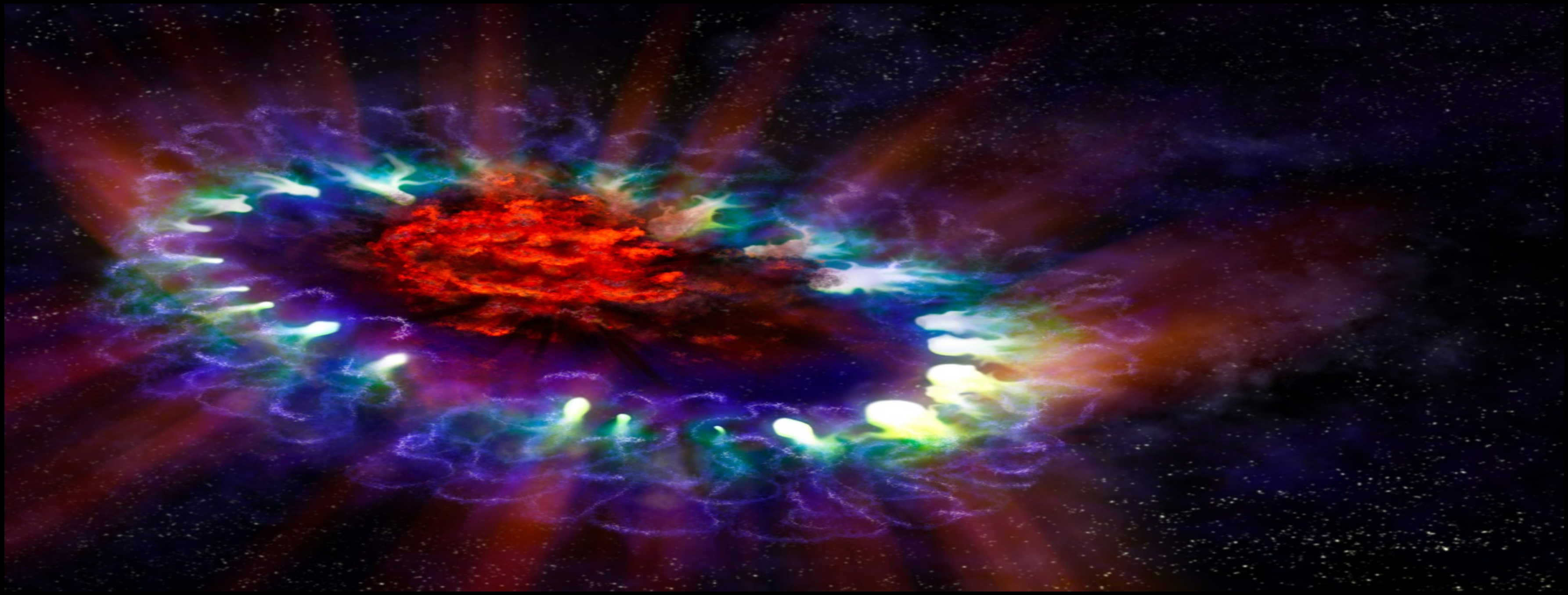
Observing Supernova Neutrinos… Within the Next Three Years!



Mark Vagins

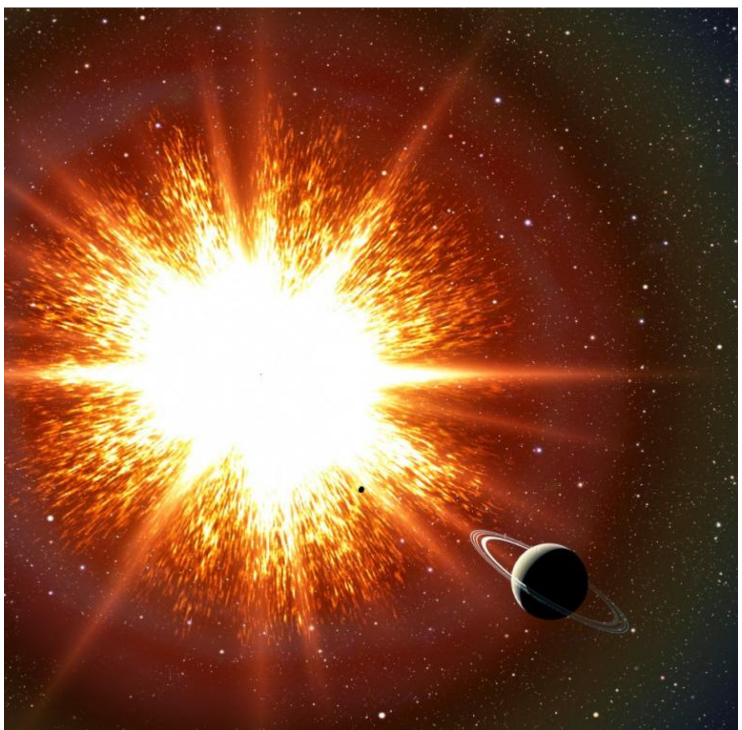
Kavli IPMU, UTokyo

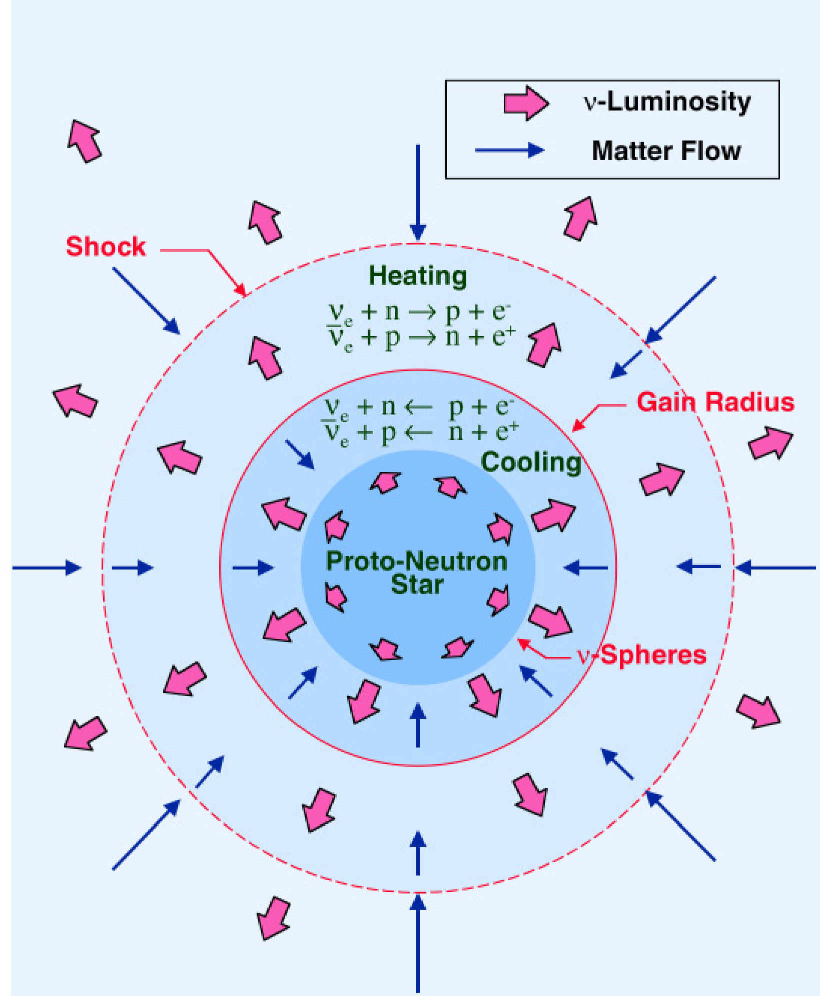
Kavli IPMU's 10th Anniversary Symposium

Kashiwanoha October 17, 2017

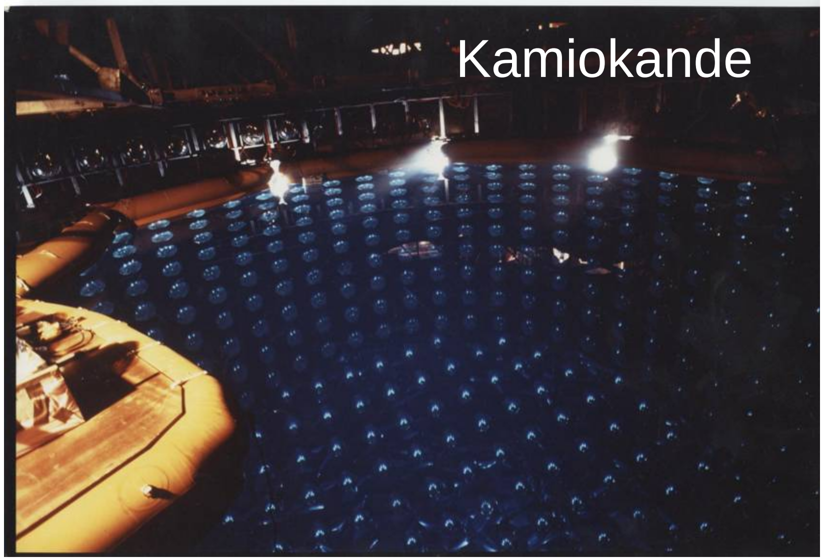
A core-collapse supernova is a nearly perfect "neutrino bomb".

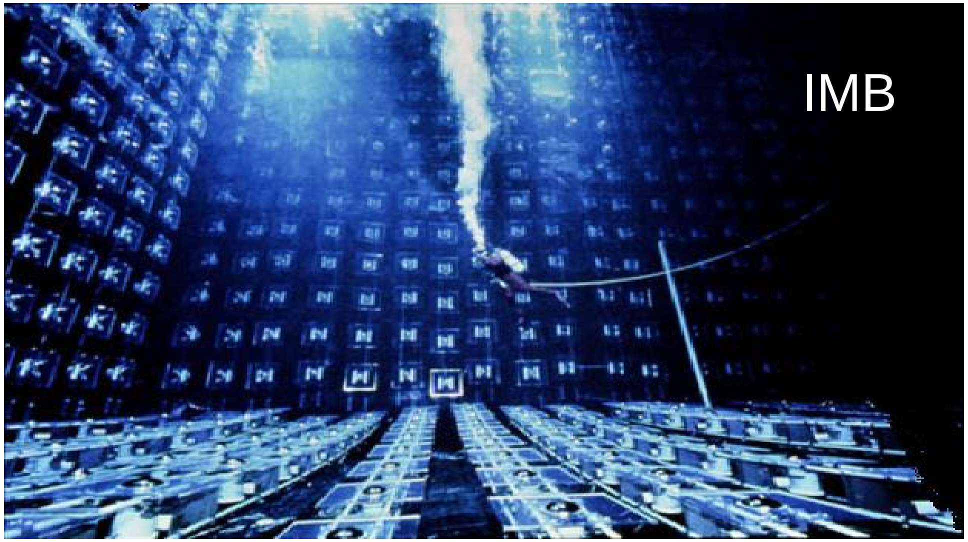
Within ten seconds of collapse it releases >98% of its huge energy (equal to 一兆 ,or 10^{12}, hydrogen bombs exploding per second since the beginning of the universe!) as neutrinos.

