Super-Kamiokande: Gadiated at Last!

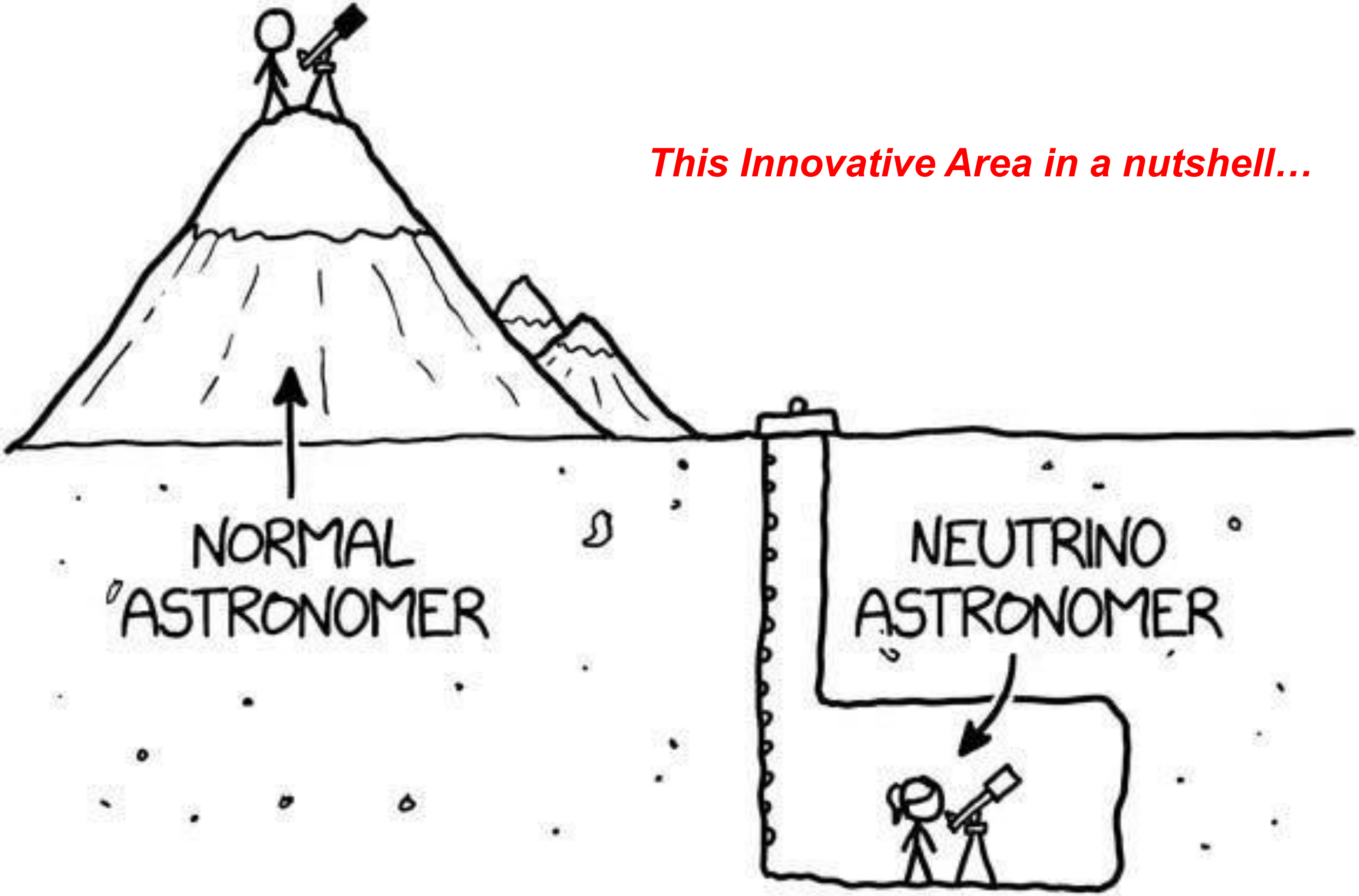
Mark Vagins (Kavli IPMU, UTokyo)

"Unraveling the History of the Universe and Matter Evolution with Underground Physics"

Tokyo University of Science, Noda Campus

June 14, 2022

This Innovative Area in a nutshell…

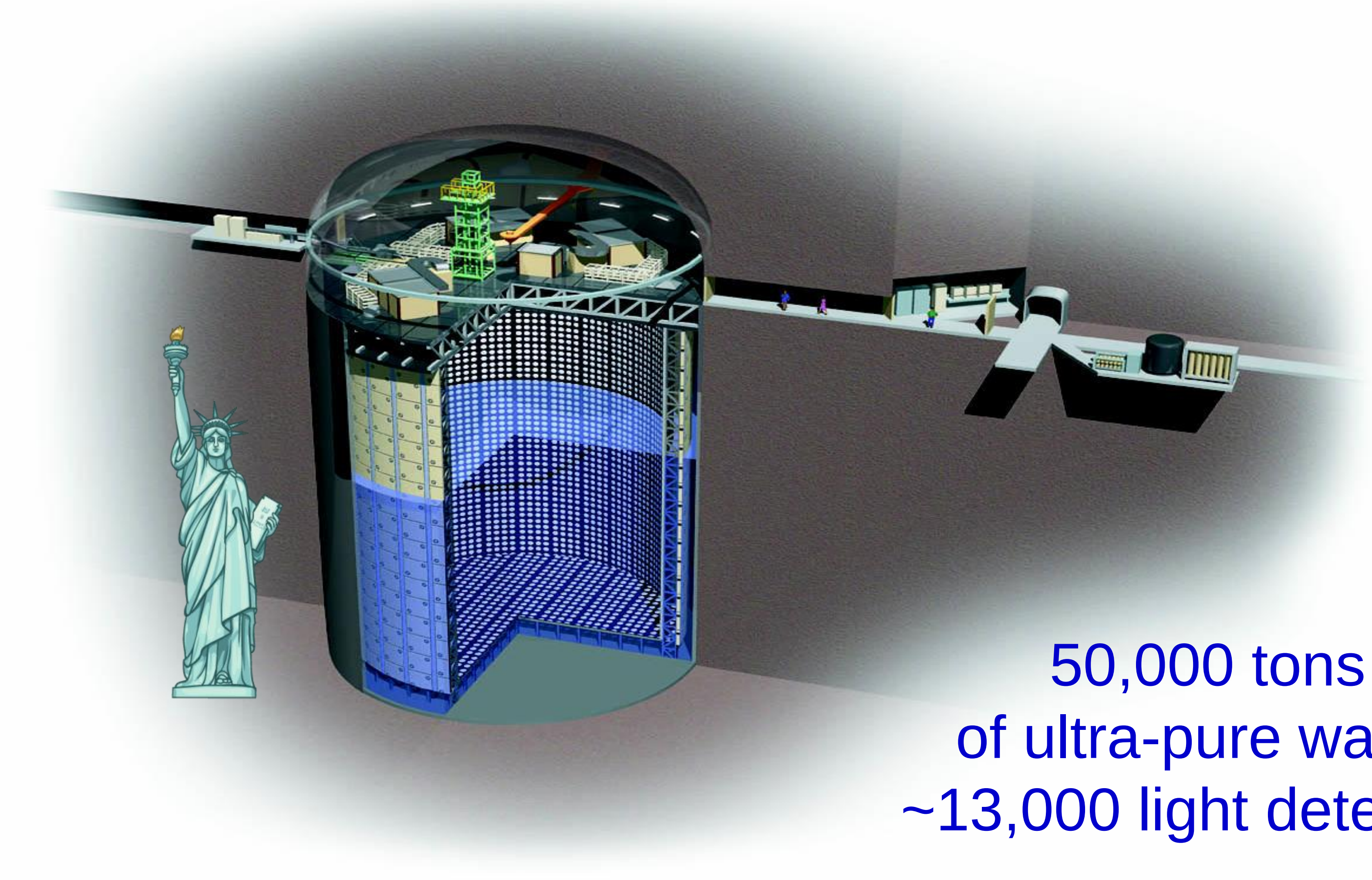


The Super-Kamiokande Collaboration

Kamioka Observatory, ICRR, Univ. of Tokyo, Japan
RCCN, ICRR, Univ. of Tokyo, Japan
University Autonoma Madrid, Spain
BC Institute of Technology, Canada
Boston University, USA
University of California, Irvine, USA
California State University, USA
Chonnam National University, Korea
Duke University, USA
Fukuoka Institute of Technology, Japan
Gifu University, Japan
GIST, Korea
University of Hawaii, USA
IBS, Korea
IFIRSE, Vietnam
Imperial College London, UK
ILANCE, France
INFN Bari, Italy
INFN Napoli, Italy
INFN Padova, Italy
INFN Roma, Italy
Kavli IPMU, The Univ. of Tokyo, Japan
Keio University, Japan
KEK, Japan
King's College London, UK
Kobe University, Japan
Kyoto University, Japan
University of Liverpool, UK
LLR, Ecole polytechnique, France
Miyagi University of Education, Japan
ISEE, Nagoya University, Japan
NCBJ, Poland
Okayama University, Japan
University of Oxford, UK
Rutherford Appleton Laboratory, UK
Seoul National University, Korea
University of Sheffield, UK
Shizuoka University of Welfare, Japan
Sungkyunkwan University, Korea
Stony Brook University, USA
Tohoku University, Japan
Tokai University, Japan
The University of Tokyo, Japan
Tokyo Institute of Technology, Japan
Tokyo University of Science, japan
TRIUMF, Canada
Tsinghua University, China
University of Warsaw, Poland
Warwick University, UK
The University of Winnipeg, Canada
Yokohama National University, Japan

