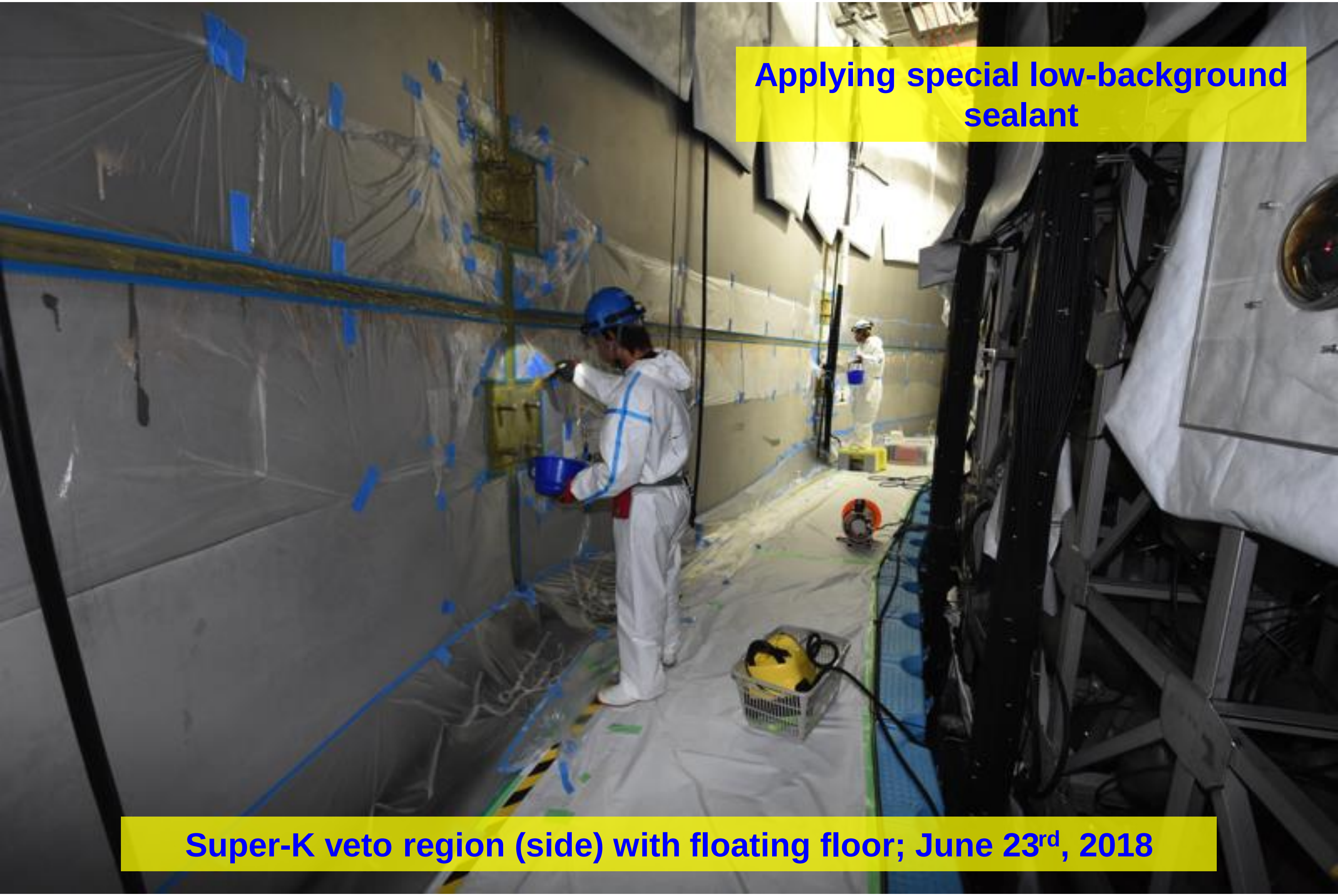

Main jobs to get ready for Gd loading:
1) Fix SK leak
2) Clean up interior
3) Replace dead PMTs
4) Augment internal plumbing
Entering Super-K for the first time since 2006; June 1st, 2018