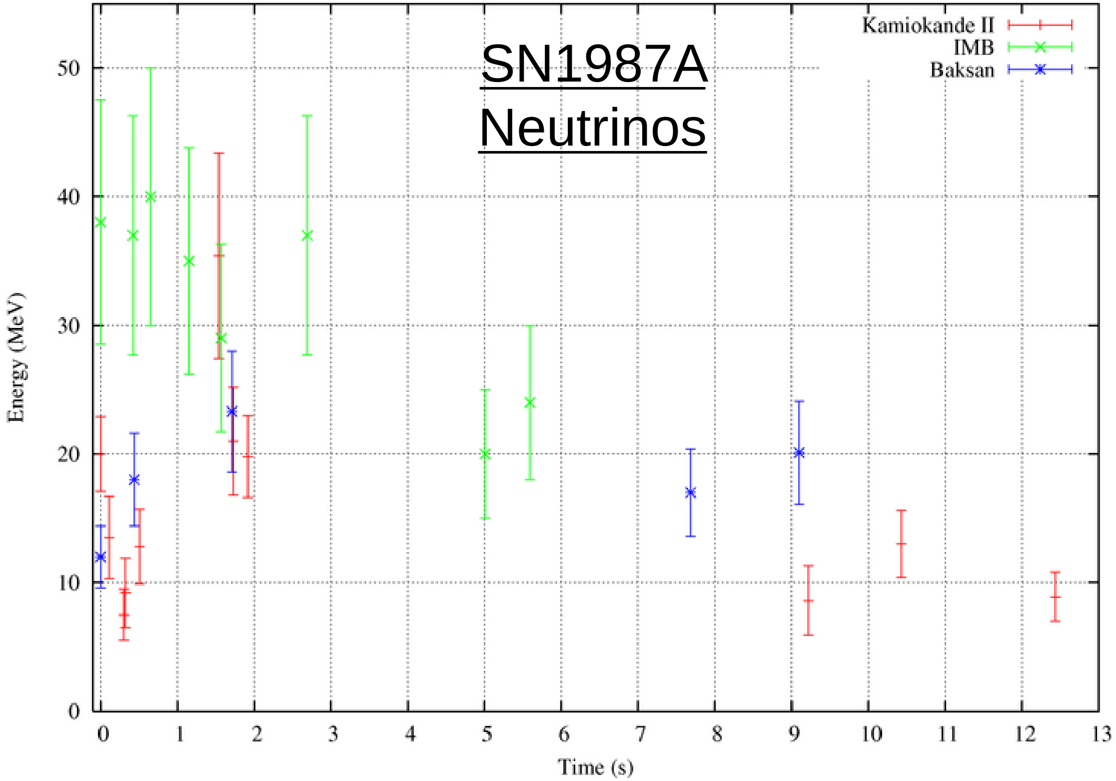


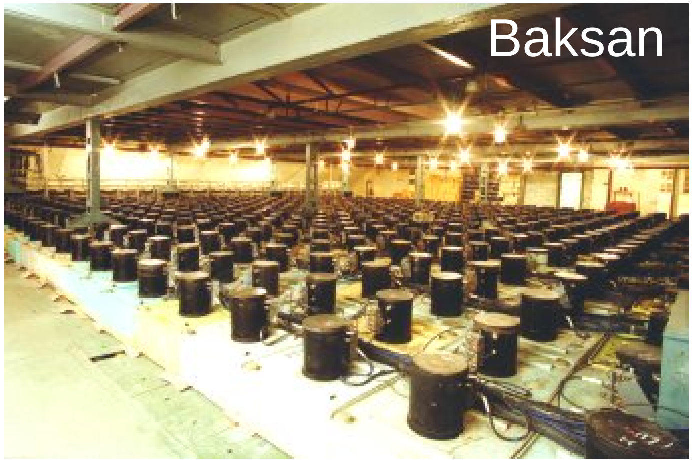


Neutrinos, along with gravitational waves, provide the only possible windows into core collapses' inner dynamics.



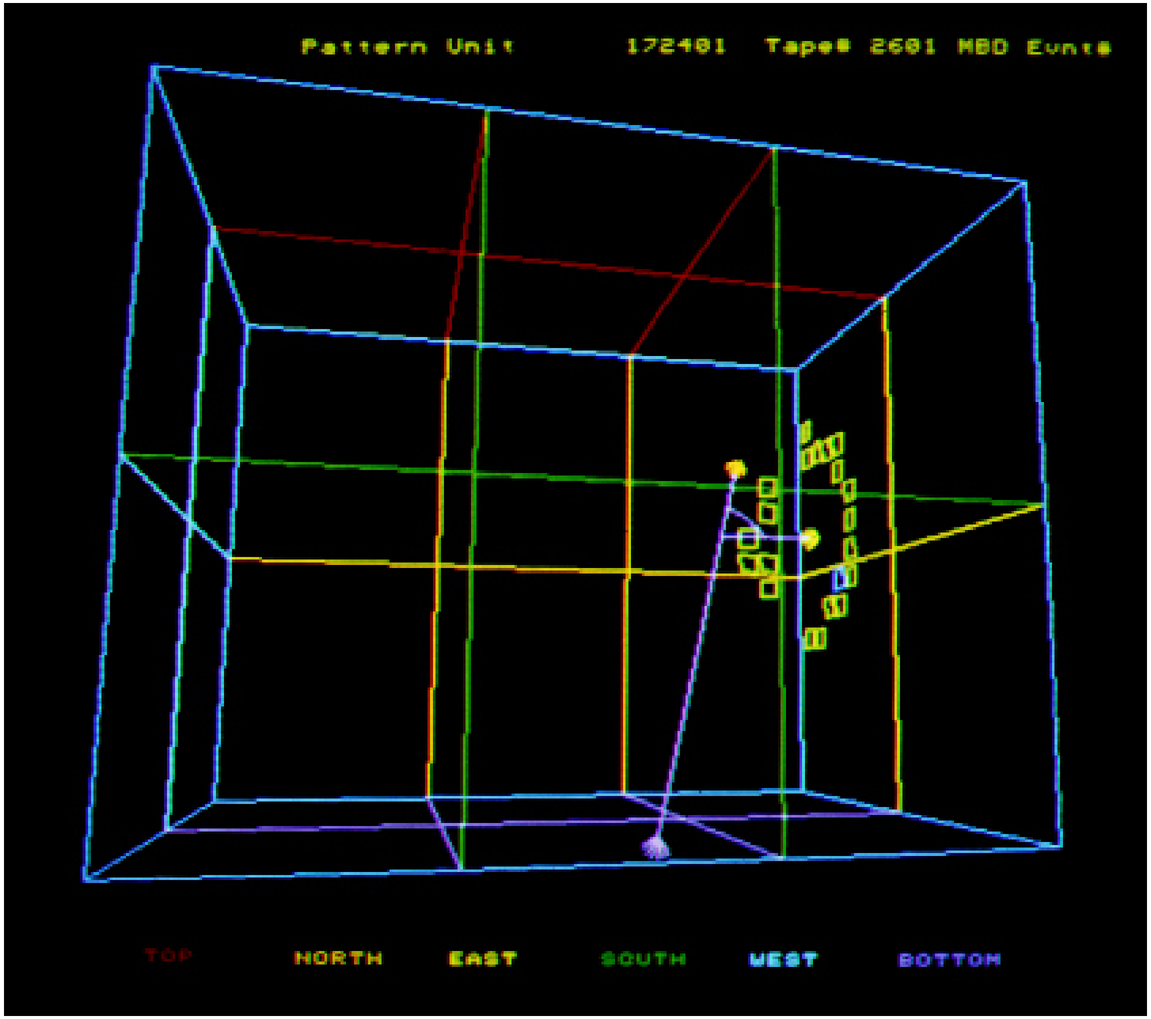






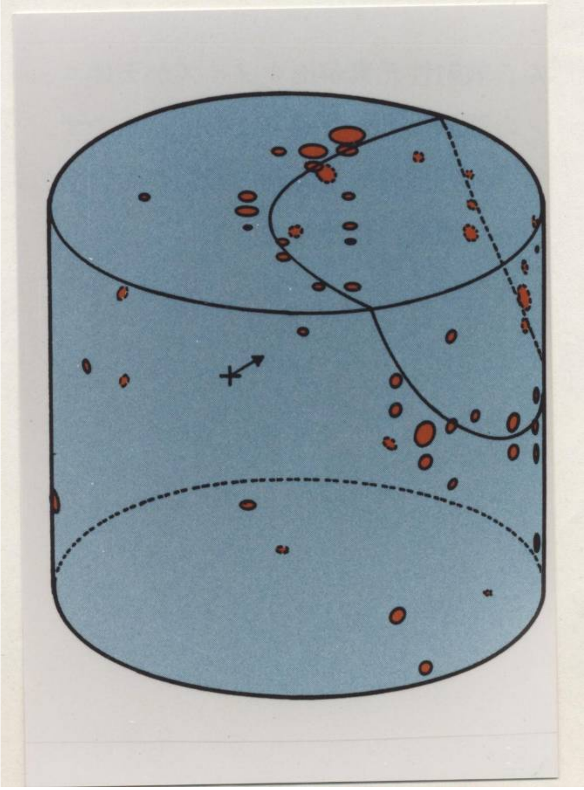
One paper every ten days…

for the last 30 years!



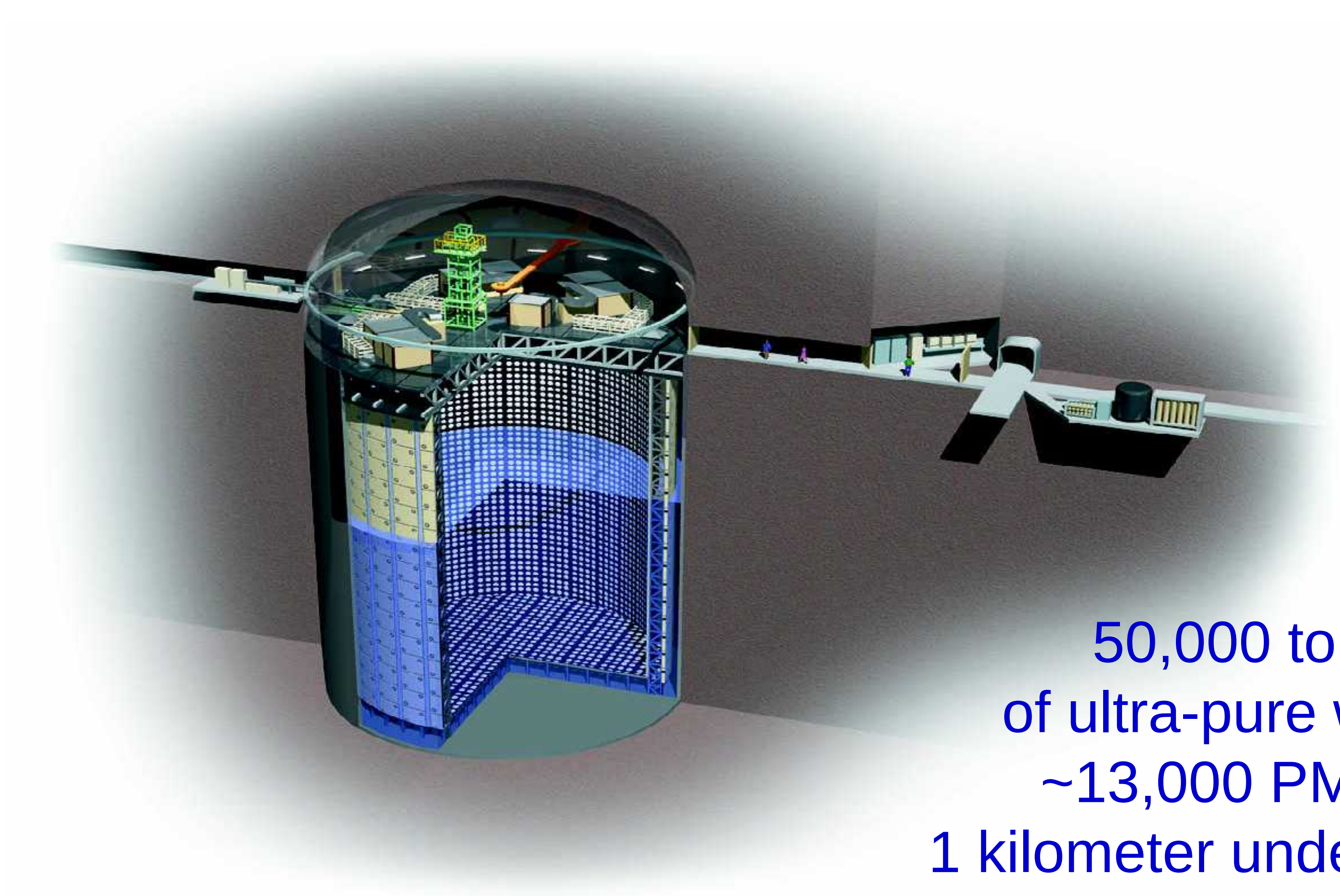
IMB
(in USA)

Kamiokande
(in Japan)