~230 collaborators from 51 institutes in 11 countries

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



50,000 tons
of ultra-pure water,
~13,000 light detectors

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

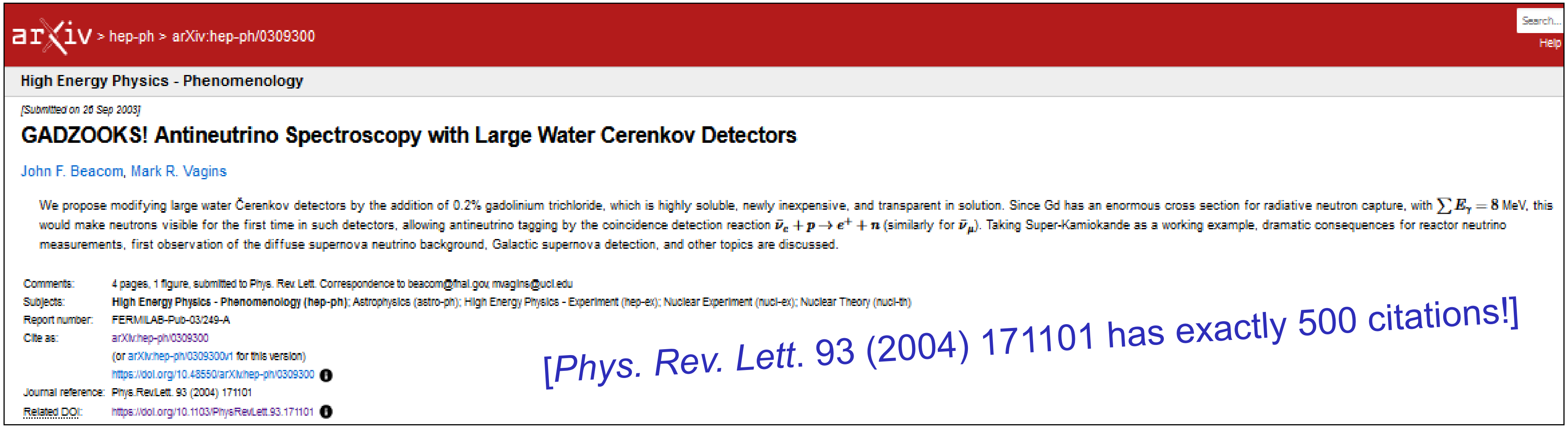
→ **We will let the world know the light is on its way.** ←

But waiting for a galactic supernova can… take a while, and many of us would really like to see some supernova neutrinos!

So, after one of the sessions at Neutrino 2002 in Munich, theorist John Beacom and I decided to try and actually *do* something about it.

→

↓



arXiv > hep-ph > arXiv:hep-ph/0309300

High Energy Physics - Phenomenology

[Submitted on 26 Sep 2003]

GADZOOKS! Antineutrino Spectroscopy with Large Water Cerenkov Detectors

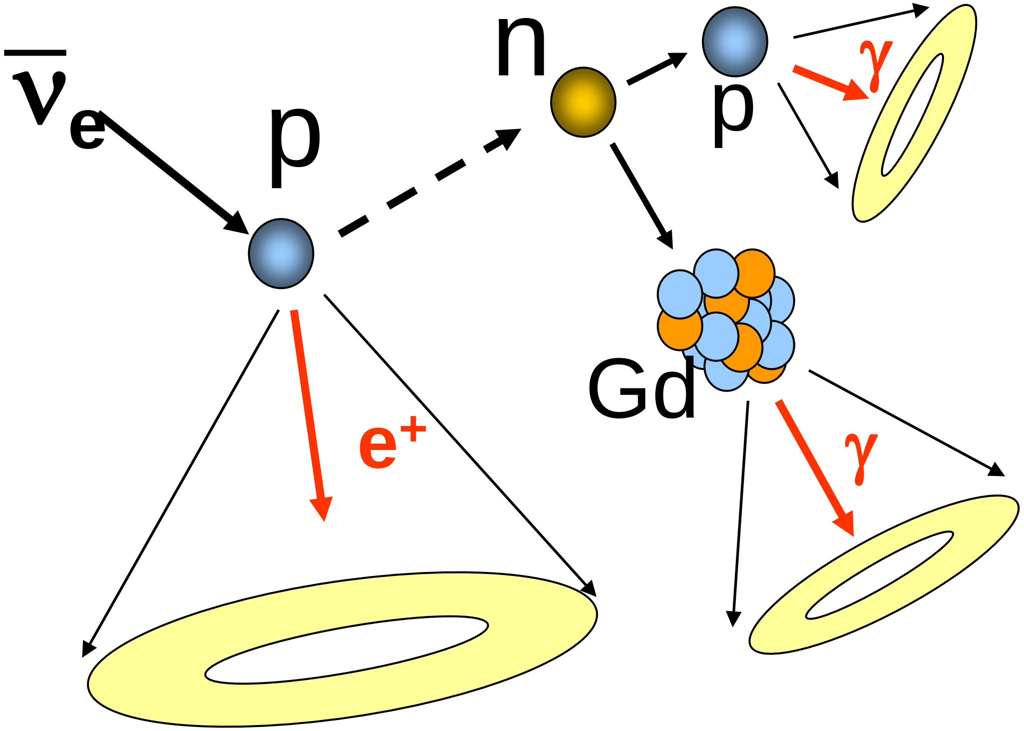
John F. Beacom, Mark R. Vagins

We propose modifying large water Čerenkov detectors by the addition of 0.2% gadolinium trichloride, which is highly soluble, newly inexpensive, and transparent in solution. Since Gd has an enormous cross section for radiative neutron capture, with $\sum E_\gamma = 8$ MeV, this would make neutrons visible for the first time in such detectors, allowing antineutrino tagging by the coincidence detection reaction $\bar{\nu}_e + p \rightarrow e^+ + n$ (similarly for $\bar{\nu}_\mu$). Taking Super-Kamiokande as a working example, dramatic consequences for reactor neutrino measurements, first observation of the diffuse supernova neutrino background, Galactic supernova detection, and other topics are discussed.

Comments: 4 pages, 1 figure, submitted to Phys. Rev. Lett. Correspondence to beacom@fnal.gov, mvagins@ucl.edu
Subjects: **High Energy Physics - Phenomenology (hep-ph)**; Astrophysics (astro-ph); High Energy Physics - Experiment (hep-ex); Nuclear Experiment (nucl-ex); Nuclear Theory (nucl-th)
Report number: FERMILAB-Pub-03/249-A
Cite as: arXiv:hep-ph/0309300
(or arXiv:hep-ph/0309300v1 for this version)
https://doi.org/10.48550/arXiv.hep-ph/0309300
Journal reference: Phys.Rev.Lett. 93 (2004) 171101
Related DOI: https://doi.org/10.1103/PhysRevLett.93.171101

[*Phys. Rev. Lett*. 93 (2004) 171101 has exactly 500 citations!]

In addition to first introducing the term "DSNB", basically we said, "Let's add 0.1% gadolinium - using a water soluble gadolinium compound - to Super-K!"



Positron and gamma ray vertices within ~50 cm.

Possibility 1: 10% or less

n+p→d + γ

2.2 MeV γ-ray

Possibility 2: 90% or more

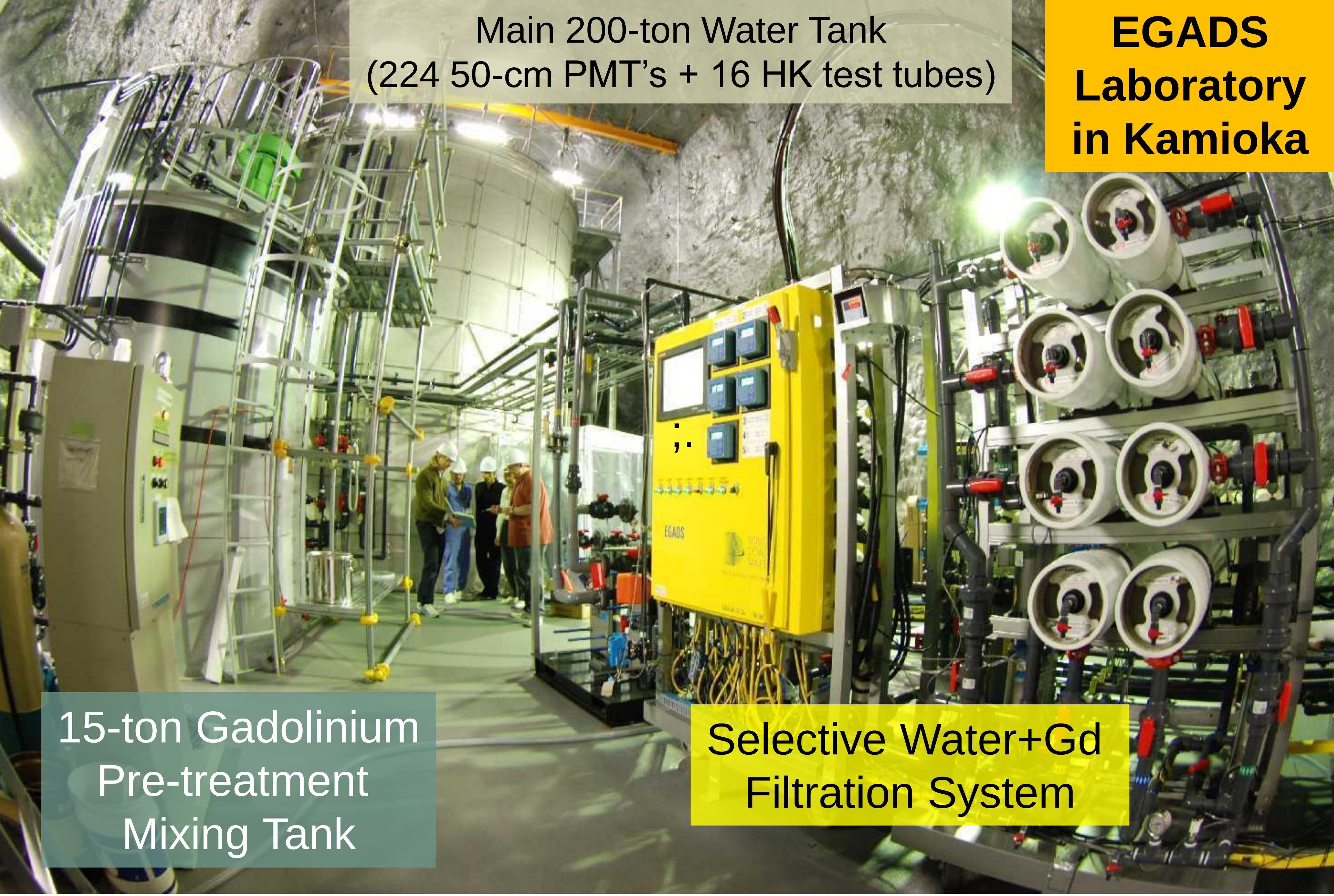
n+Gd →~8 MeV γ

ΔT = ~30 μsec

$\bar{\nu}_e$ can be individually identified by delayed coincidence: "Gd heartbeat"