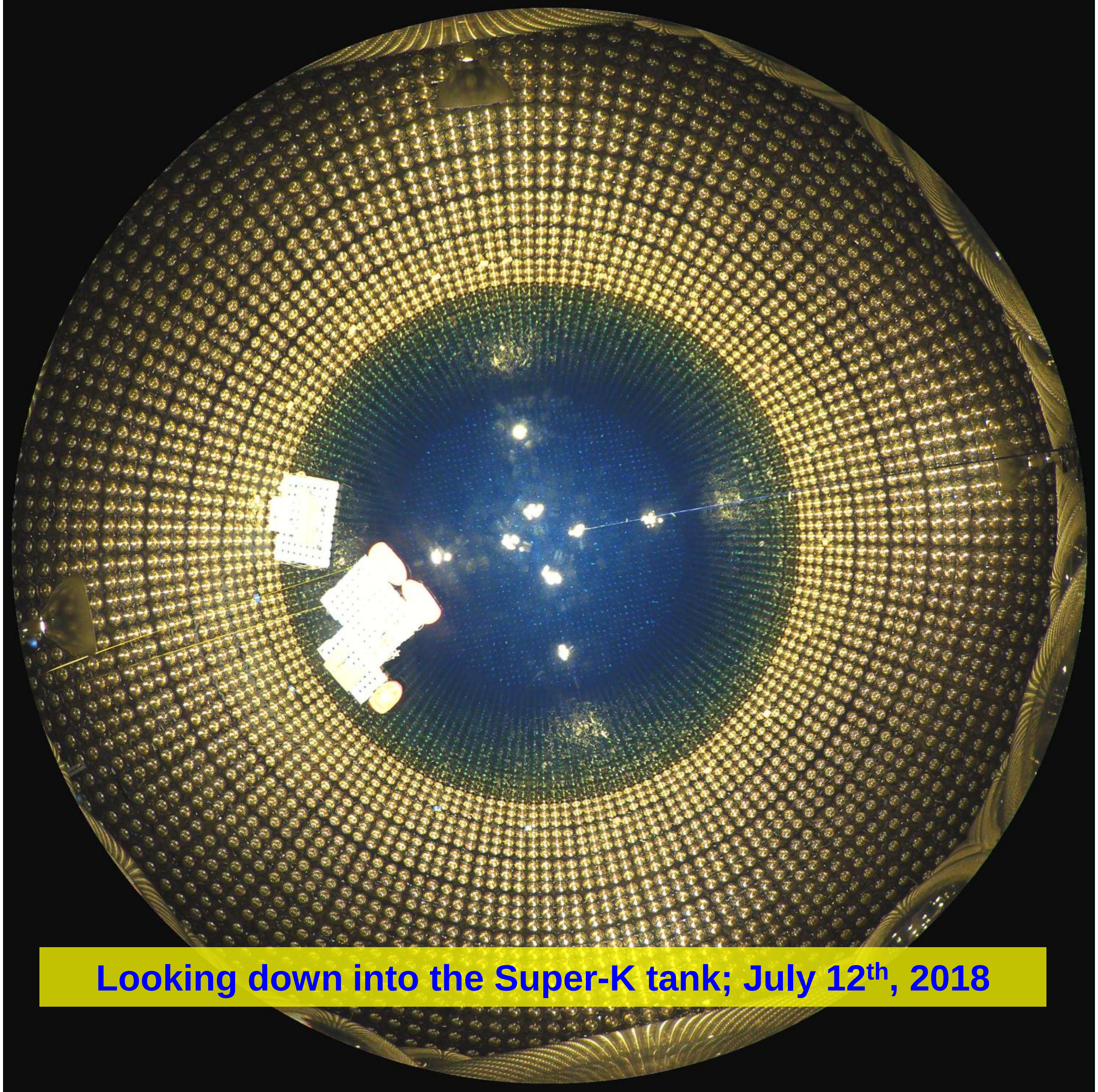
From March 2018 → October 2018,
2683 person-days of work were required!