Event Displays of Actual Neutrinos from SN1987A

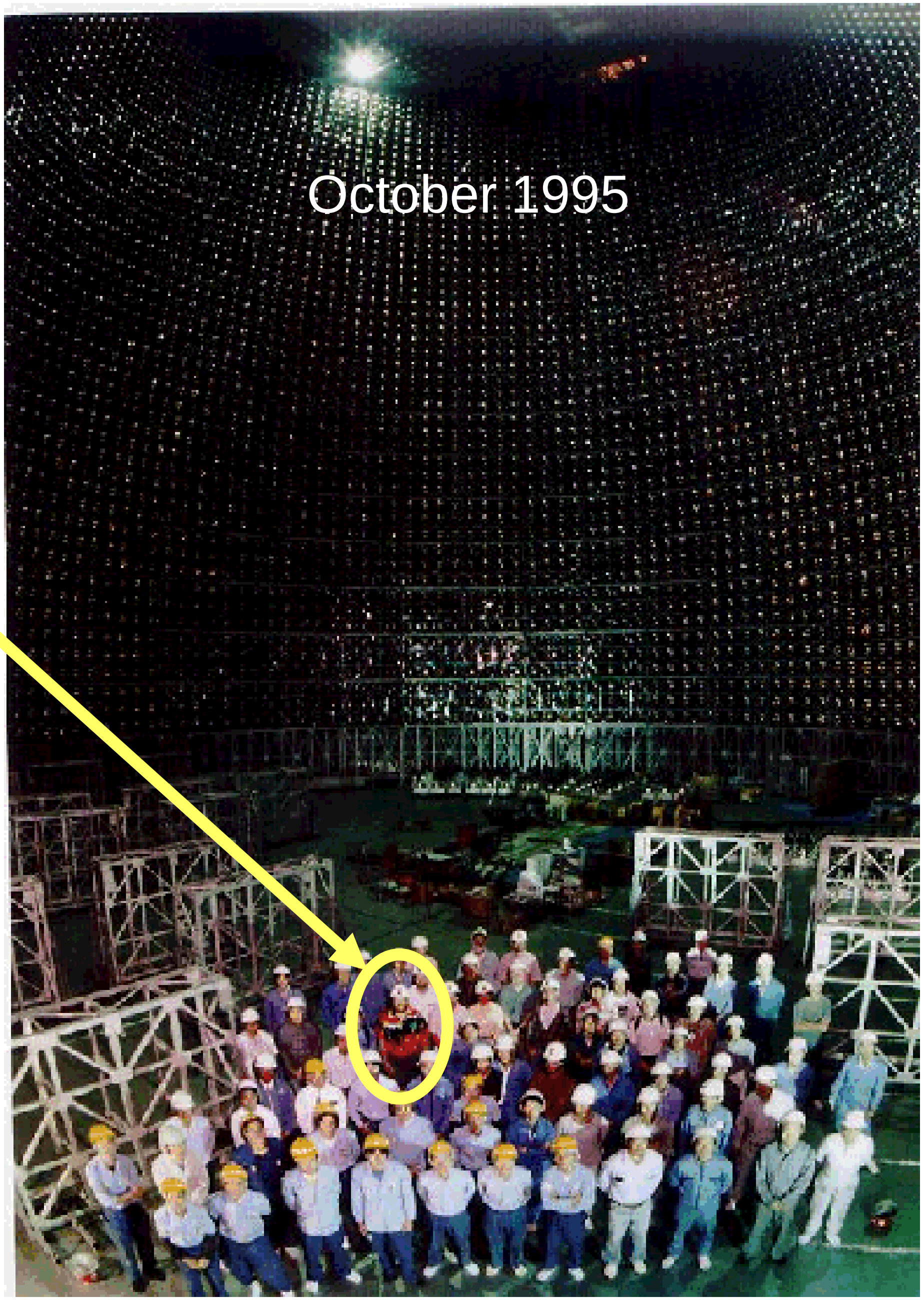
Our (ICRR/IPMU) beloved Super-Kamiokande is one of the best and most successful neutrino and proton decay detectors in the world.



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

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

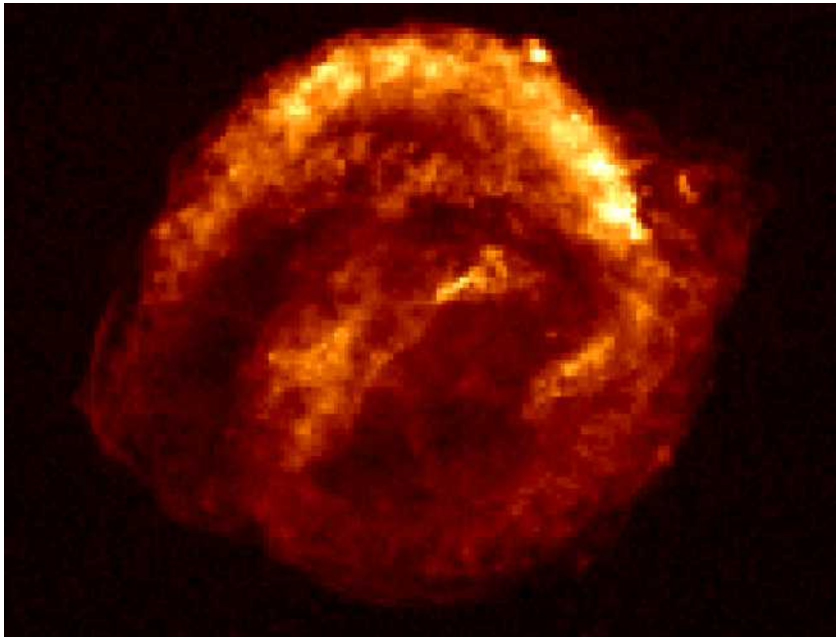
January 1996

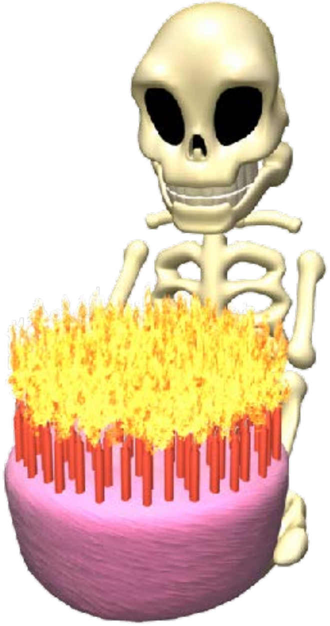


Super-Kamiokande is ready (~99% SN uptime) and waiting to detect supernova neutrinos from an explosion anywhere in our galaxy.

→ **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 three decades since SN1987A, and today is the 413th anniversary of Kepler's first observation of the last supernova to be seen within our own galaxy.

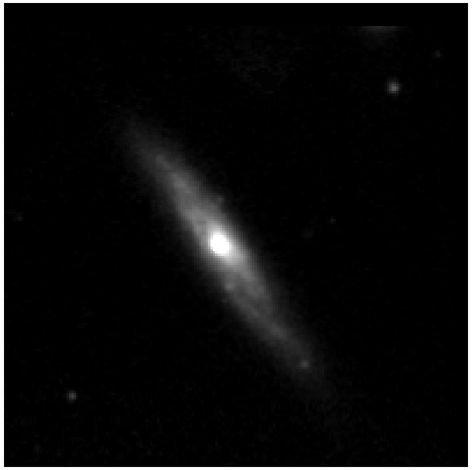
Yes, it's been a long, cold winter for SN neutrinos…
but there is hope!

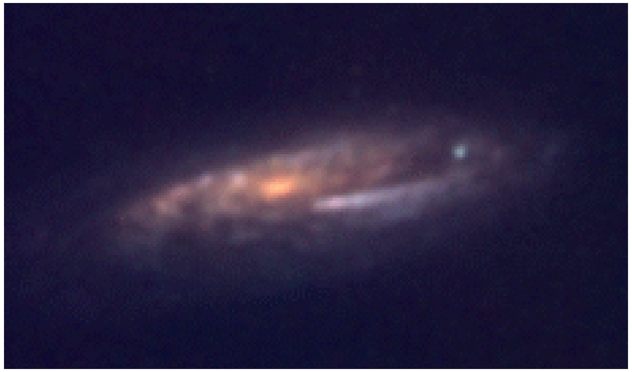
So, how can we be certain to see more supernova neutrinos without having to wait too long?

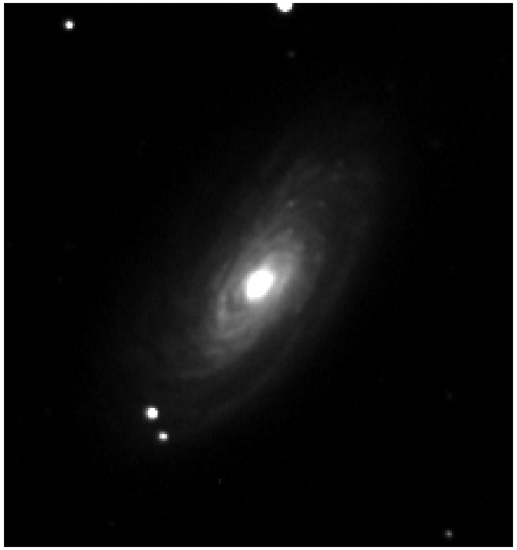
This is not the typical view of a supernova.

Which, of course…
is a good thing.

A supernova's shock wave will completely sterilize everything within ~100 light years.



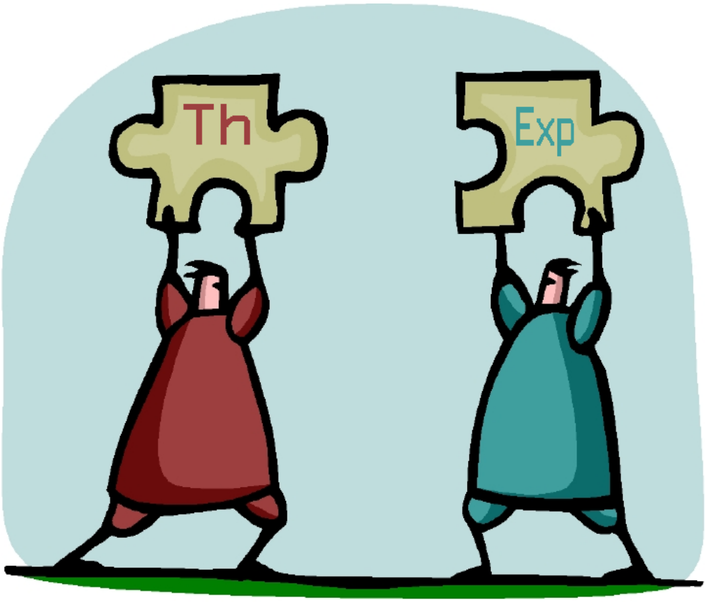




Here's how most SN look to us (video is looped).

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].



Very much in the spirit of Kavli IPMU, theorist John Beacom and I wrote the original GADZOOKS!

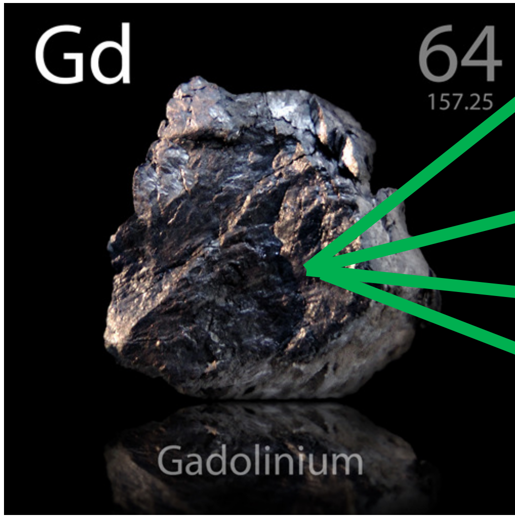
(Gadolinium Antineutrino Detector Zealously Outperforming Old Kamiokande, Super!) paper.

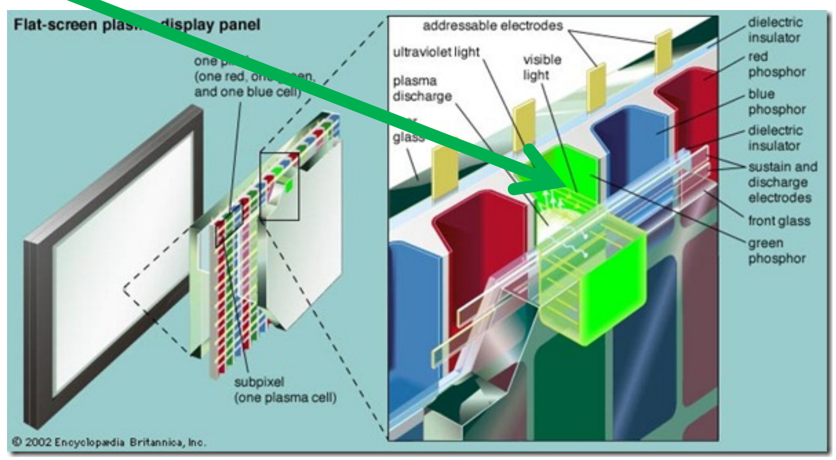
It proposed loading big WC detectors, specifically Super-K, with water soluble gadolinium, and evaluated the physics potential and backgrounds of a giant antineutrino detector.