→ n-tags greatly reduce backgrounds to DSNB, p-decay, etc

EGADS Laboratory in Kamioka



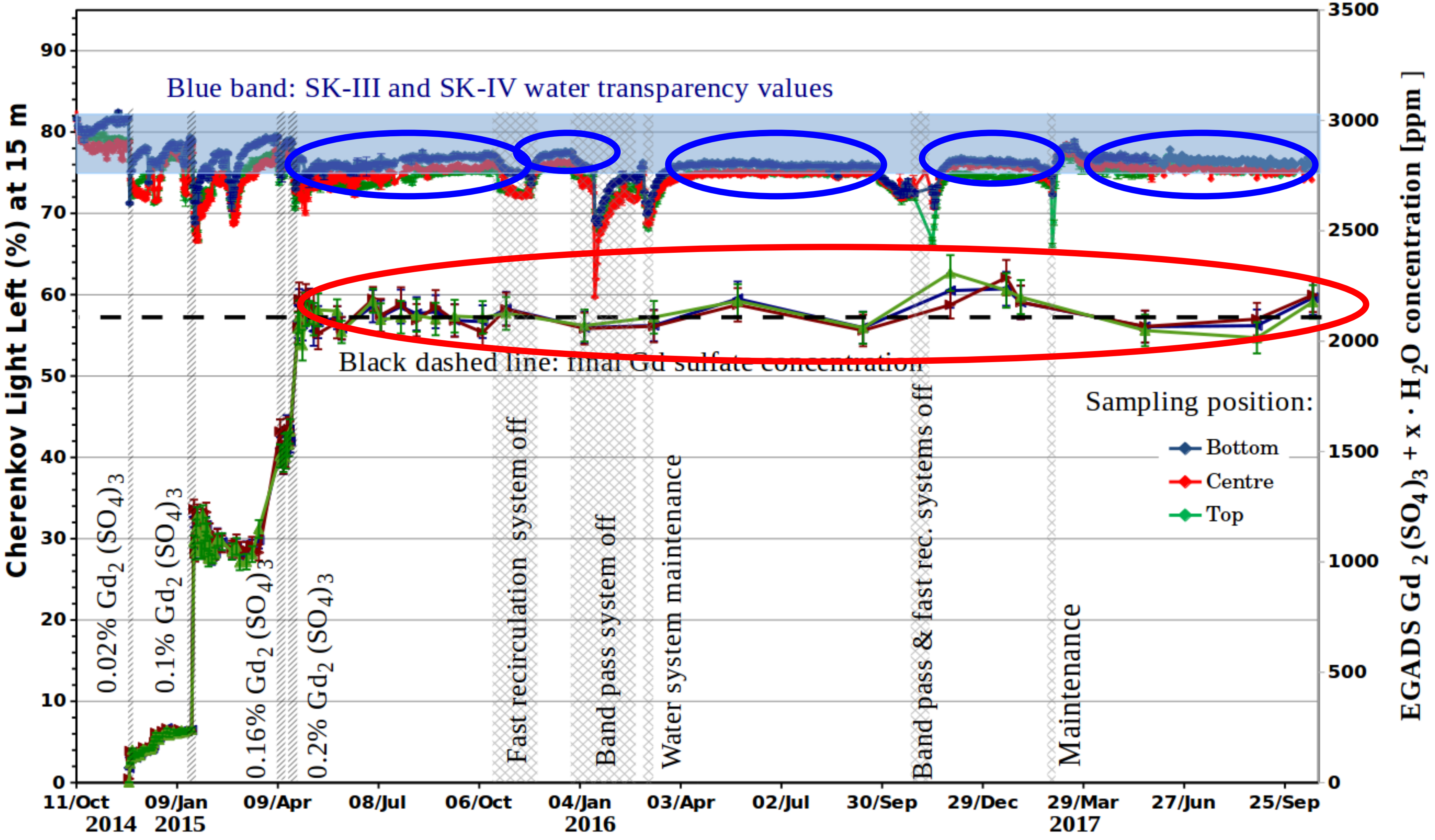
Main 200-ton Water Tank
(224 50-cm PMT’s + 16 HK test tubes)

15-ton Gadolinium
Pre-treatment
Mixing Tank

Selective Water+Gd
Filtration System

Worldwide, over $10M (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, during stable operations EGADS water transparency remains within the SK ultrapure range.

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

November 6th, 2017; This view is directed up the side wall from the bottom of the 200-ton EGADS tank. Looks great after 2.5 years of exposure to 0.1% Gd-loaded water!

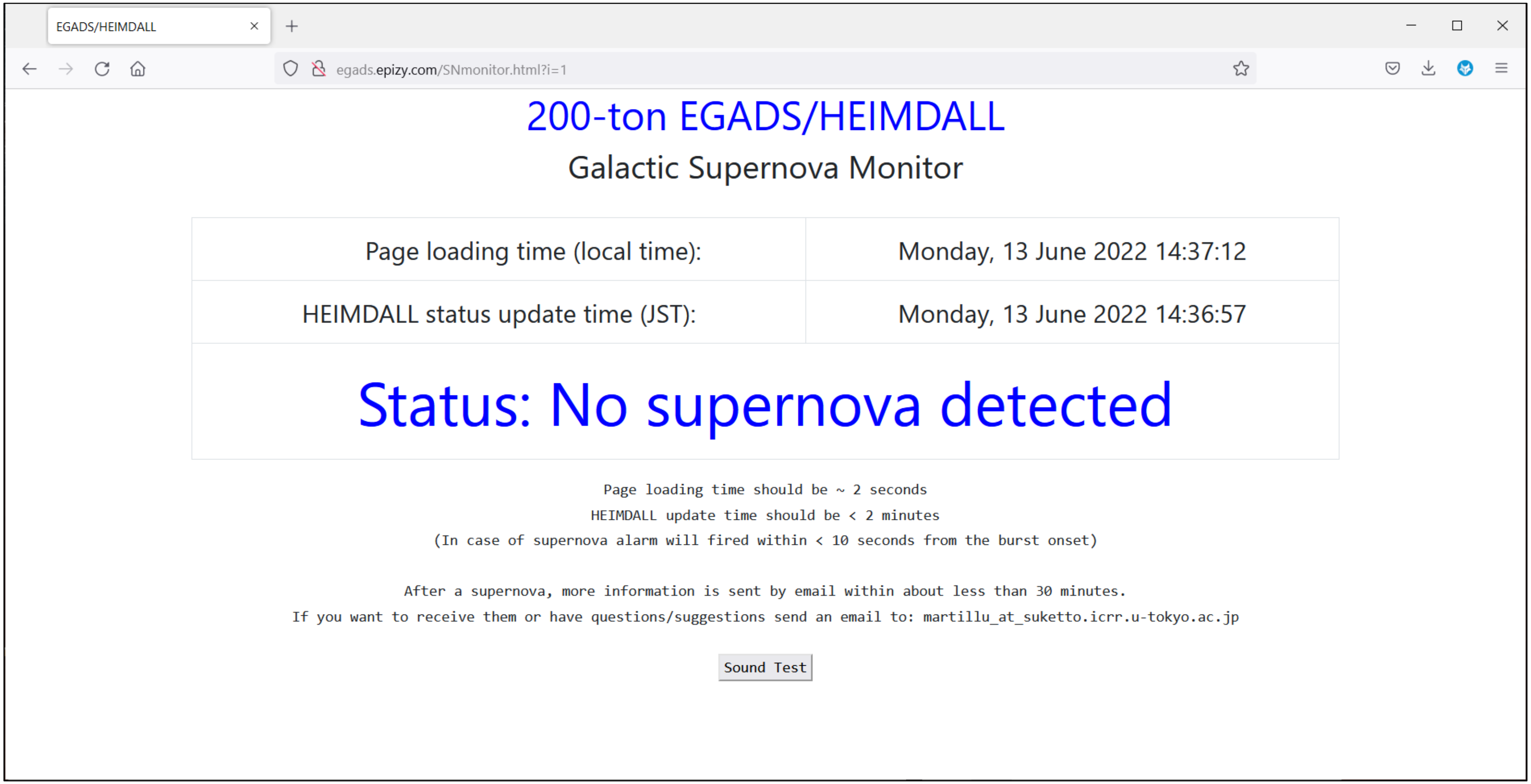
With an R&D program of mostly long-duration tests, EGADS also functions as a dedicated, Gd-loaded SN detector. Its realtime alerts are open to the public.

~90,000 ν events
@ Betelgeuse

~40 ν events
@ G.C.