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

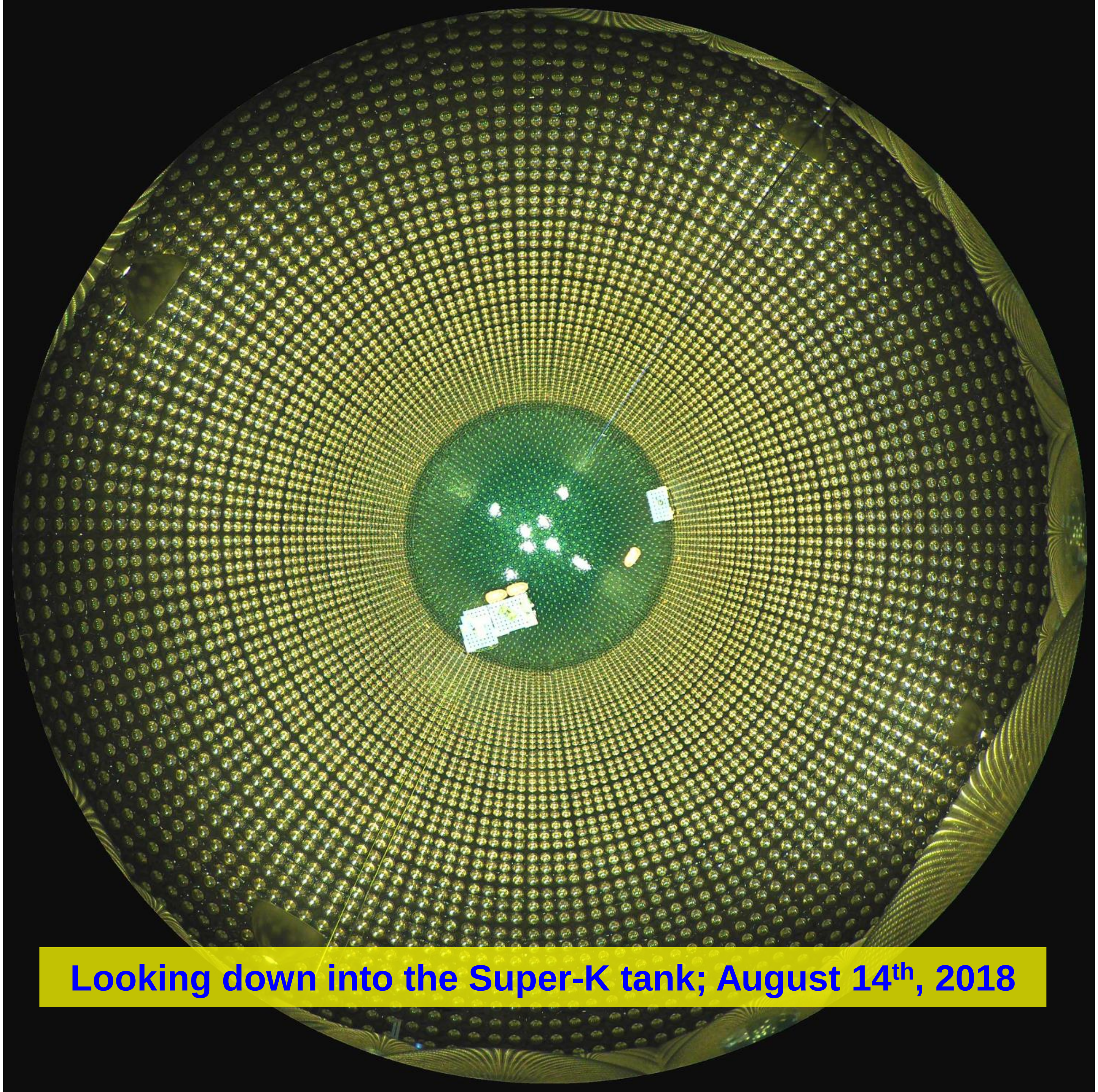


Inside Super-K; June 12th, 2018