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

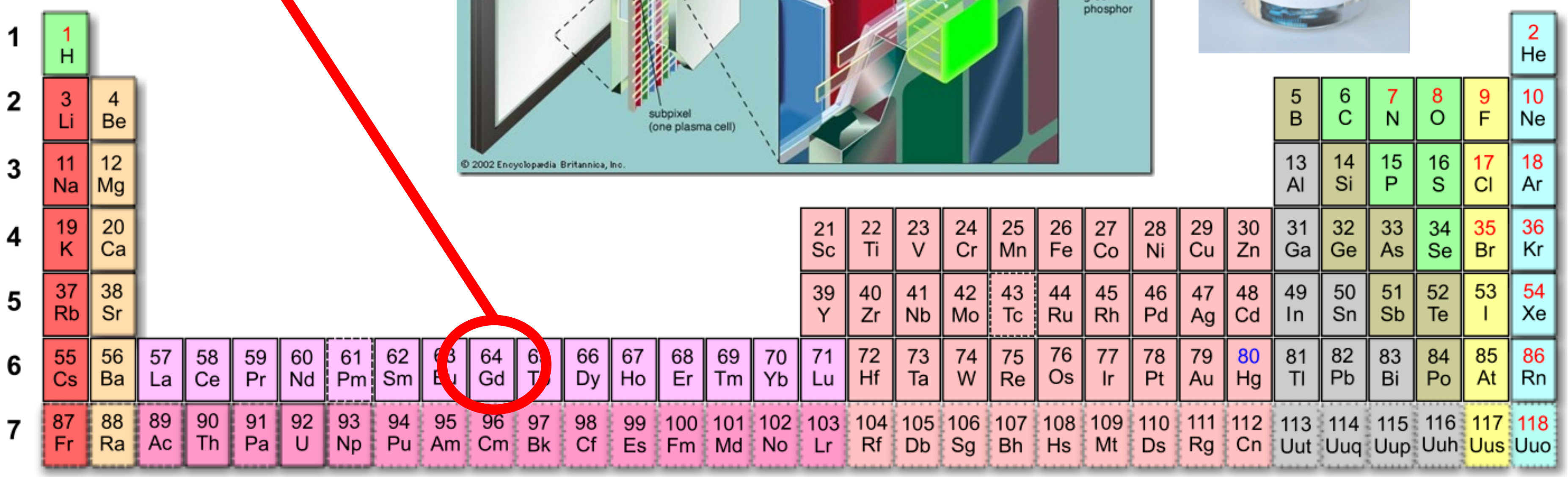
(308 citations → one every 15 days for thirteen years)

Gadolinium

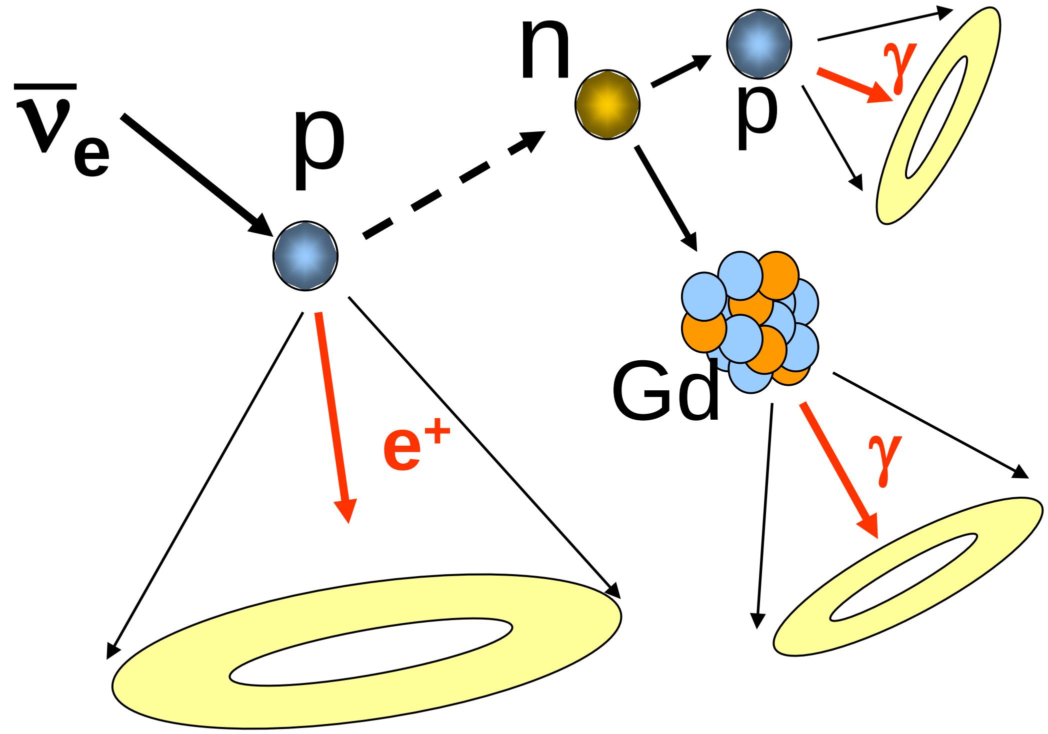

Gd
64
157.25
Gadolinium


addressable electrodes
ultraviolet light
visible light
plasma discharge
dielectric insulator
red phosphor
blue phosphor
dielectric insulator
sustain and discharge electrodes
front glass
green phosphor
subpixel (one plasma cell)
© 2002 Encyclopædia Britannica, Inc.


0.5M Injection
Lot No:
100909
Exp. Date:
09/11


1 H 2 He
3 Li 4 Be 5 B 6 C 7 N 8 O 9 F 10 Ne
11 Na 12 Mg 13 Al 14 Si 15 P 16 S 17 Cl 18 Ar
19 K 20 Ca 21 Sc 22 Ti 23 V 24 Cr 25 Mn 26 Fe 27 Co 28 Ni 29 Cu 30 Zn 31 Ga 32 Ge 33 As 34 Se 35 Br 36 Kr
37 Rb 38 Sr 39 Y 40 Zr 41 Nb 42 Mo 43 Tc 44 Ru 45 Rh 46 Pd 47 Ag 48 Cd 49 In 50 Sn 51 Sb 52 Te 53 I 54 Xe
55 Cs 56 Ba 57 La 58 Ce 59 Pr 60 Nd 61 Pm 62 Sm 64 Gd 66 Dy 67 Ho 68 Er 69 Tm 70 Yb 71 Lu 72 Hf 73 Ta 74 W 75 Re 76 Os 77 Ir 78 Pt 79 Au 80 Hg 81 Tl 82 Pb 83 Bi 84 Po 85 At 86 Rn
87 Fr 88 Ra 89 Ac 90 Th 91 Pa 92 U 93 Np 94 Pu 95 Am 96 Cm 97 Bk 98 Cf 99 Es 100 Fm 101 Md 102 No 103 Lr 104 Rf 105 Db 106 Sg 107 Bh 108 Hs 109 Mt 110 Ds 111 Rg 112 Cn 113 Uut 114 Uuq 115 Uup 116 Uuh 117 Uus 118 Uuo

Inverse Beta Decay with 0.1% Gadolinium



Possibility 1: 10% or less

$n+p \rightarrow d + \gamma$

2.2 MeV γ-ray

Possibility 2: 90% or more

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

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

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

Prompt and delayed event vertices are within ~50 cm: "Gd Heartbeat"

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].

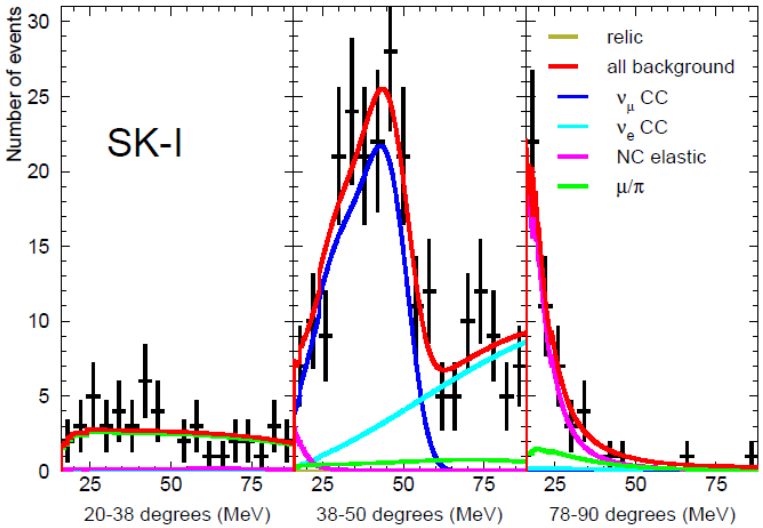
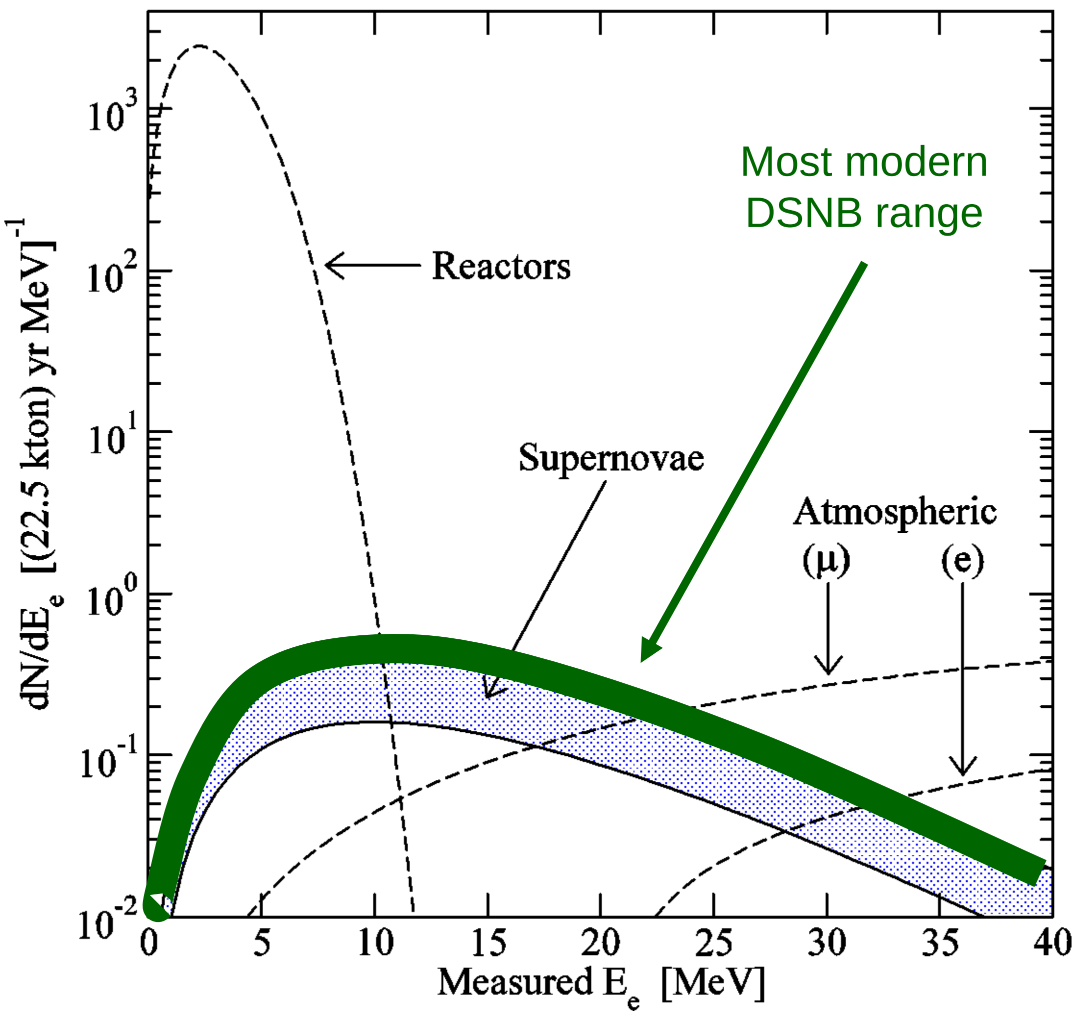


FIG. 14. SK-I LMA best fit result. The relic best fit is negative, so a relic fit of 0 is shown.