EGADS is now the lowest latency SN neutrino detector in the world. We'll send out an announcement within ***a few seconds*** of a MW SN neutrino burst's arrival!

http://egads.epizy.com/SNmonitor.html



200-ton EGADS/HEIMDALL

Galactic Supernova Monitor

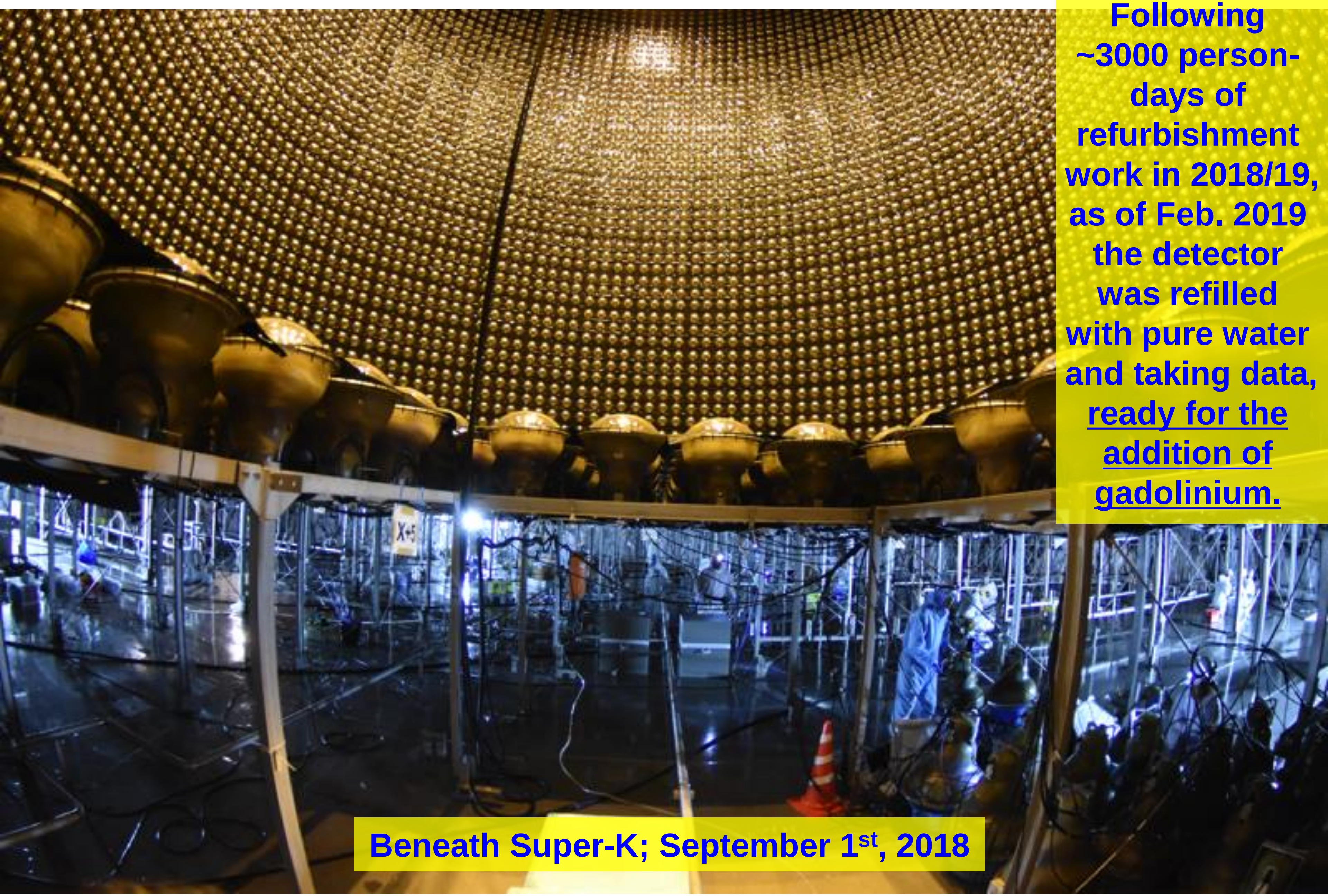
Page loading time (local time):	Monday, 13 June 2022 14:37:12
HEIMDALL status update time (JST):	Monday, 13 June 2022 14:36:57

Status: No supernova detected

Page loading time should be ~ 2 seconds
HEIMDALL update time should be < 2 minutes
(In case of supernova alarm will fired within < 10 seconds from the burst onset)

After a supernova, more information is sent by email within about less than 30 minutes.
If you want to receive them or have questions/suggestions send an email to: martillu_at_suketto.icrr.u-tokyo.ac.jp

Sorry, but there was no Milky Way supernova while I was preparing this talk yesterday.



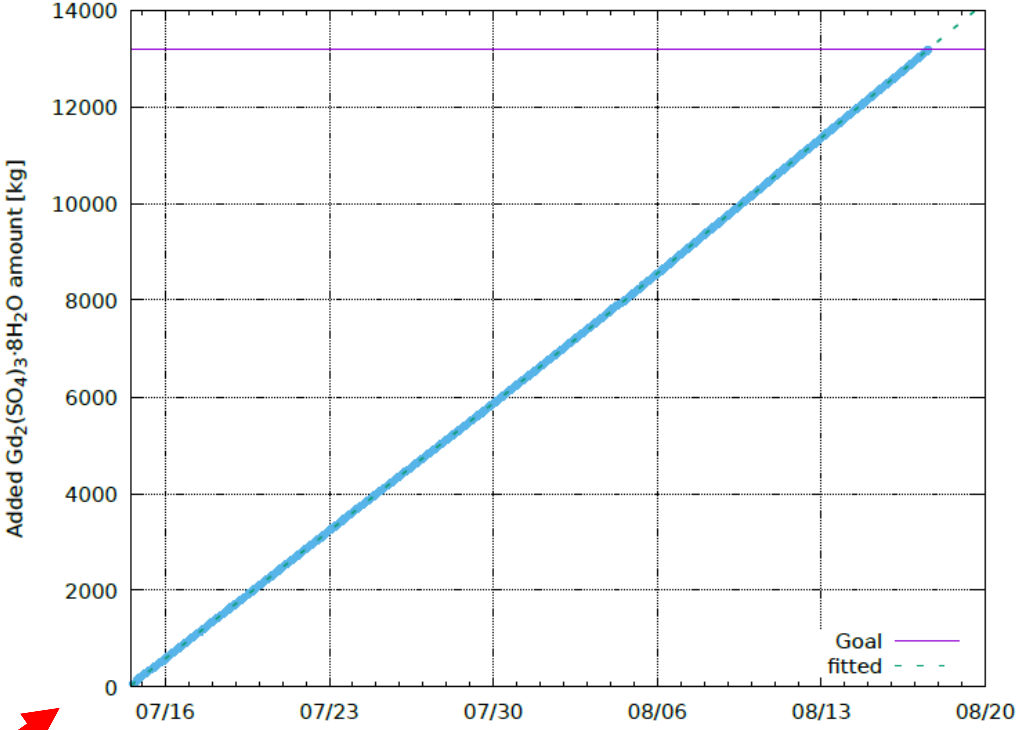
Following ~3000 person-days of refurbishment work in 2018/19, as of Feb. 2019 the detector was refilled with pure water and taking data, ready for the addition of gadolinium.

Beneath Super-K; September 1st, 2018

Loading Super-Kamiokande with Gadolinium (First Step)

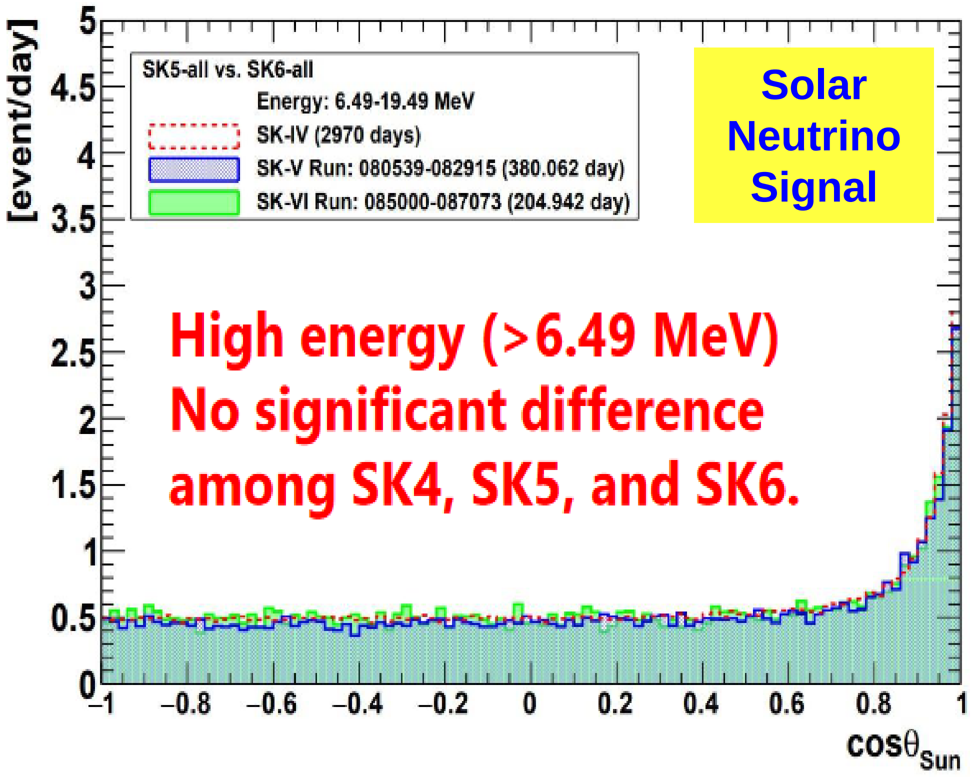
After nearly 20 years of R&D, planning, and preparation, culminating with a major detector refurbishment in 2018/9, Super-K was finally loaded with 0.01% gadolinium (meaning 13.2 tons of $Gd_2(SO_4)_3$*$8H_2O$) in July/August 2020 → SK-VI