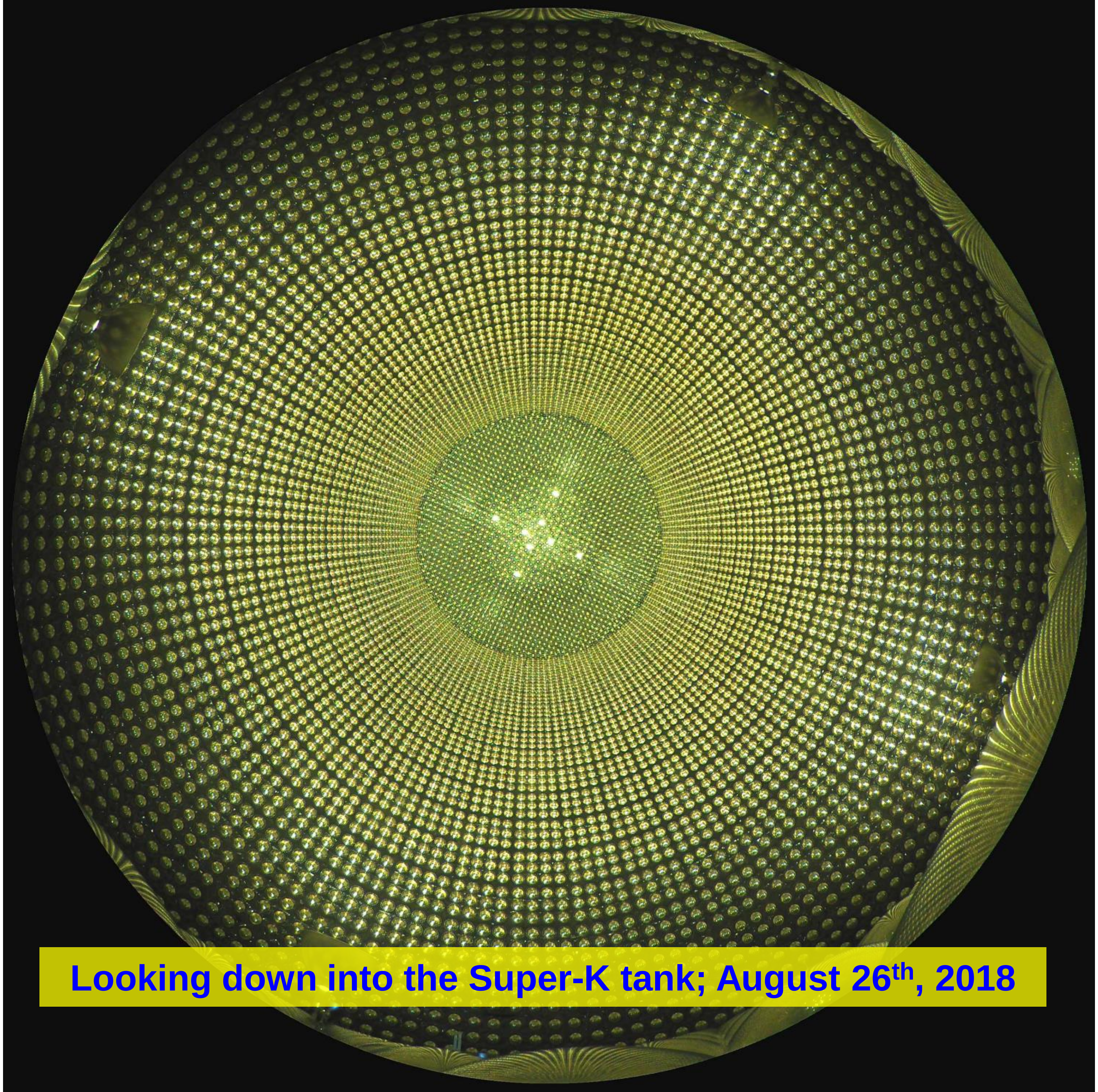

Applying special low-background sealant
Super-K veto region (side) with floating floor; June 23rd, 2018