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>

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):



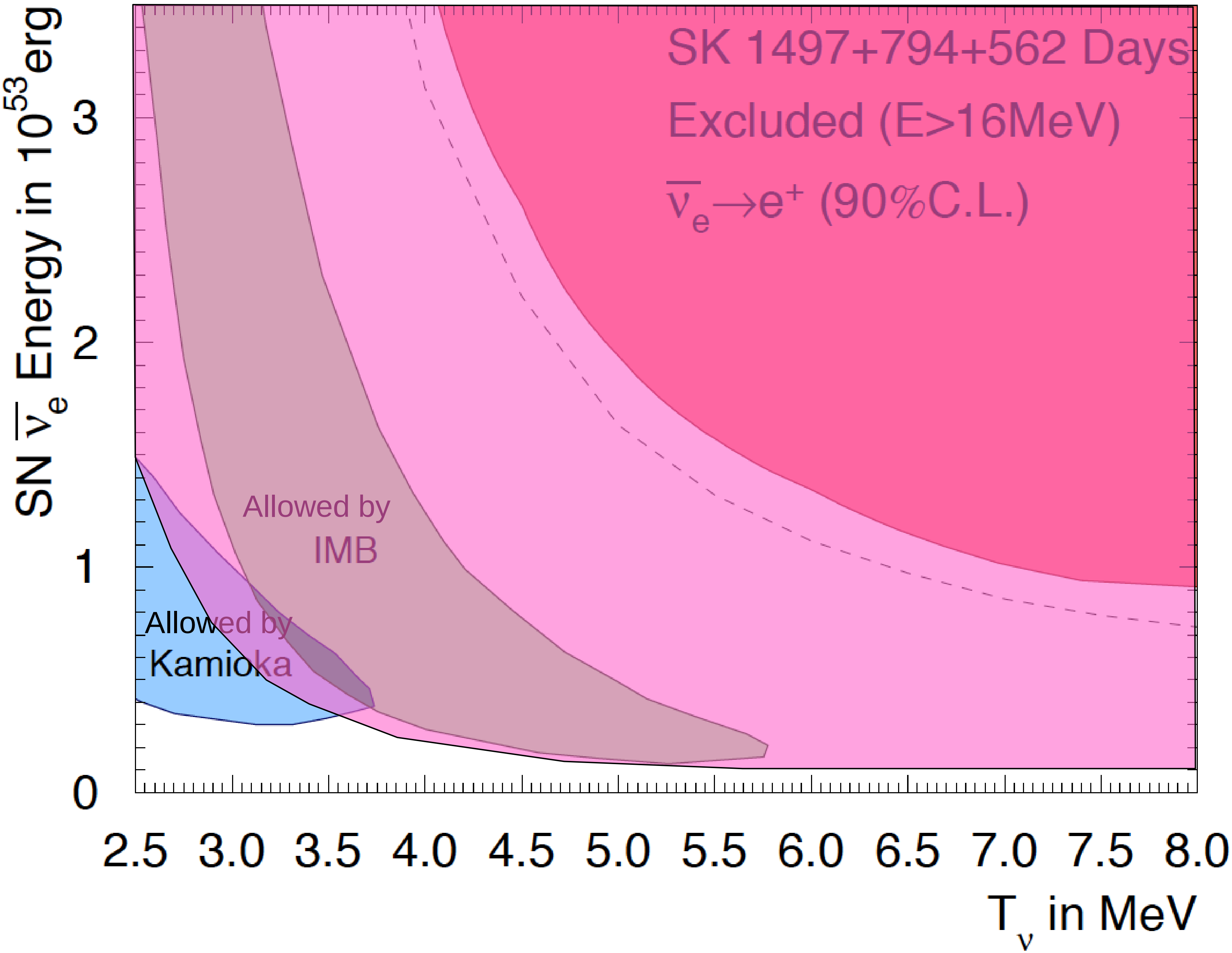
$\bar{\nu}_e + p \rightarrow e^+ + n$

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

λ=~4cm, τ=~30μs

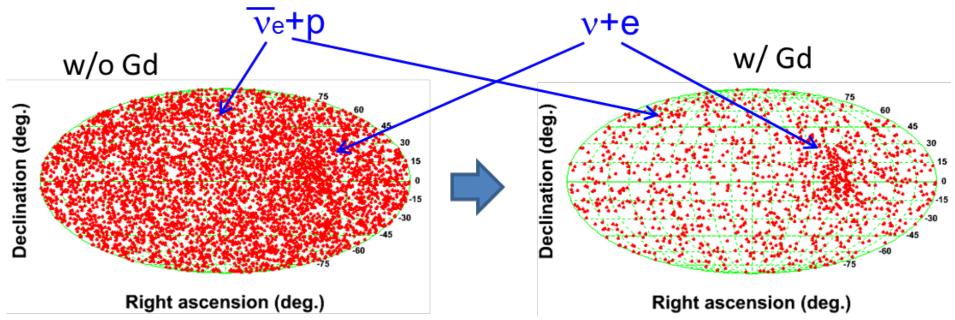
→ A few clean events/yr in Super-K with Gd

DSNB Sensitivity Region After Six Years With Gd In SK



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

- Determines the exact $\bar{\nu}_e$ flux, energy spectrum, and time profile.
- 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.
  (please see the poster by Charles Simpson)

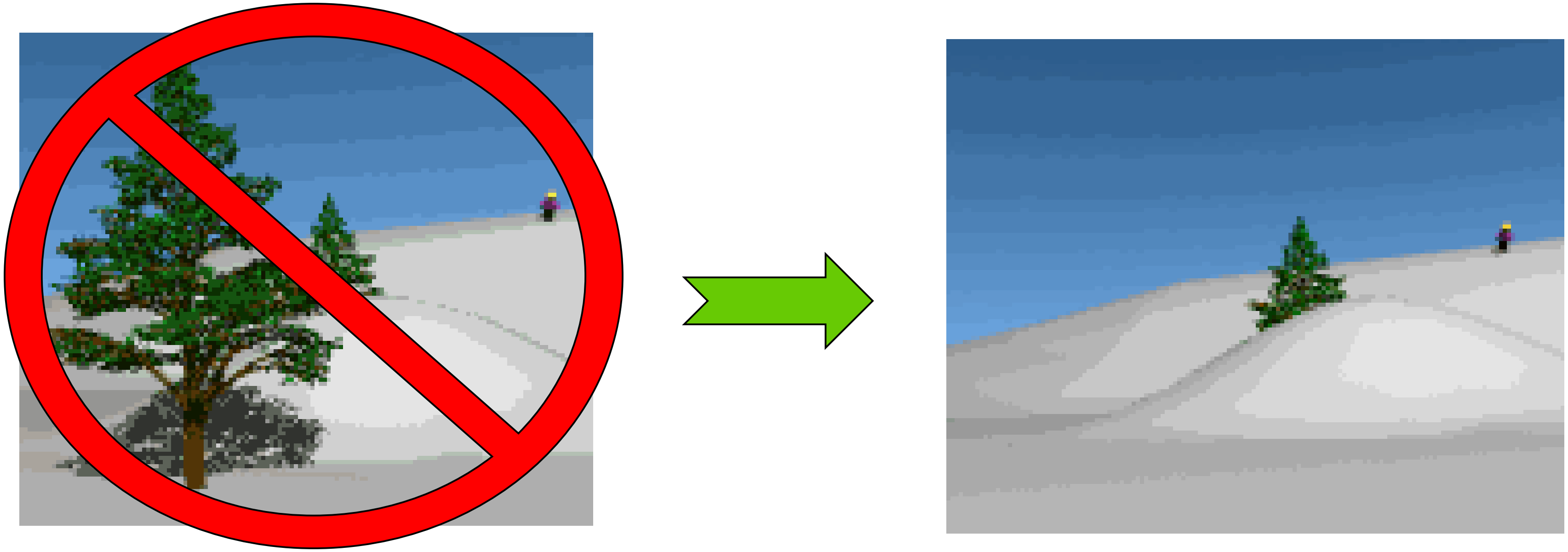
Neutron tagging from Gd loading will also improve SK’s existing proton decay searches, atmospheric, solar, and long-baseline neutrino analyses. It will make reactor neutrino studies possible in SK, as well.

Now, John 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 were 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?

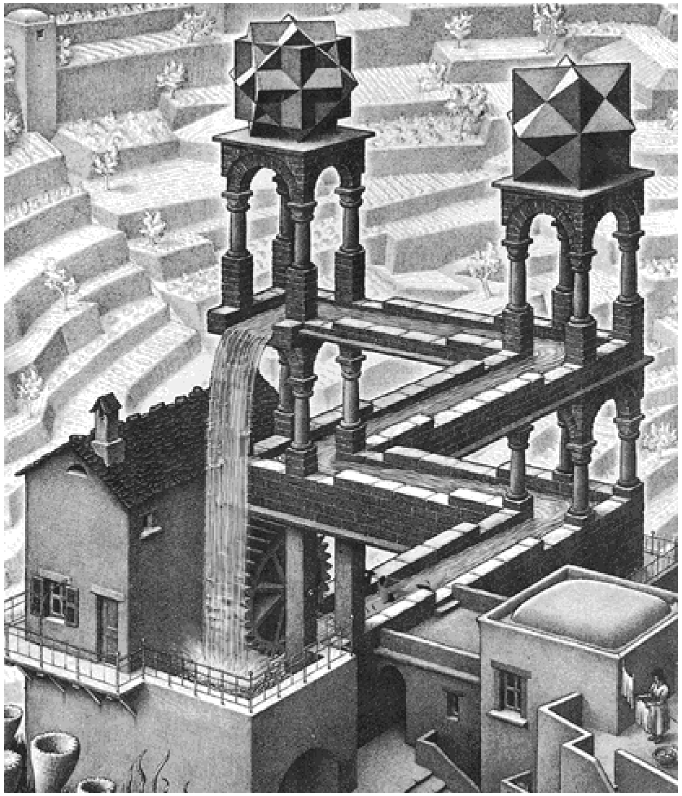
As a matter of fact, I very rapidly made two discoveries regarding $GdCl_3$ while carrying a sample from Los Angeles to Tokyo:

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

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

The experimental selective filtration setup at UC Irvine continually evolved until we knew enough for a large-scale test: EGADS.

Meanwhile,
in 2008 I underwent a
significant transformation…

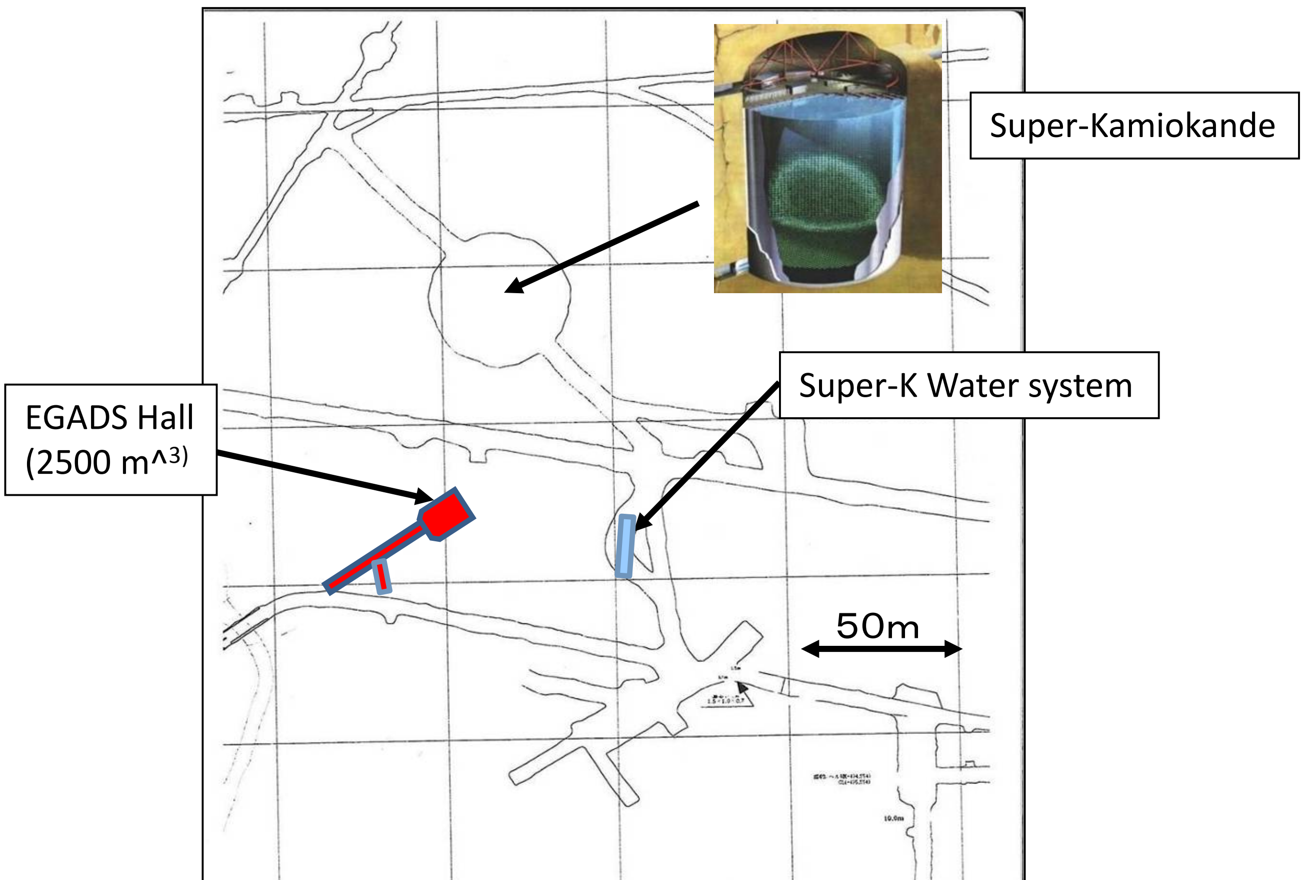
I joined UTokyo's
newly-formed IPMU
as their first full-time
gaijin professor, though I
still retain a "without salary"
position at UCI and have
continued Gd studies there.