Gd Loading Super-Kamiokande in 2020



"First Gadolinium Loading to Super-Kamiokande", Super-K Collaboration, *Nuclear Inst. And Methods in Physics Research*, **A 1027** (2022) 166248

After nearly two years running with 0.01% Gd in SK, things are going well:

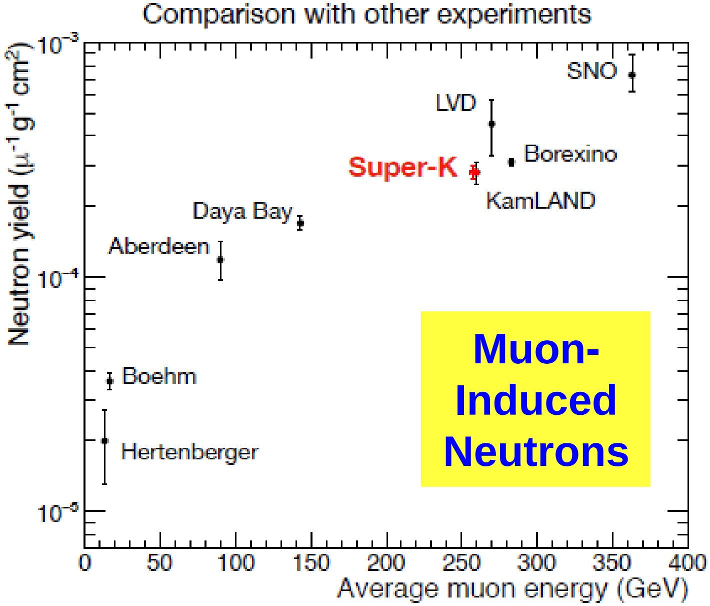


Solar Neutrino Signal

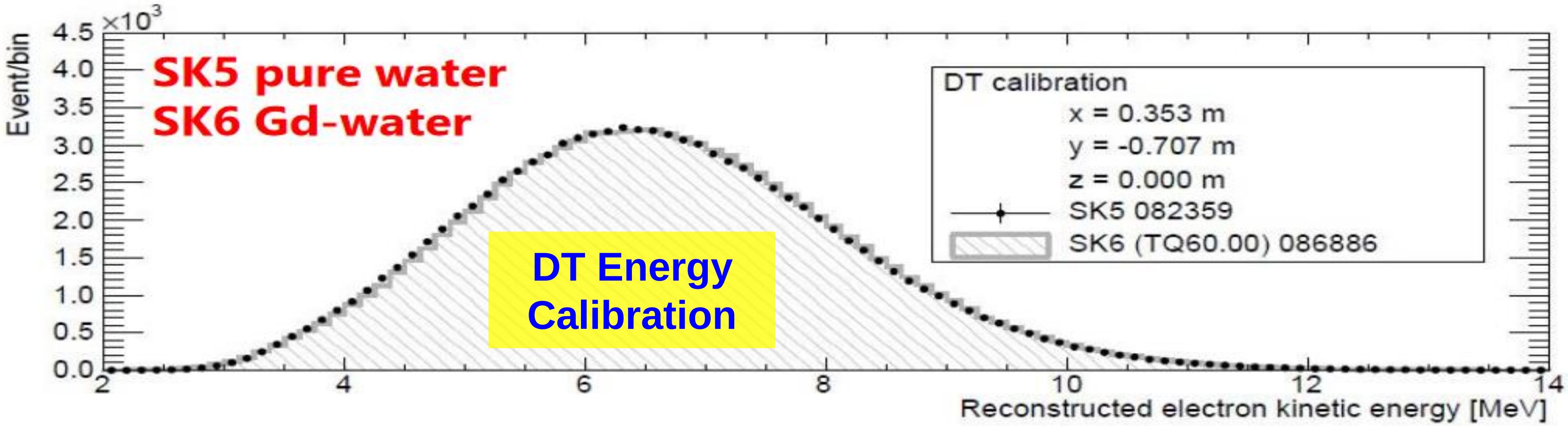
High energy (>6.49 MeV)
No significant difference
among SK4, SK5, and SK6.

The result of neutron yield measurement:

Y_n = (2.81 ± 0.06 (stat.) ± 0.18 (syst.)) × 10^{-4} $\mu^{-1}g^{-1}cm^2$



Muon-Induced Neutrons



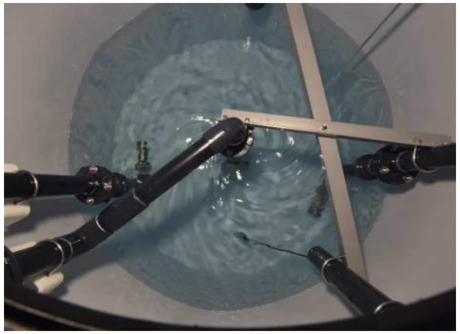
SK5 pure water
SK6 Gd-water

DT Energy Calibration

And so…

Loading Super-Kamiokande with Gadolinium (Next Step)

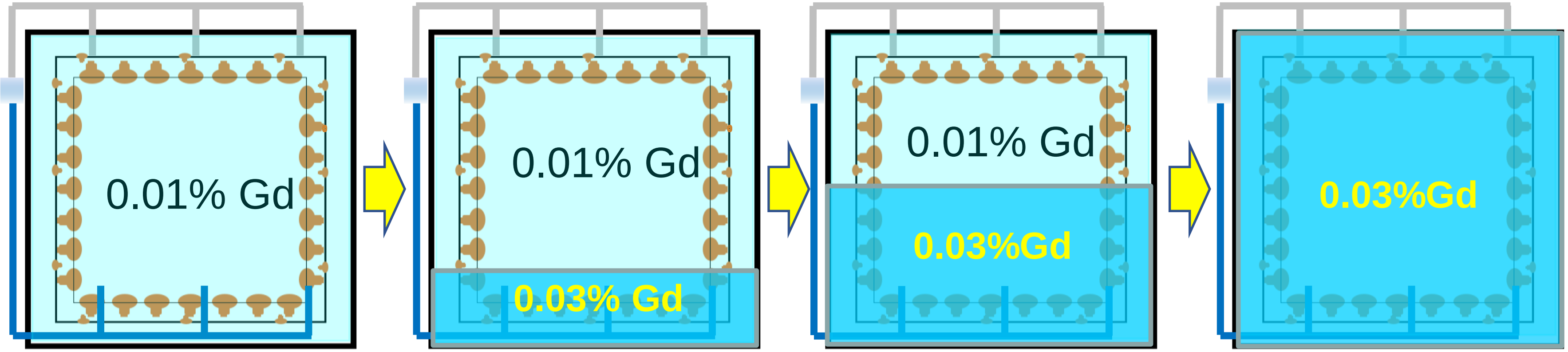
Starting on June 1st, 2022, the next phase of SK operations (SK-VII) began. At 10:26 a.m. JST, the continuous loading of another 26 tons of $Gd_2(SO_4)_3$*$8H_2O$ was started. This will bring the Gd concentration to 0.03% within July.



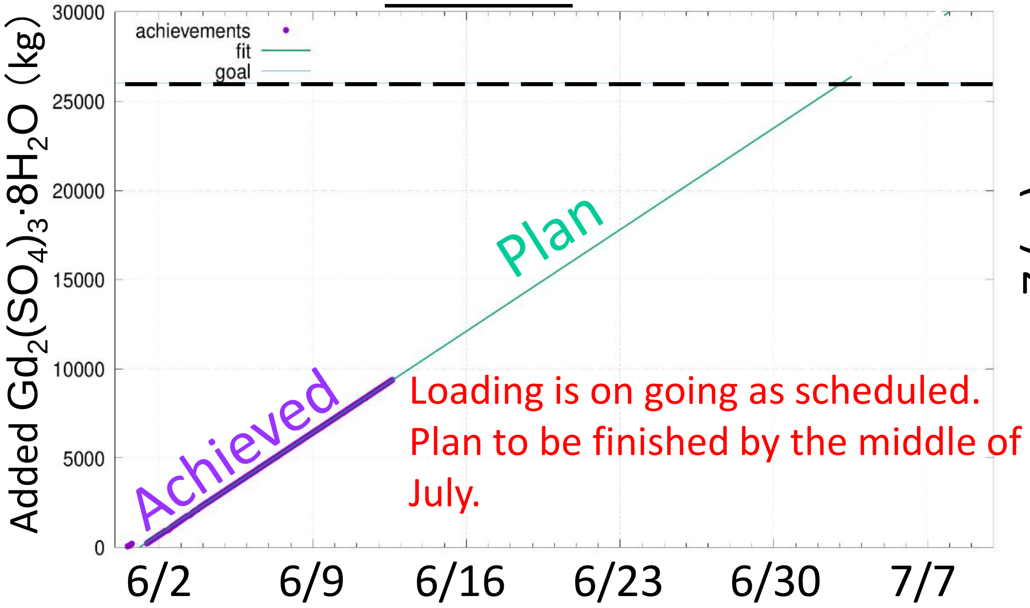
For an obscure rare earth element typically purchased by the gram, these two SK lots of ultra-radiopure (paper in prep) gadolinium sulfate, at 13 and 26 tons, are by far the largest orders of Gd in history!