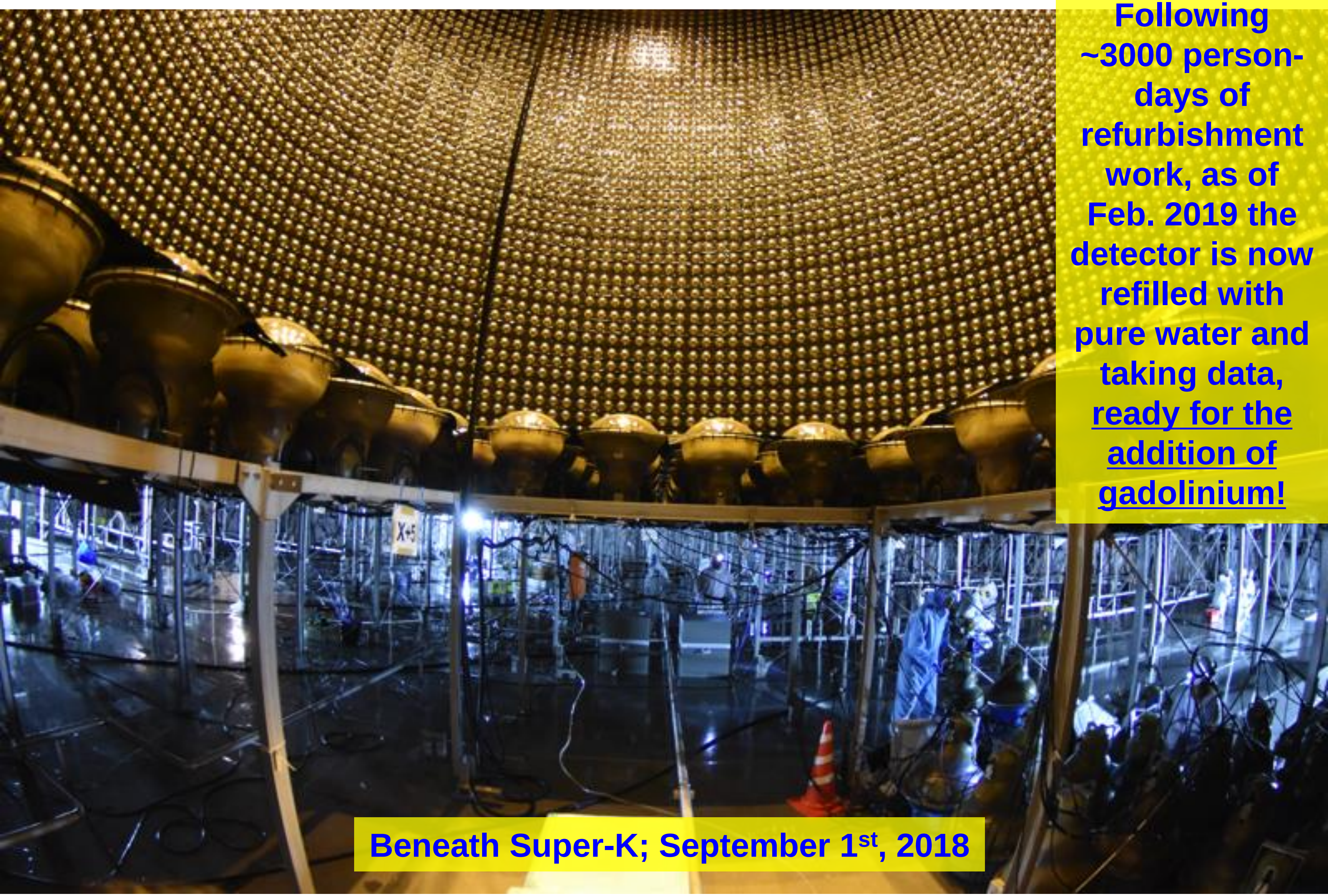
Looking down into the Super-K tank; July 12th, 2018