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

IPMU INSTITUTE FOR THE PHYSICS AND MATHEMATICS OF THE UNIVERSE

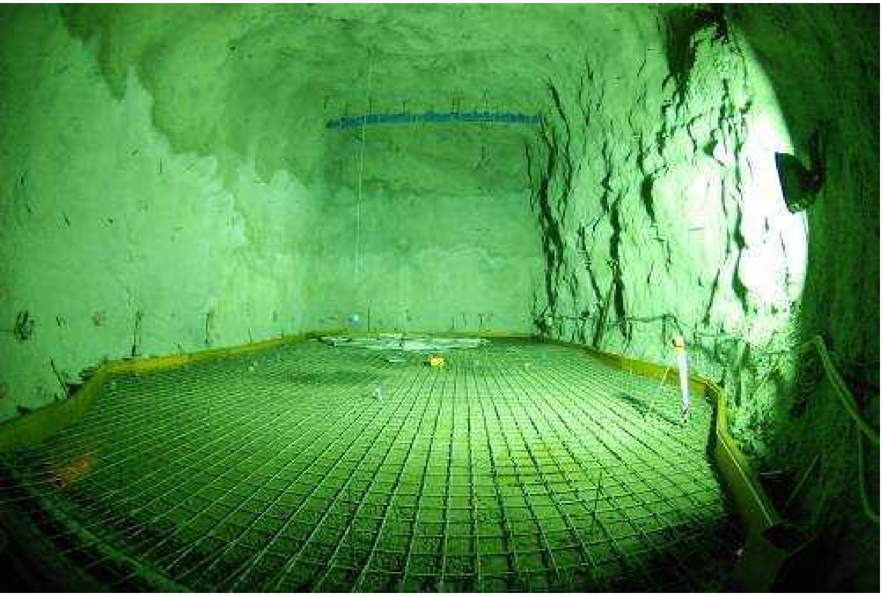
To confirm that Gd loading will work in Super-K, a dedicated Gd test facility was built in the Kamioka mine, complete with its own water filtration system, 50-cm PMT's, and DAQ electronics.

Kavli IPMU/ICRR's 200-ton scale R&D project is called EGADS: Evaluating Gadolinium's Action on Detector Systems



Hall E and EGADS

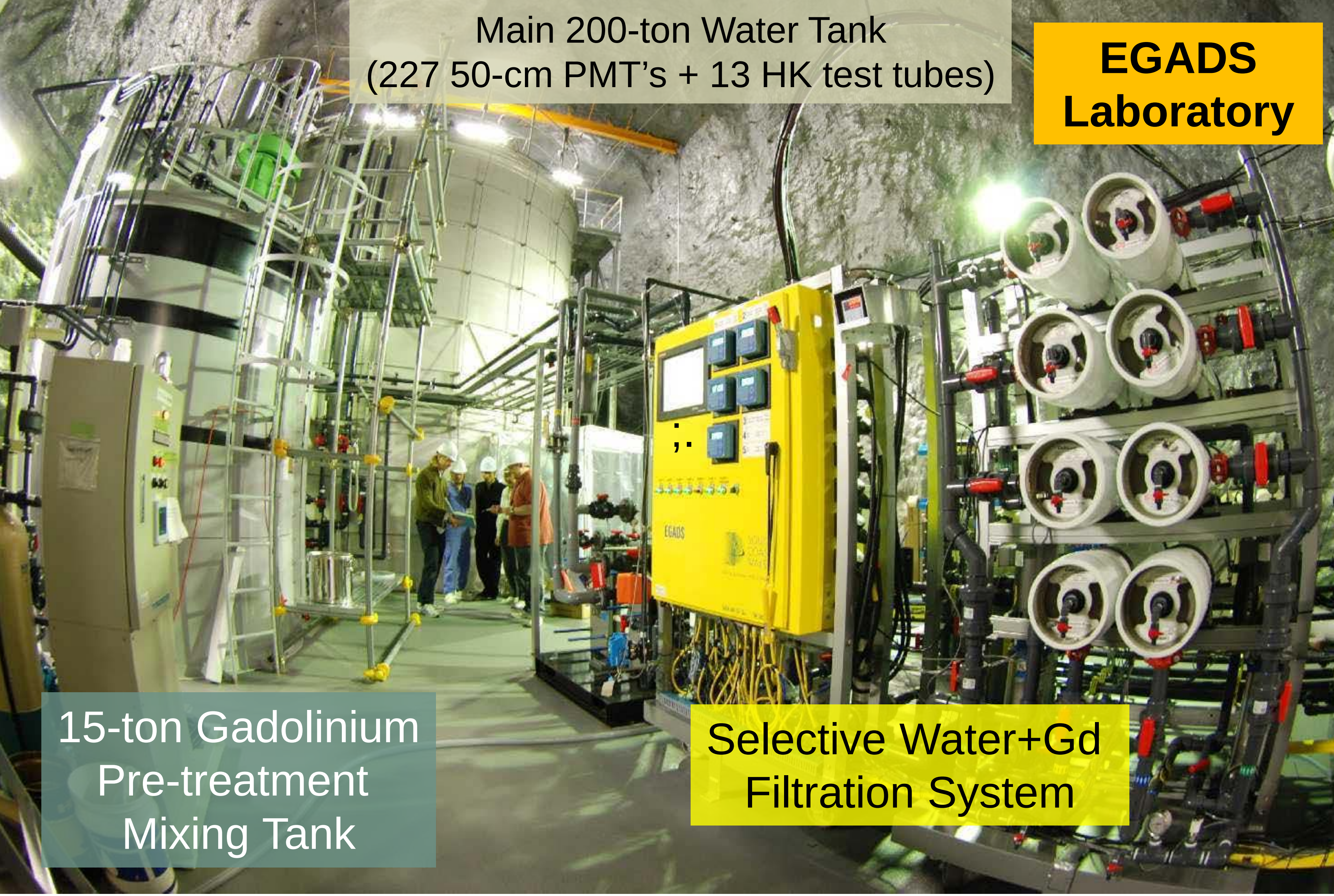
12/2009



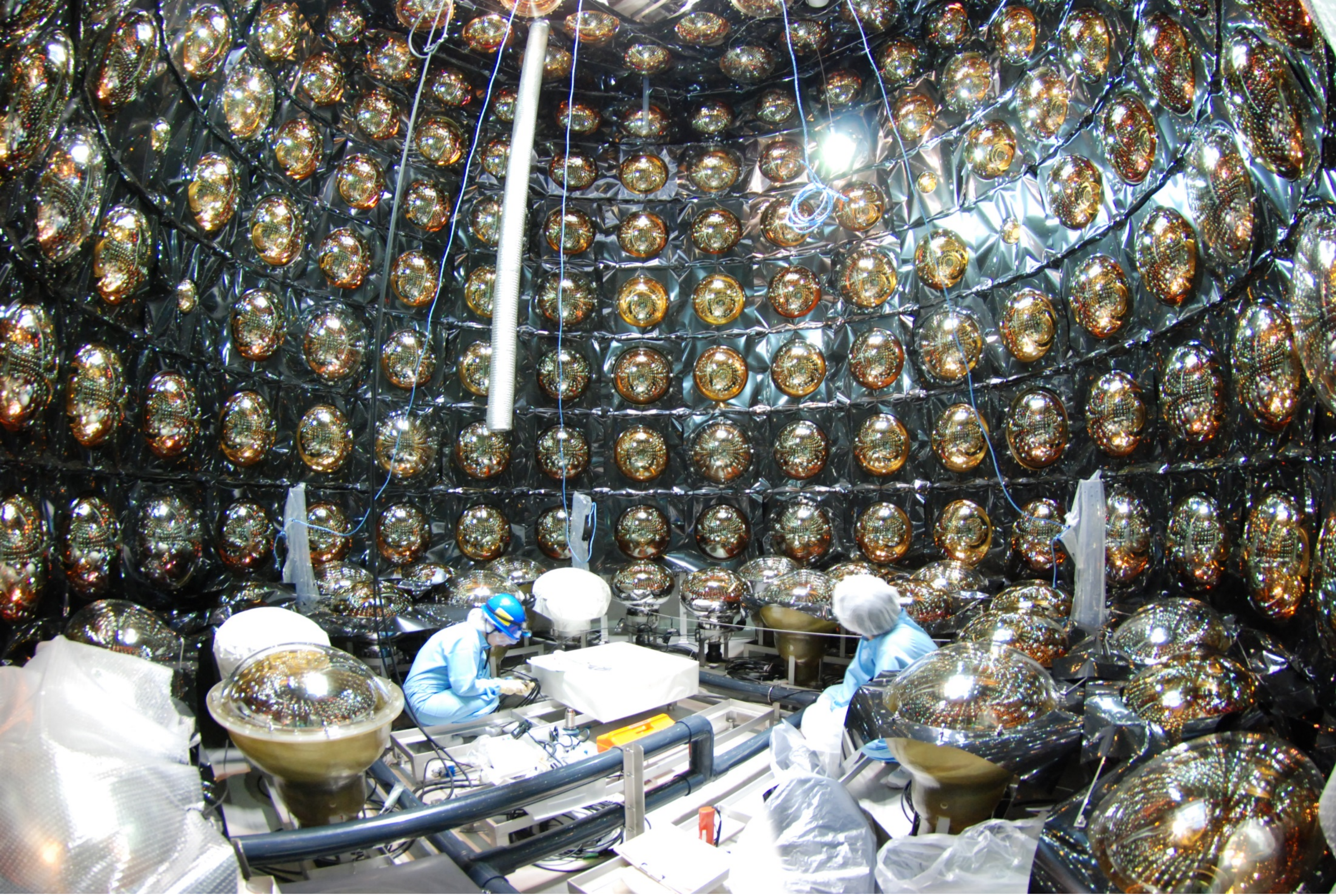
2/2010

6/2010

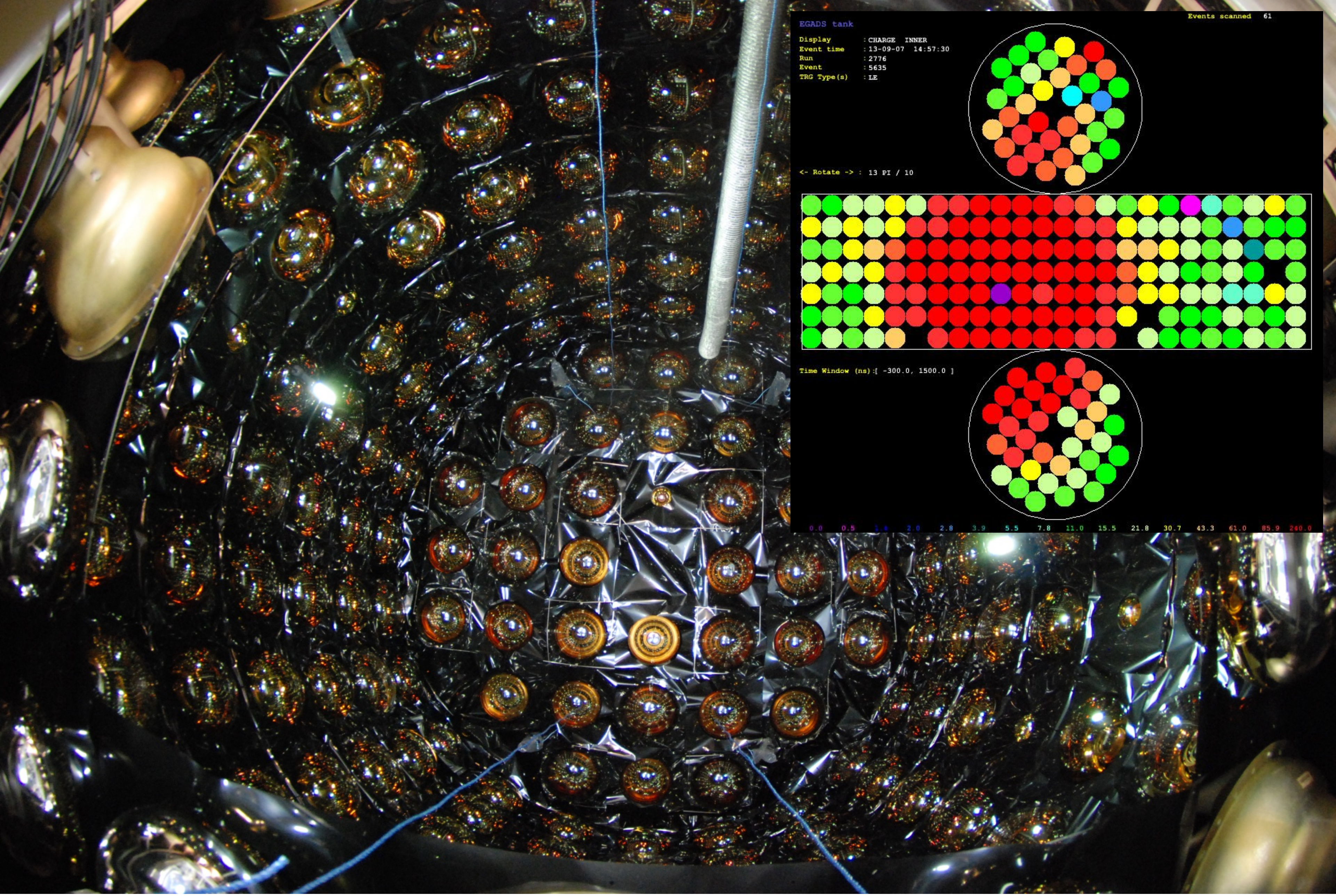
12/2010



Worldwide, over $20,000,000 dollars (!) has been invested in developing and proving the viability of the Gd-in-water concept.