Status of additional Gd-loading （as of June 12, 2022)

Method: Return 0.01% Gd-loaded water from top and supply 0.03% Gd-loaded water



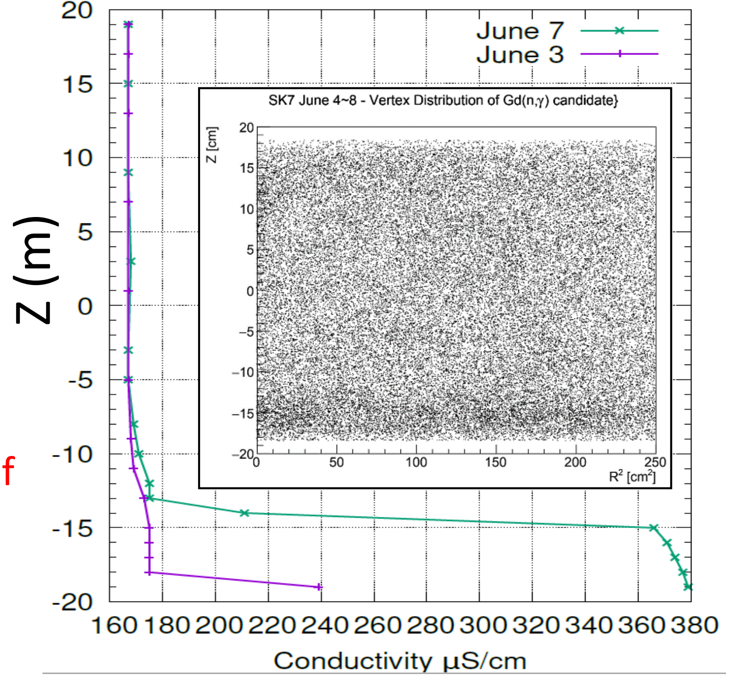
Cumulative amount of $Gd_2(SO_4)_3$ added over time

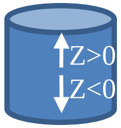


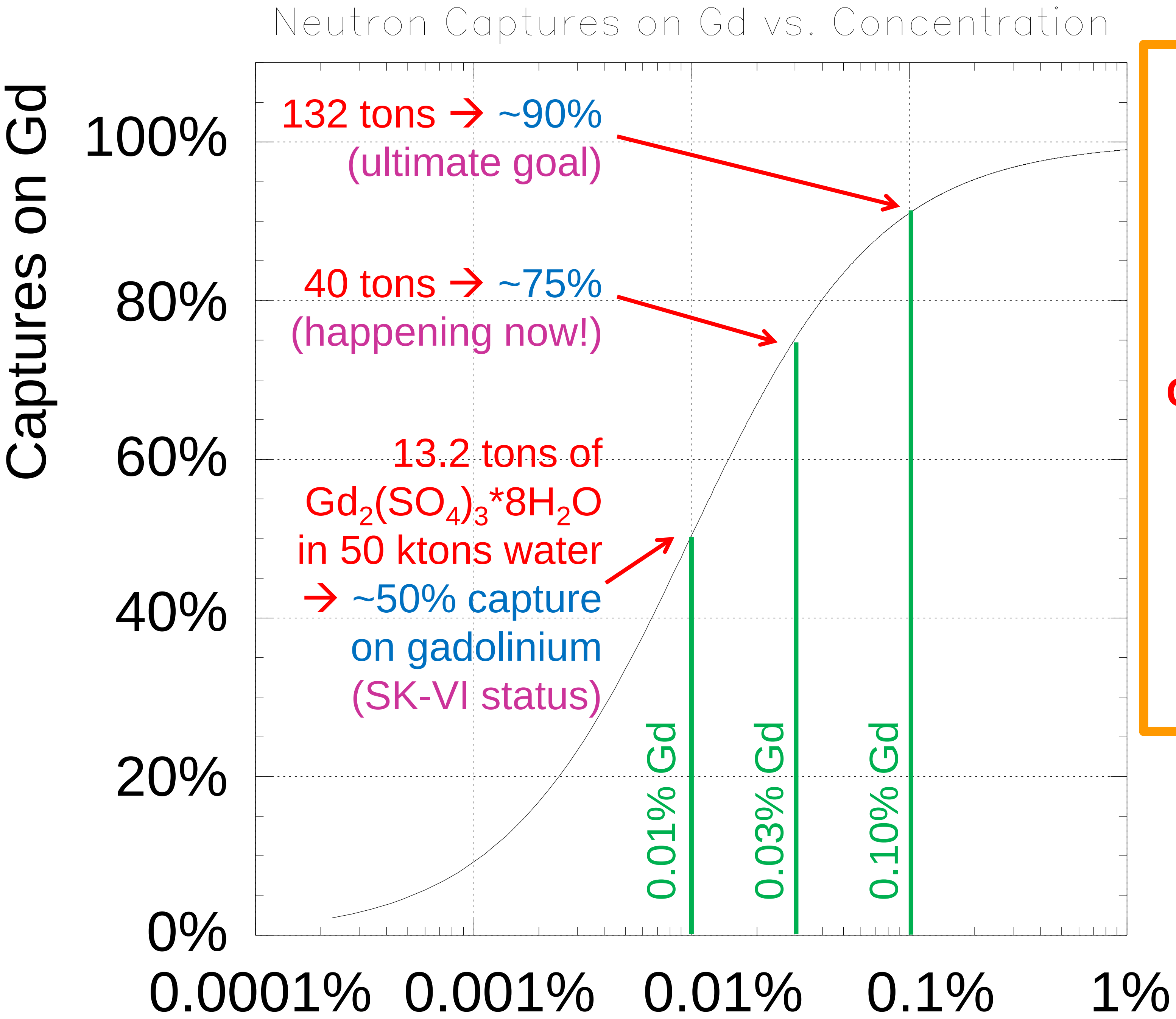
Loading is on going as scheduled.
Plan to be finished by the middle of July.

Loading was started on June 1.

Measured conductivity and neutron event vertex distribution







132 tons → ~90%
(ultimate goal)

40 tons → ~75%
(happening now!)

13.2 tons of
$Gd_2(SO_4)_3*8H_2O$
in 50 ktons water
→ ~50% capture
on gadolinium
(SK-VI status)

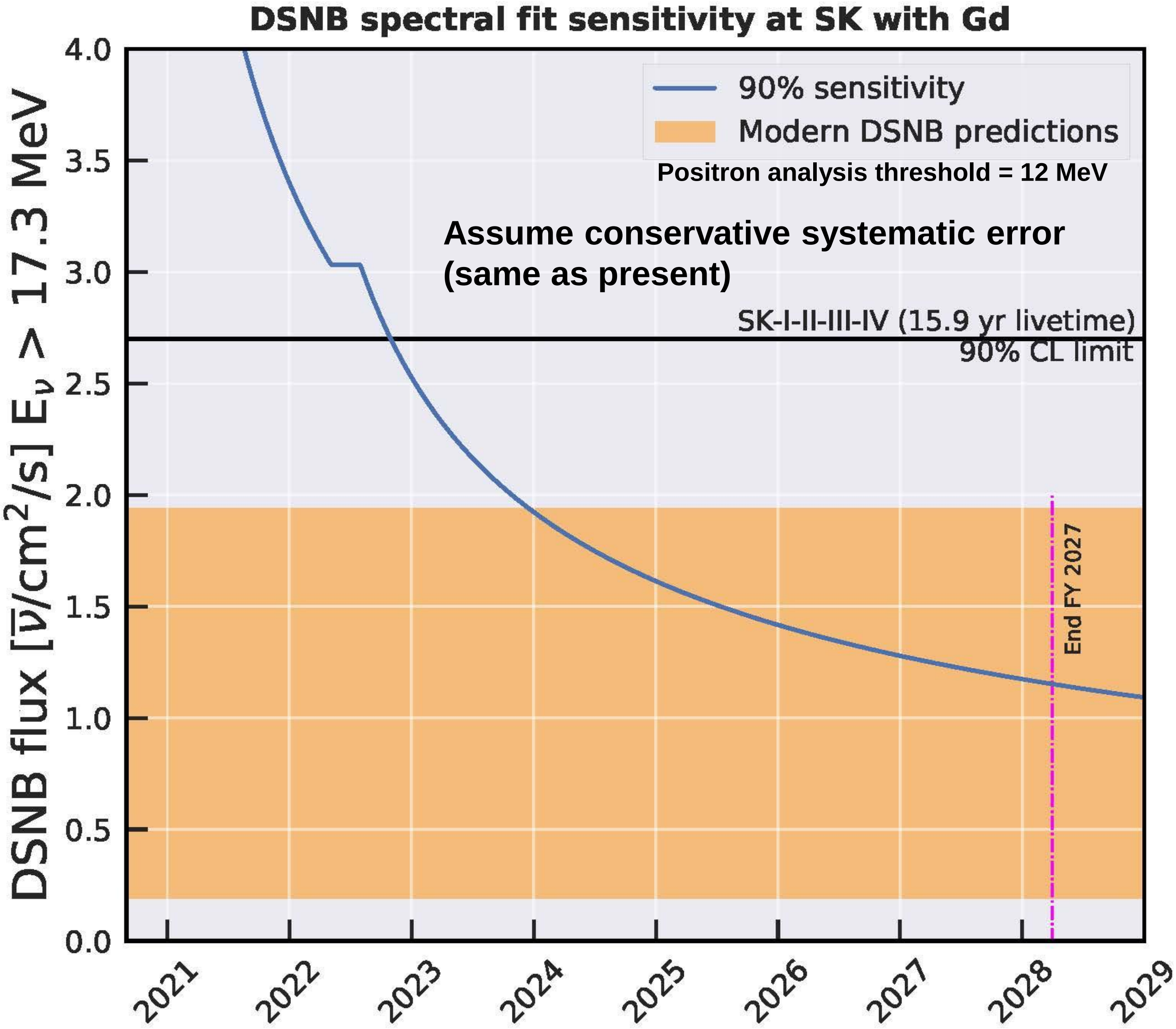
<u>Thermal neutron capture cross section (barns)</u>