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



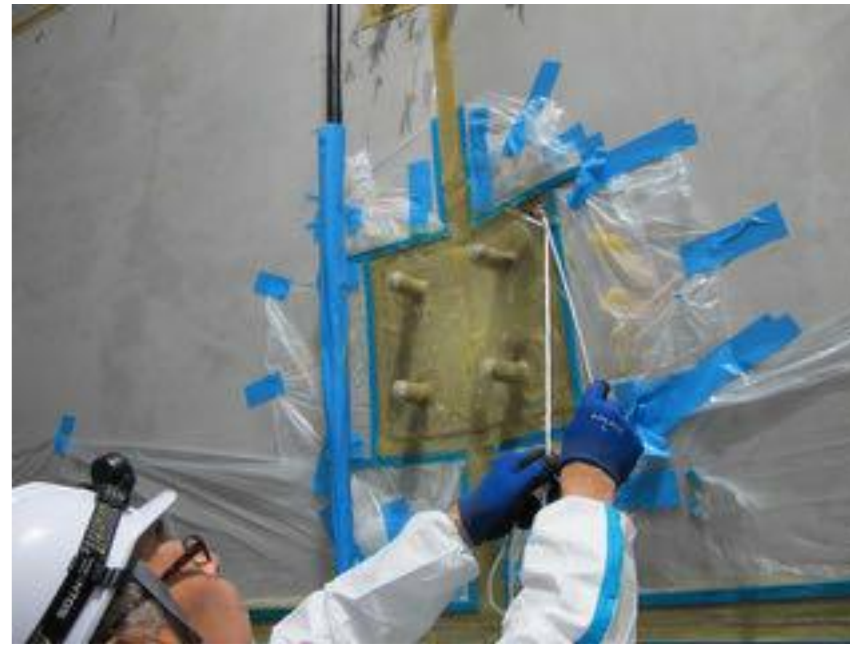
Looking down into the Super-K tank; August 26th, 2018



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!

Beneath Super-K; September 1st, 2018

“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!

The very first Super-K paper with “gadolinium” in the title has just been published - in *The Astrophysical Journal* - based on the excellent thesis work of Oxford/Kavli IPMU graduate student (now Dr.) Charles Simpson.