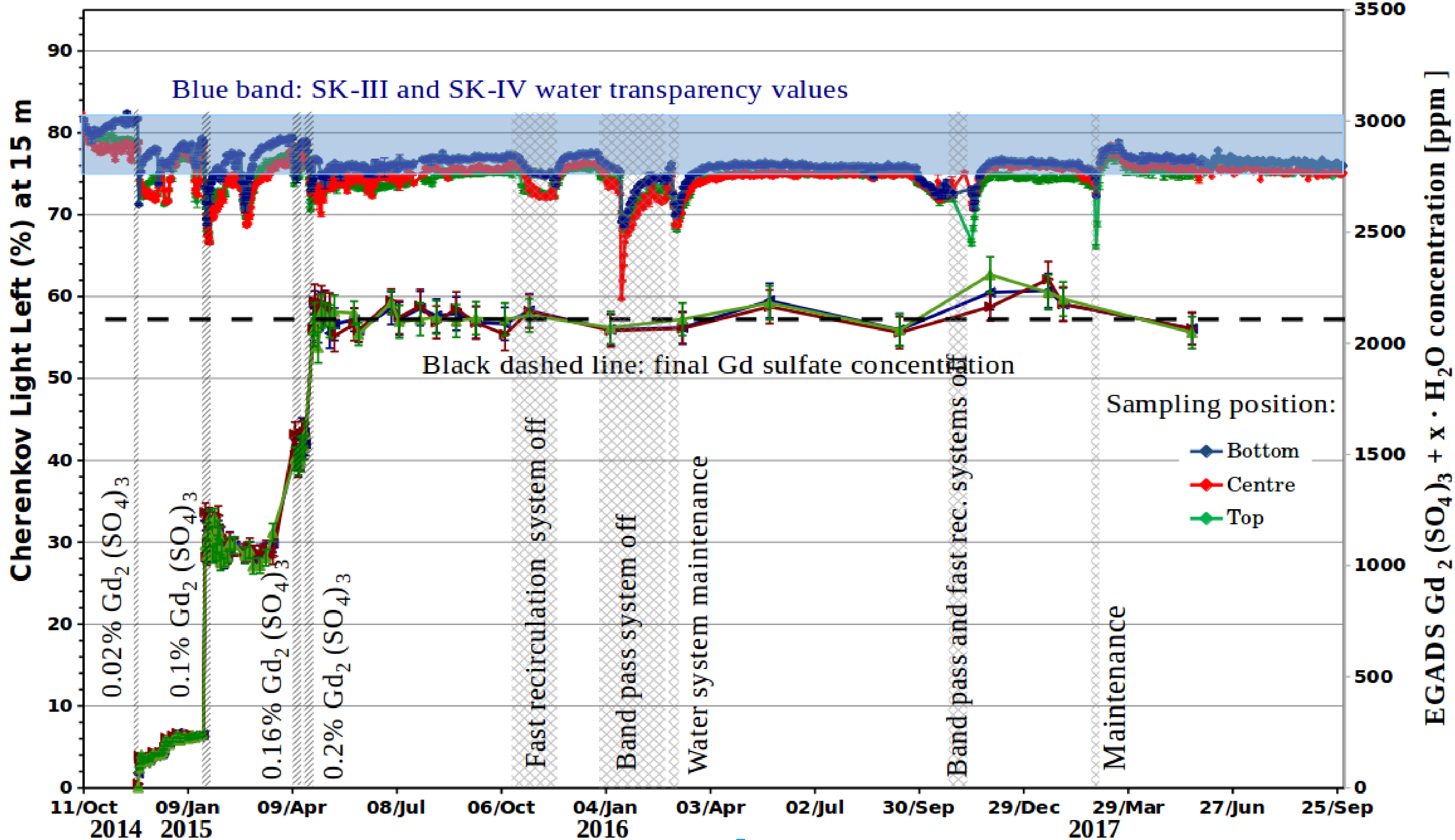
Working Inside the EGADS Tank; August 2013



Looking Down Into the Completed EGADS Detector; August 2013

Insert: Event Display of a Downward-Going Cosmic Ray Muon

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

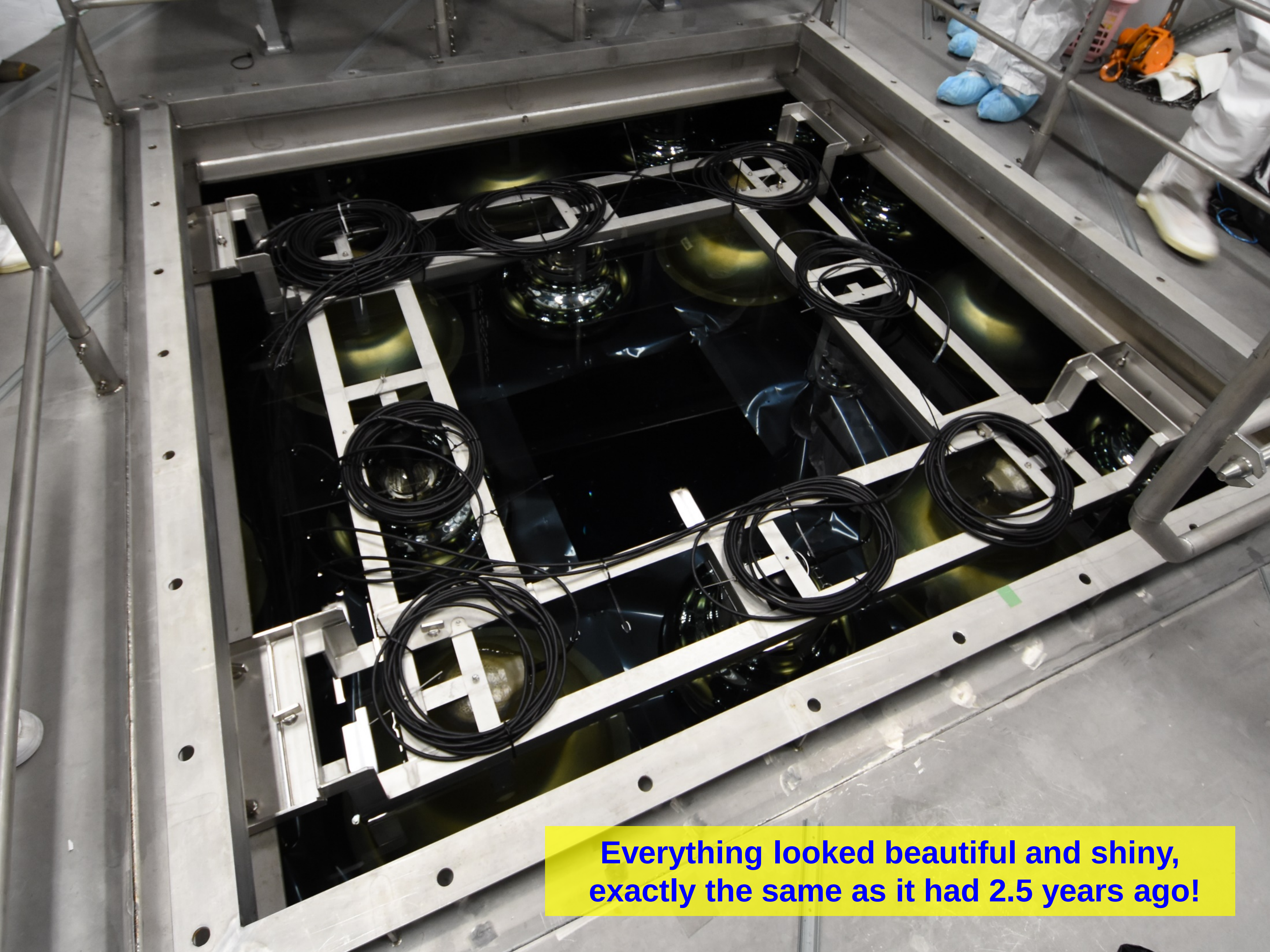


After more than two years at full Gd loading, during stable operations EGADS water transparency remains within the SK ultrapure range.

→ No detectable loss of Gd after more than 500 complete turnovers. ←

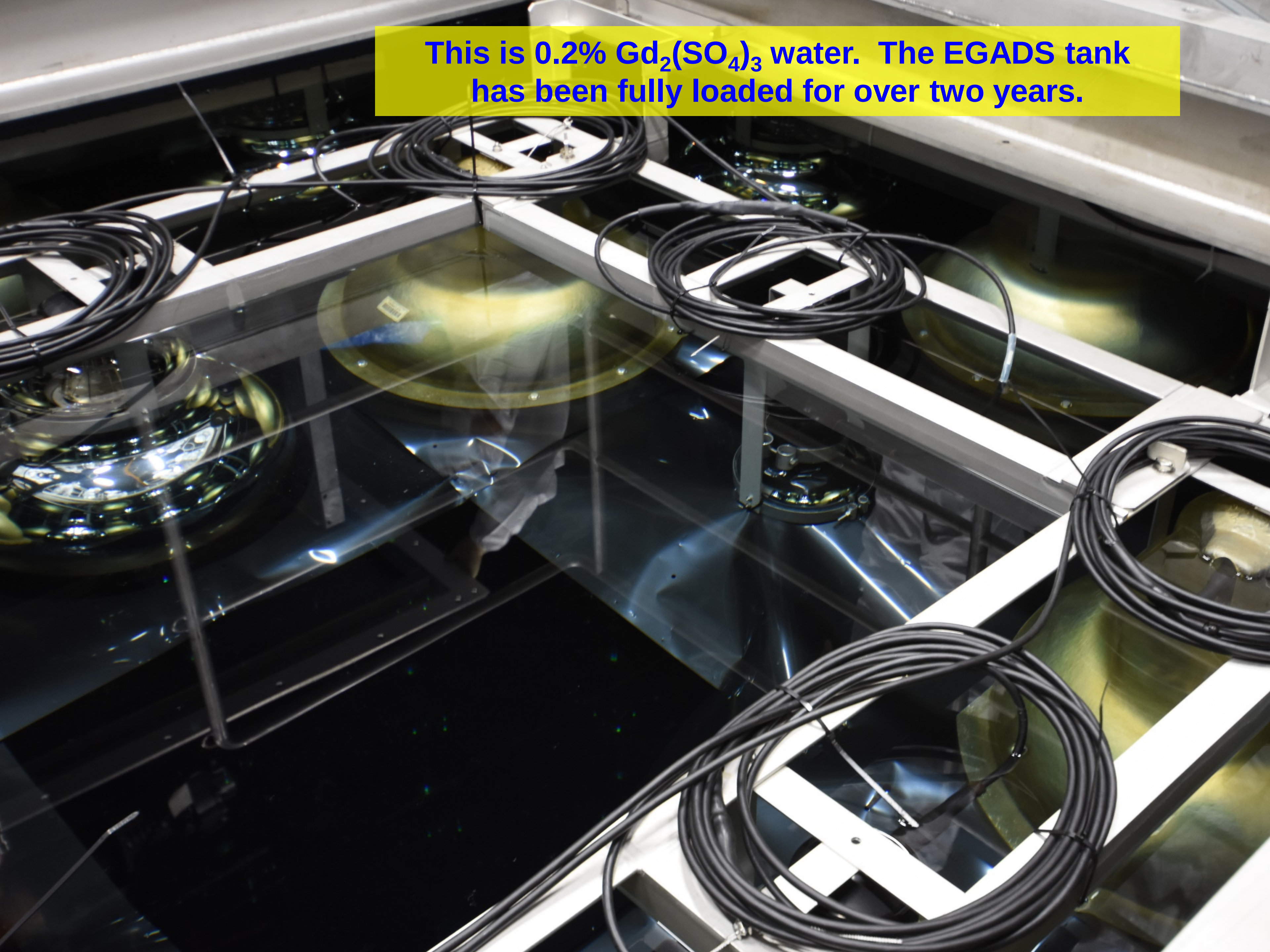
On May 16th, 2017, we opened the EGADS 200-ton tank. This was to be our first look inside since October 2014.

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



Everything looked beautiful and shiny, exactly the same as it had 2.5 years ago!

This is 0.2% $Gd_2(SO_4)_3$ water. The EGADS tank has been fully loaded for over two years.