Gd = 49700

S = 0.53

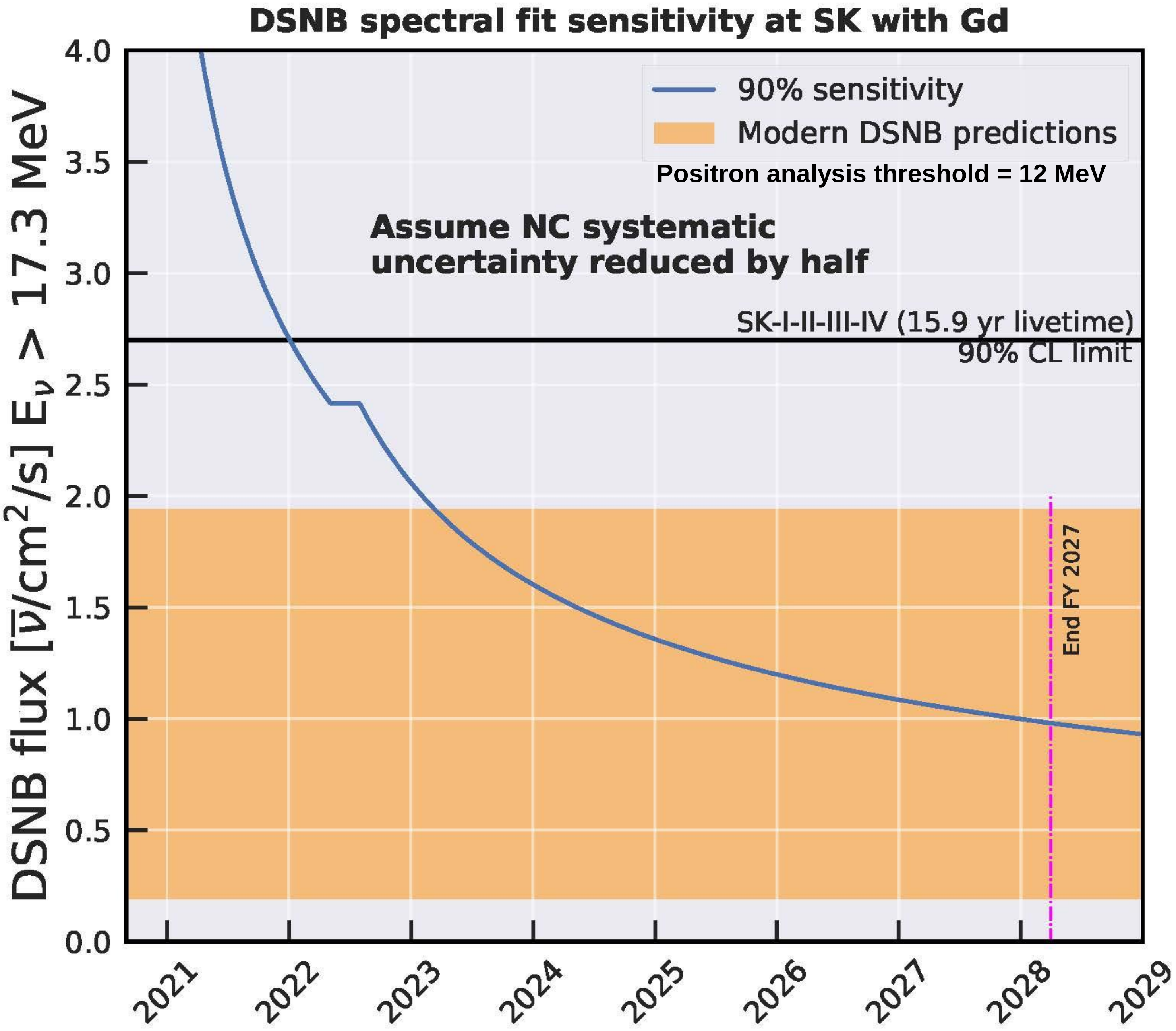
H = 0.33

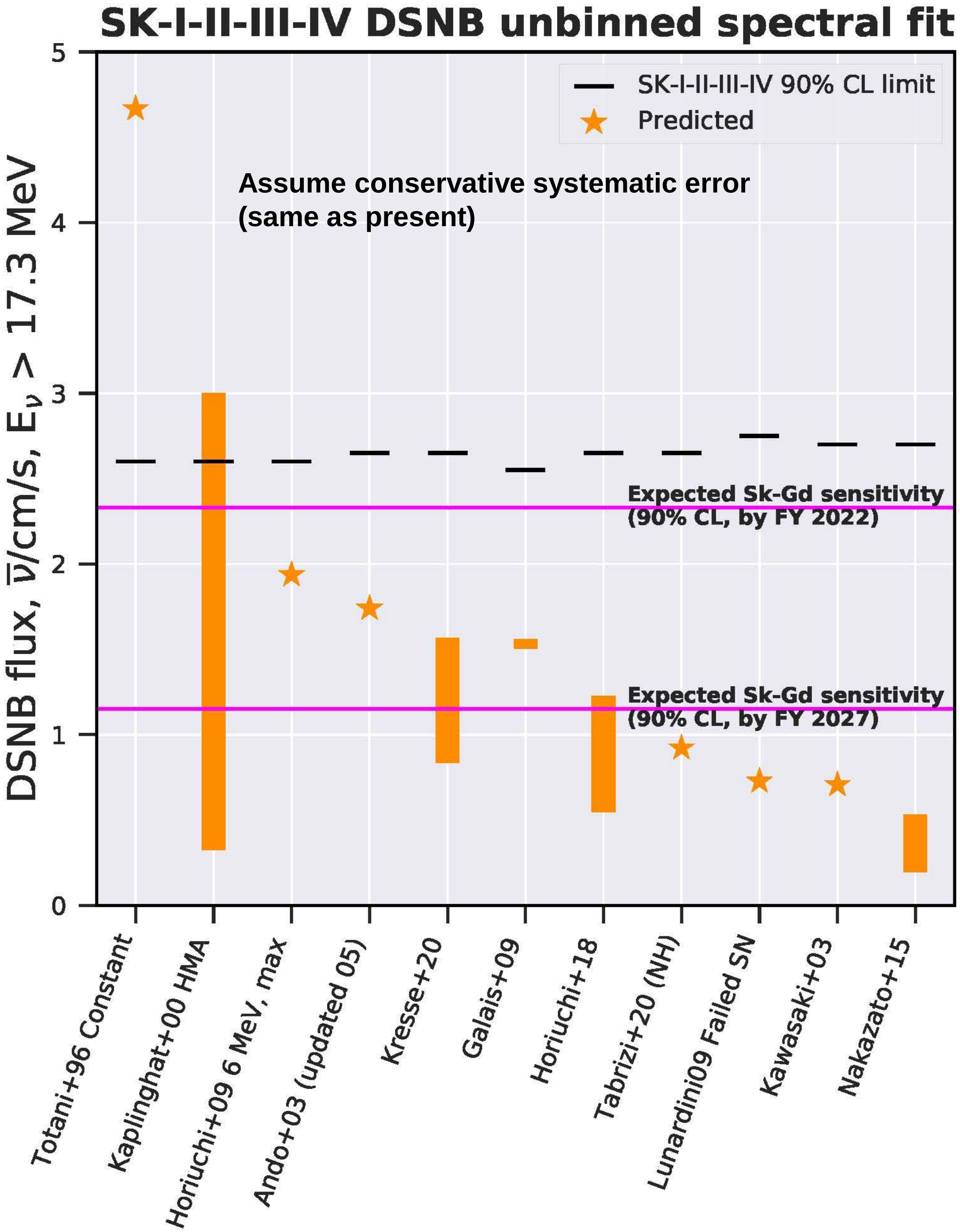
O = 0.0002



Positron analysis threshold = 12 MeV

Assume conservative systematic error (same as present)