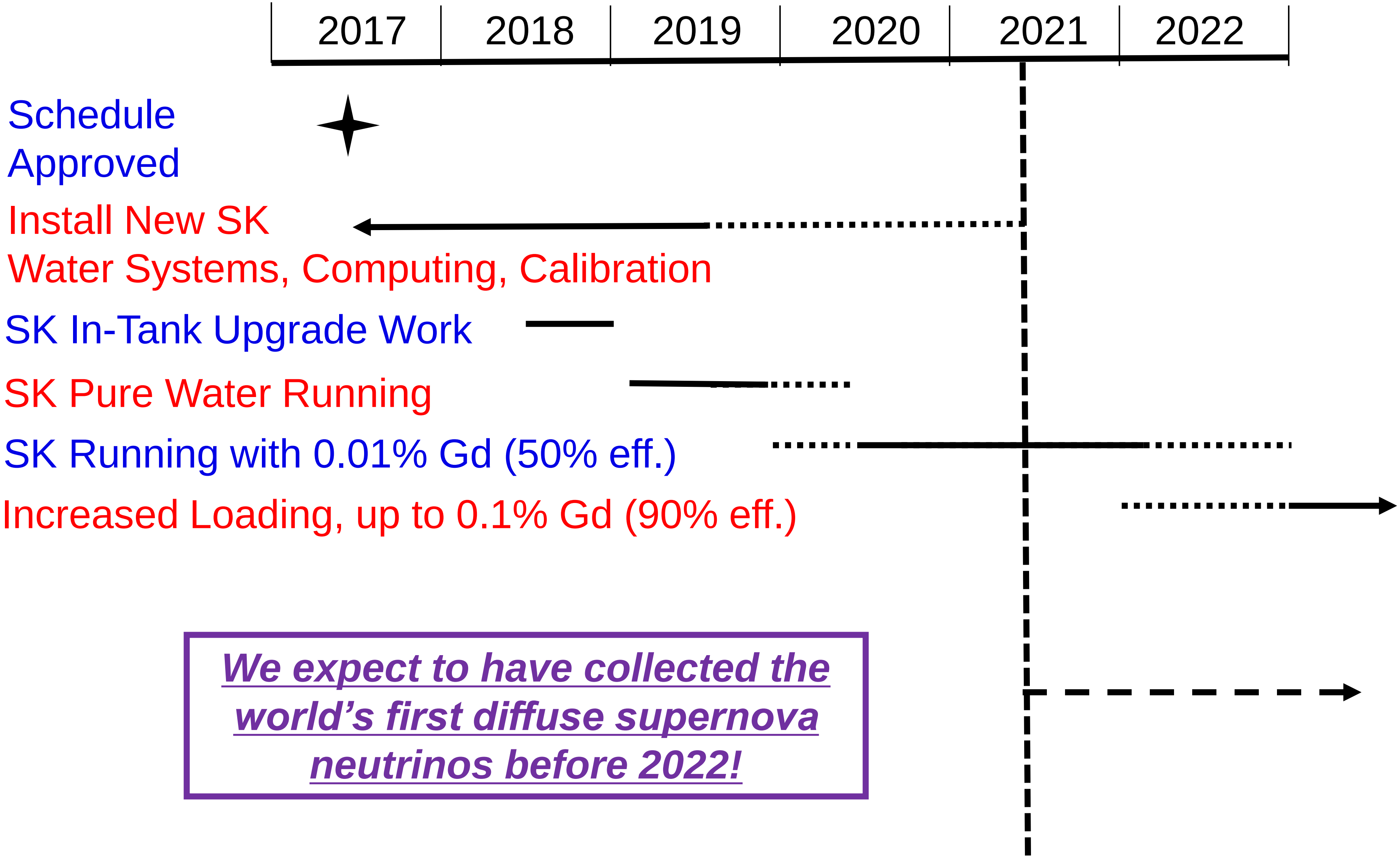
THE ASTROPHYSICAL JOURNAL, 885:133 (14pp), 2019 November 10 https://doi.org/10.3847/1538-4357/ab4883

CrossMark

Sensitivity of Super-Kamiokande with Gadolinium to Low Energy Antineutrinos from Pre-supernova Emission