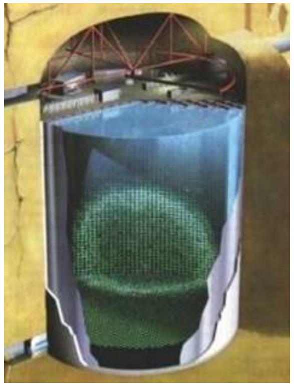


After years of testing and study

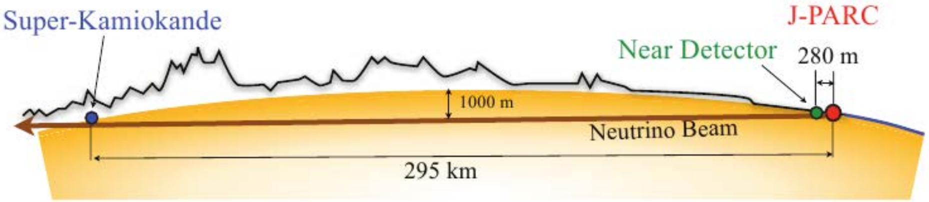
– culminating in these powerful EGADS results –

no technical showstoppers have been encountered. And so…

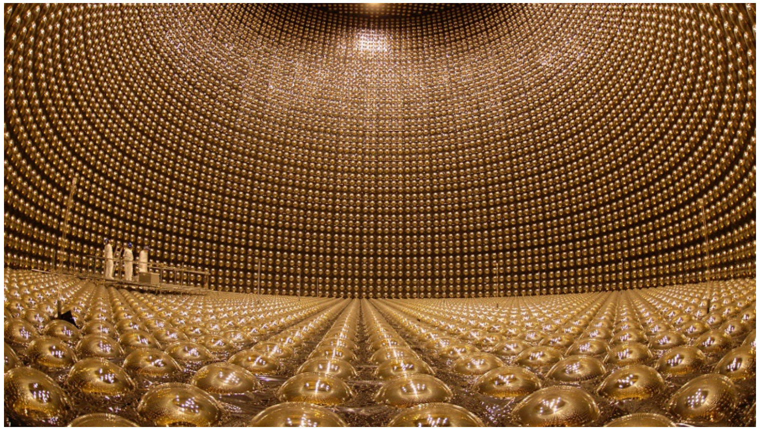
June 27, 2015: The Super-Kamiokande Collaboration approved the addition of gadolinium to the detector, pending discussions with T2K.

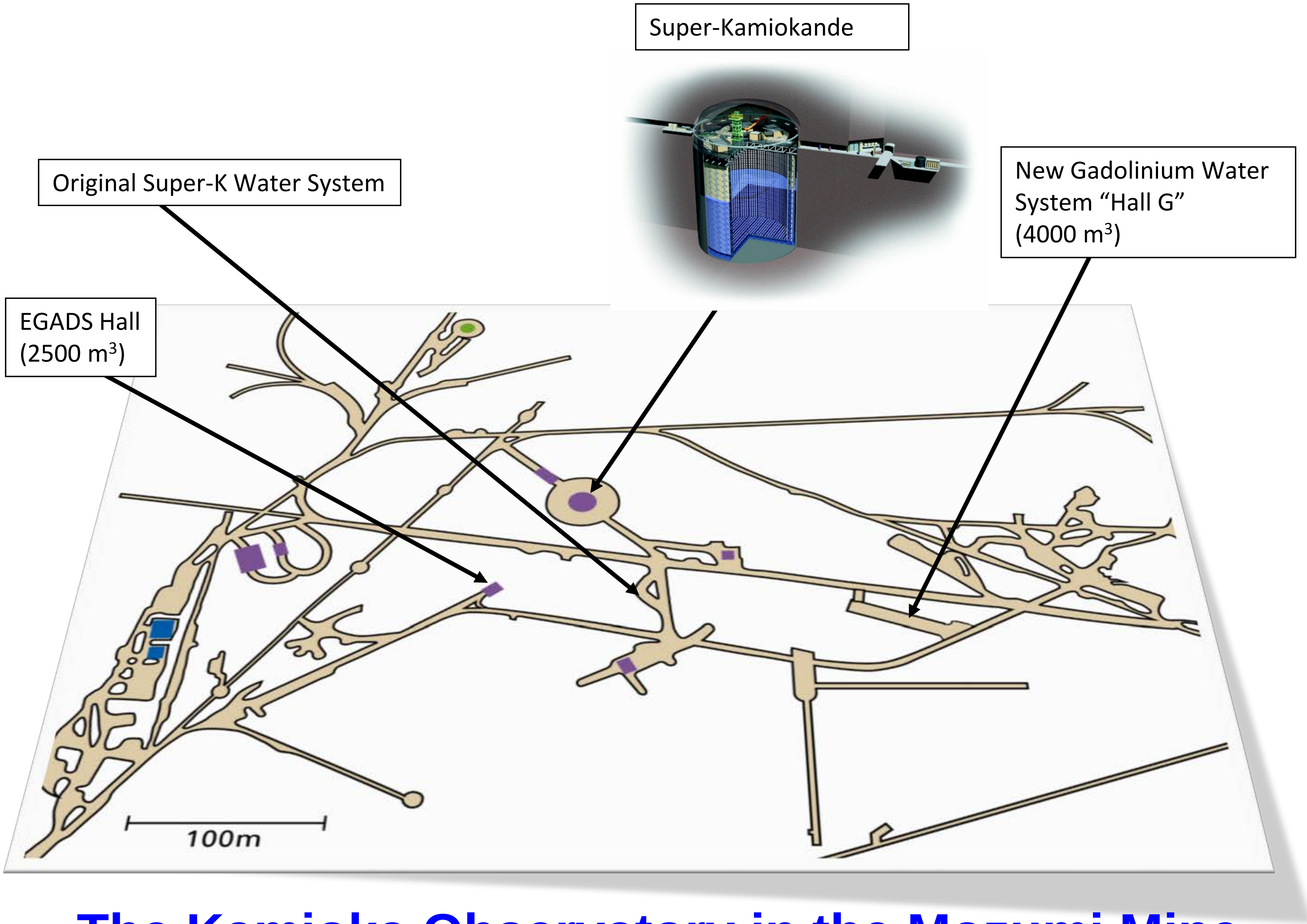


January 30, 2016: The T2K Collaboration approved addition of gadolinium to Super-Kamiokande, with the precise timing to be jointly determined based on the needs of both projects.



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



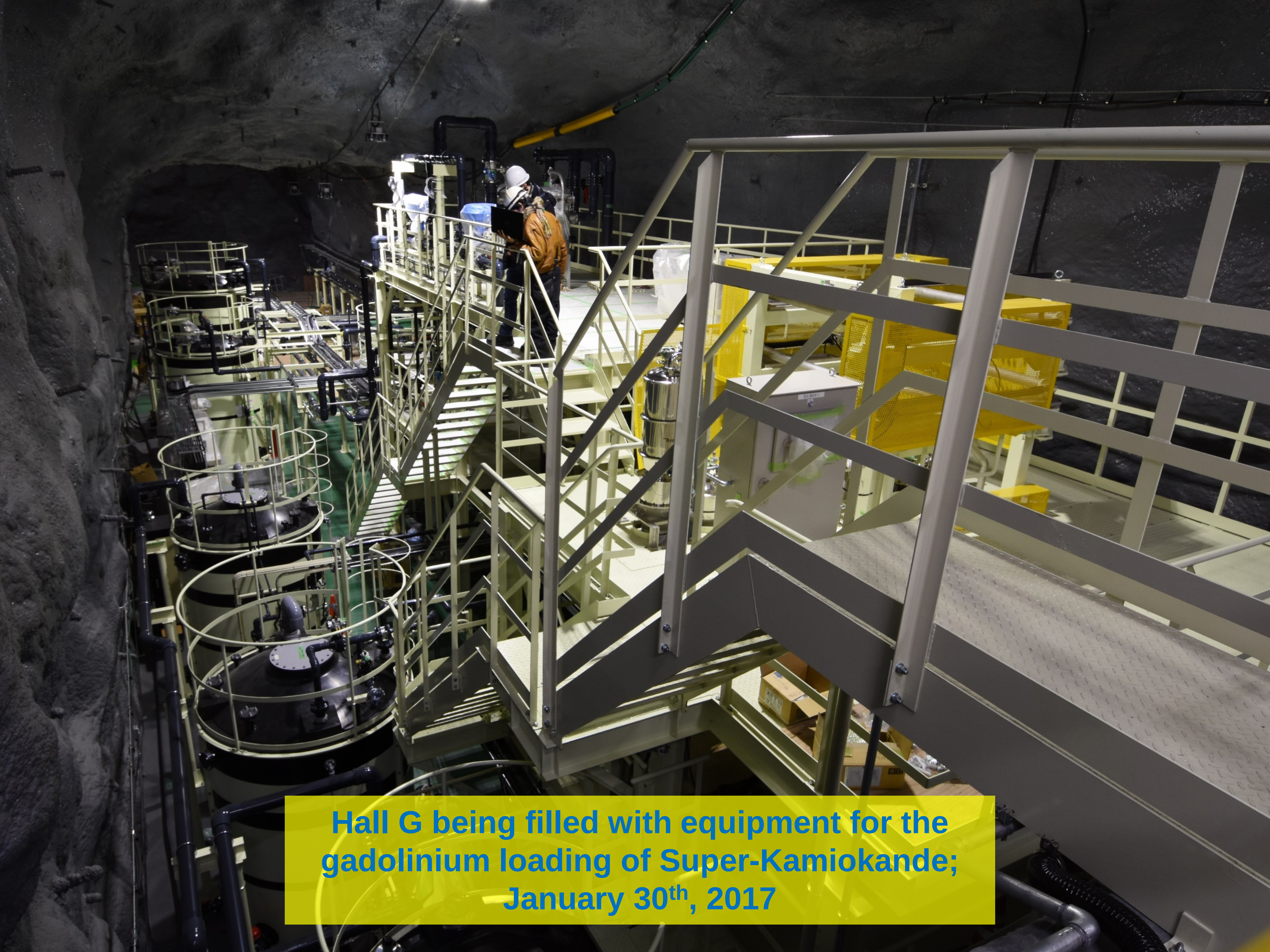


The Kamioka Observatory in the Mozumi Mine

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

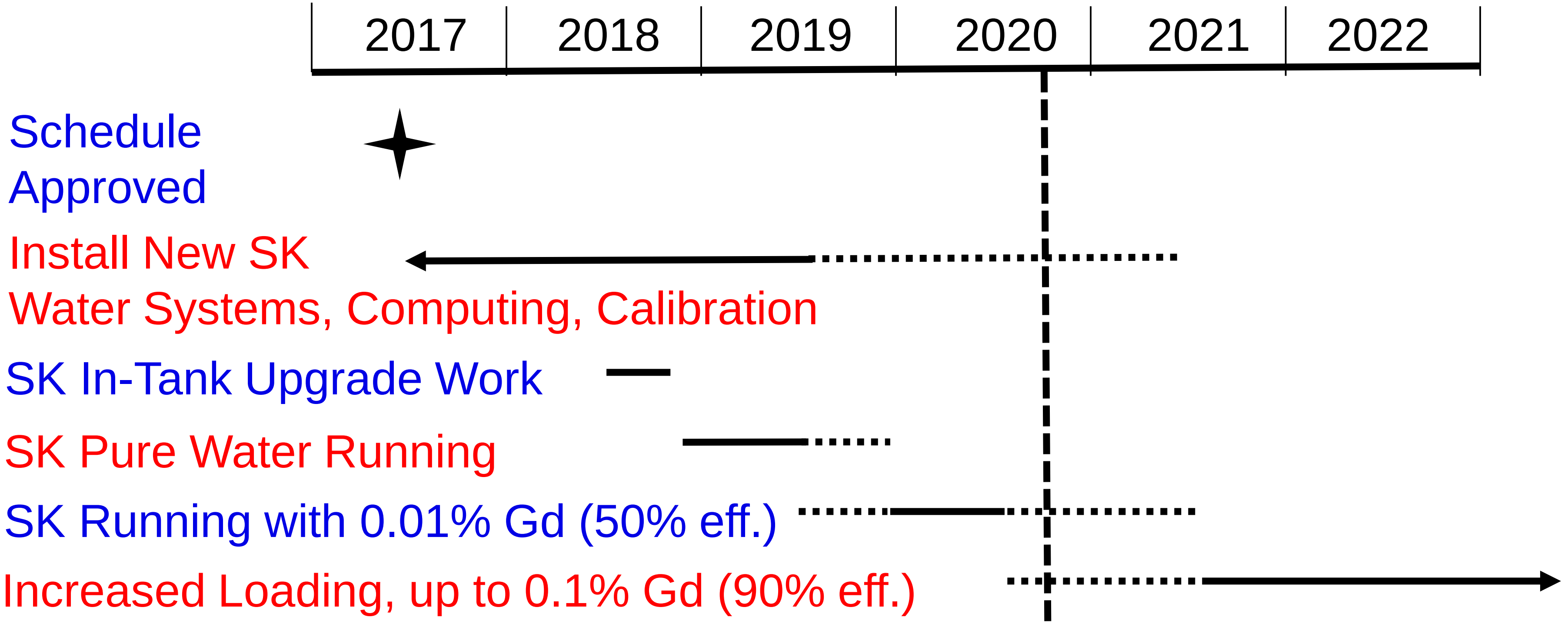
Hall G ready for occupancy;
April 22nd, 2016

Hall G being filled with equipment for the gadolinium loading of Super-Kamiokande; November 10th, 2016



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

Expected timeline for SK-Gd



We should have collected some new supernova neutrinos within three years from today!

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.

SK will begin in-tank work for Gd loading in June of 2018.