C. Simpson[1,2], K. Abe[2,3], C. Bronner[3], Y. Hayato[2,3], M. Ikeda[3], H. Ito[3], K. Iyogi[3], J. Kameda[2,3], Y. Kataoka[3], Y. Kato[3], Y. Kishimoto[2,3], Ll. Marti[3], M. Miura[2,3], S. Moriyama[2,3], T. Mochizuki[3], M. Nakahata[2,3], Y. Nakajima[2,3], S. Nakayama[2,3], T. Okada[3], K. Okamoto[3], A. Orii[3], G. Pronost[3], H. Sekiya[2,3], M. Shiozawa[2,3], Y. Sonoda[3], A. Takeda[2,3], A. Takenaka[3], H. Tanaka[3], T. Yano[3], R. Akutsu[4], T. Kajita[2,4], K. Okumura[2,4], R. Wang[4], J. Xia[4], D. Bravo-Berguño[5], L. Labarga[5], P. Fernandez[5], F. d. M. Blaszczyk[6], C. Kachulis[6], E. Kearns[2,6], J. L. Raaf[6], J. L. Stone[2,6], L. Wan[6], T. Wester[6], S. Sussman[6], S. Berkman[7], J. Bian[8], N. J. Griskevich[8], W. R. Kropp[8], S. Locke[8], S. Mine[8], M. B. Smy[2,8], H. W. Sobel[2,8], V. Takhistov[8,51], P. Weatherly[8], K. S. Ganezer[9,52], J. Hill[9], J. Y. Kim[10], I. T. Lim[10], R. G. Park[10], B. Bodur[11], K. Scholberg[2,11], C. W. Walter[2,11], A. Coffani[12], O. Drapier[12], M. Gonin[12], J. Imber[12], Th. A. Mueller[12], P. Paganini[12], T. Ishizuka[13], T. Nakamura[14], J. S. Jang[15], K. Choi[16], J. G. Learned[16], S. Matsuno[16], R. P. Litchfield[17], A. A. Sztuc[17], Y. Uchida[17], M. O. Wascko[17], V. Berardi[18], N. F. Calabria[18], M. G. Catanesi[18], R. A. Intonti[18], E. Radicioni[18], G. De Rosa[19], G. Collazuol[20], F. Iacob[20], L. Ludovici[21], Y. Nishimura[22], S. Cao[23], M. Friend[23], T. Hasegawa[23], T. Ishida[23], T. Kobayashi[23], T. Nakadaira[23], K. Nakamura[2,23], Y. Oyama[23], K. Sakashita[23], T. Sekiguchi[23], T. Tsukamoto[23], KE. Abe[24], M. Hasegawa[24], Y. Isobe[24], H. Miyabe[24], Y. Nakano[24], T. Shiozawa[24], T. Sugimoto[24], A. T. Suzuki[24], Y. Takeuchi[2,24], A. Ali[25], Y. Ashida[25], T. Hayashino[25], S. Hirota[25], M. Jiang[25], T. Kikawa[25], M. Mori[25], KE. Nakamura[25], T. Nakaya[2,25], R. A. Wendell[2,25], L. H. V. Anthony[26], N. McCauley[26], A. Pritchard[26], K. M. Tsui[26], Y. Fukuda[27], Y. Itow[28,29], M. Murrase[28], T. Niwa[28], M. Taani[28,53], M. Tsukada[28], P. Mijakowski[30], K. Frankiewicz[30], C. K. Jung[31], X. Li[31], J. L. Palomino[31], G. Santucci[31], C. Vilela[31], M. J. Wilking[31], C. Yanagisawa[31,54], D. Fukuda[32], M. Harada[32], K. Hagiwara[32], T. Horai[32], H. Ishino[32], S. Ito[32], Y. Koshio[2,32], M. Sakuda[32], Y. Takahira[32], C. Xu[32], Y. Kuno[33], L. Cook[1,2], D. Wark[1,34], F. Di Lodovico[35], S. Molina Sedgwick[35,55], B. Richards[35,55], S. Zsoldos[35,55], S. B. Kim[36], R. Tacik[37,38], M. Thiesse[39], L. Thompson[39], H. Okazawa[40], Y. Choi[41], K. Nishijima[42], M. Koshiba[43], M. Yokoyama[2,44], A. Goldsack[1,2], K. Martens[2], M. Murdoch[2], B. Quilain[2], Y. Suzuki[2], M. R. Vagins[2,8], M. Kuze[45], Y. Okajima[45], M. Tanaka[45], T. Yoshida[45], M. Ishitsuka[46], R. Matsumoto[46], K. Ohta[46], J. F. Martin[47], C. M. Nantais[47], H. A. Tanaka[47], T. Towstego[47], M. Hartz[38], A. Konaka[38], P. de Perio[38], S. Chen[48], B. Jamieson[49], J. Walker[49], A. Minamino[50], K. Okamoto[50], and G. Pintaudi[50]
The Super-Kamiokande Collaboration

Expected timeline for Gadolinium in Super-K



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

In conclusion, 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.

After nearly two decades of R&D, the first Gd is expected to go into Super-K in April 2020!