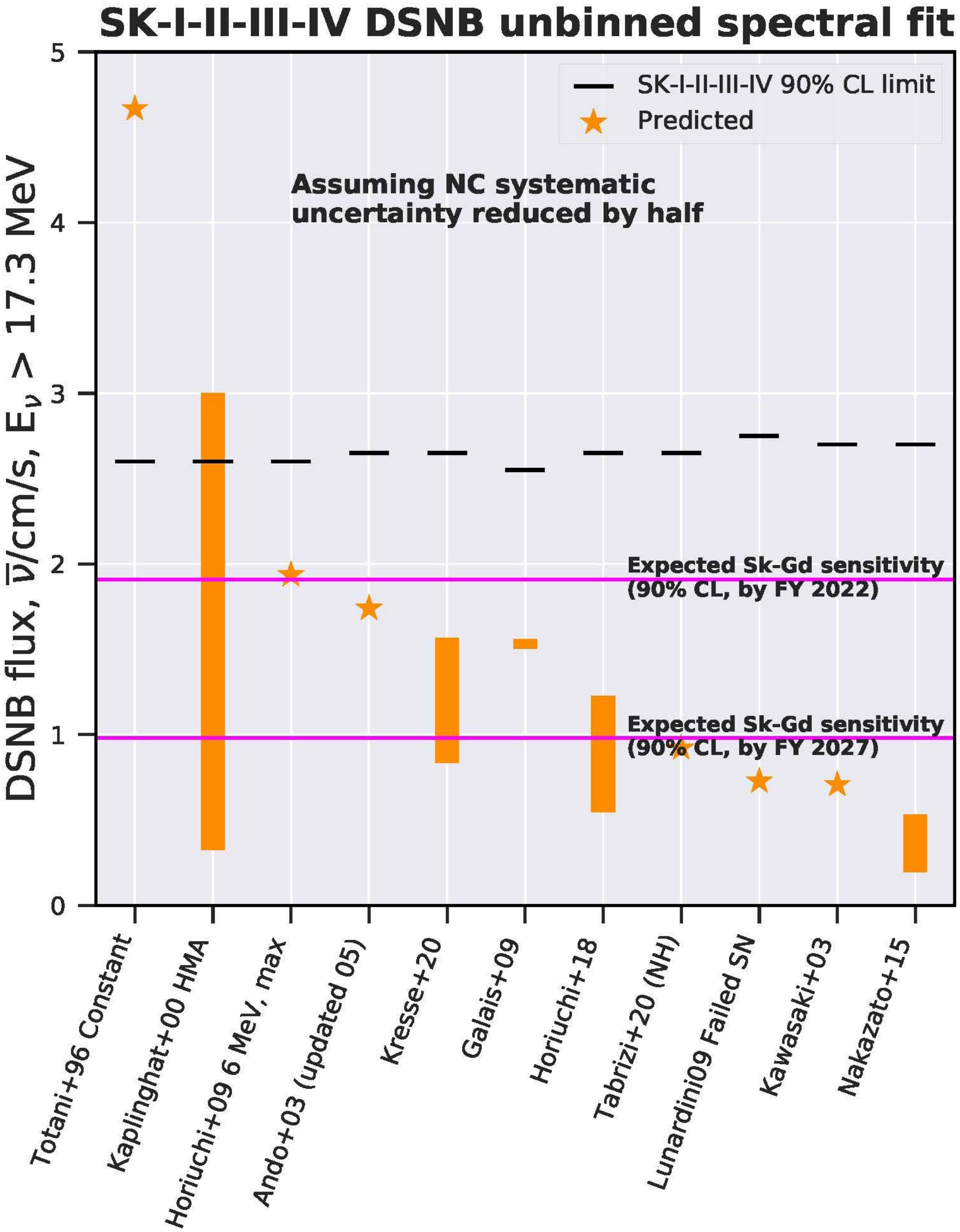

DSNB spectral fit sensitivity at SK with Gd
90% sensitivity
Modern DSNB predictions
Positron analysis threshold = 12 MeV
Assume NC systematic uncertainty reduced by half
SK-I-II-III-IV (15.9 yr livetime) 90% CL limit
End FY 2027
DSNB flux [$\overline{\nu}$/cm^2/s] E$_\nu$ > 17.3 MeV
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
2021
2022
2023
2024
2025
2026
2027
2028
2029



Assume conservative systematic error
(same as present)

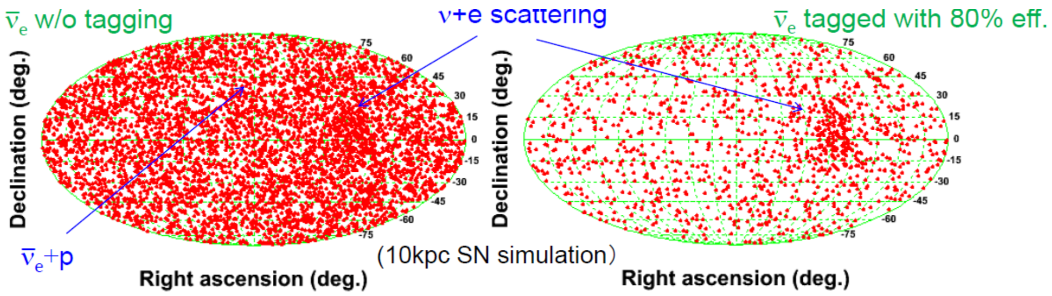
Expected Sk-Gd sensitivity
(90% CL, by FY 2022)

Expected Sk-Gd sensitivity
(90% CL, by FY 2027)


SK-I-II-III-IV DSNB unbinned spectral fit
SK-I-II-III-IV 90% CL limit
Predicted
Assuming NC systematic uncertainty reduced by half
Expected Sk-Gd sensitivity (90% CL, by FY 2022)
Expected Sk-Gd sensitivity (90% CL, by FY 2027)
DSNB flux, $\overline{\nu}$/cm/s, E_ν > 17.3 MeV
0
1
2
3
4
5
Totani+96 Constant
Kaplinghat+00 HMA
Horiuchi+09 6 MeV, max
Ando+03 (updated 05)
Kresse+20
Galais+09
Horiuchi+18
Tabrizi+20 (NH)
Lunardini09 Failed SN
Kawasaki+03
Nakazato+15

In addition to making the DSNB visible, 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 pure IBD sample.
- Instantly identifies a burst as genuine via “Gd heartbeat”.
- Increases the ES pointing accuracy.

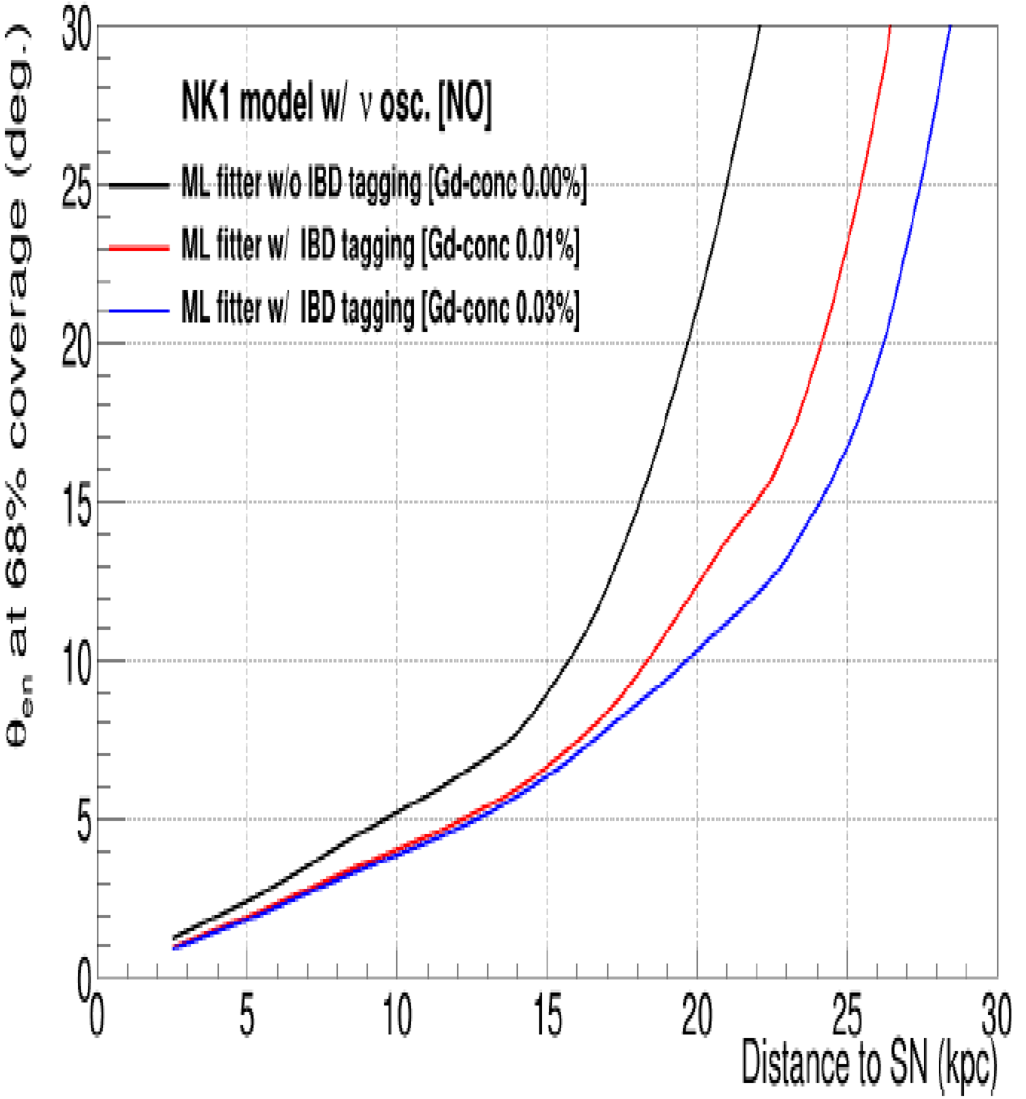


(10kpc SN simulation)

- 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.

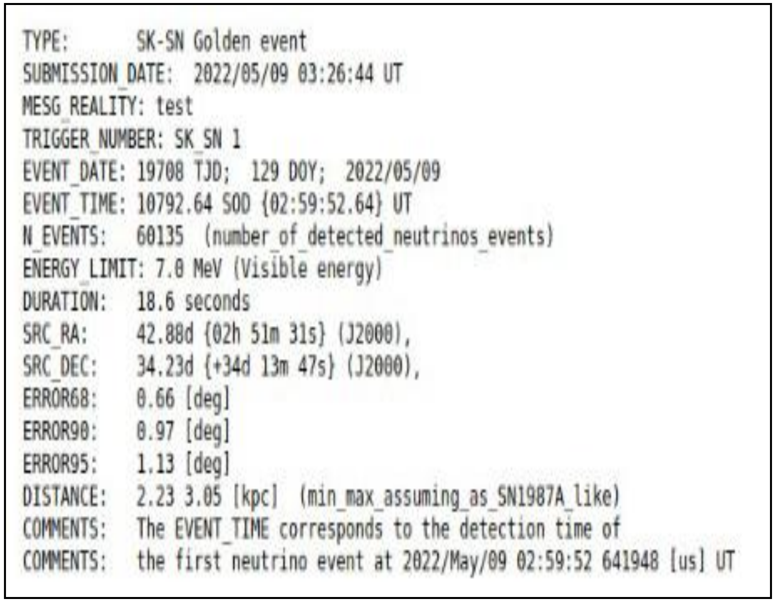
[see arXiv:2205.09881v1 [hep-ex]]

SNWatch angular resolution



Due to the increased confidence provided by Gd-tagging the IBD events, since December 2021 Super-K has been sending fully automated SN burst alerts to GCN.

Here's the output of our latest test:

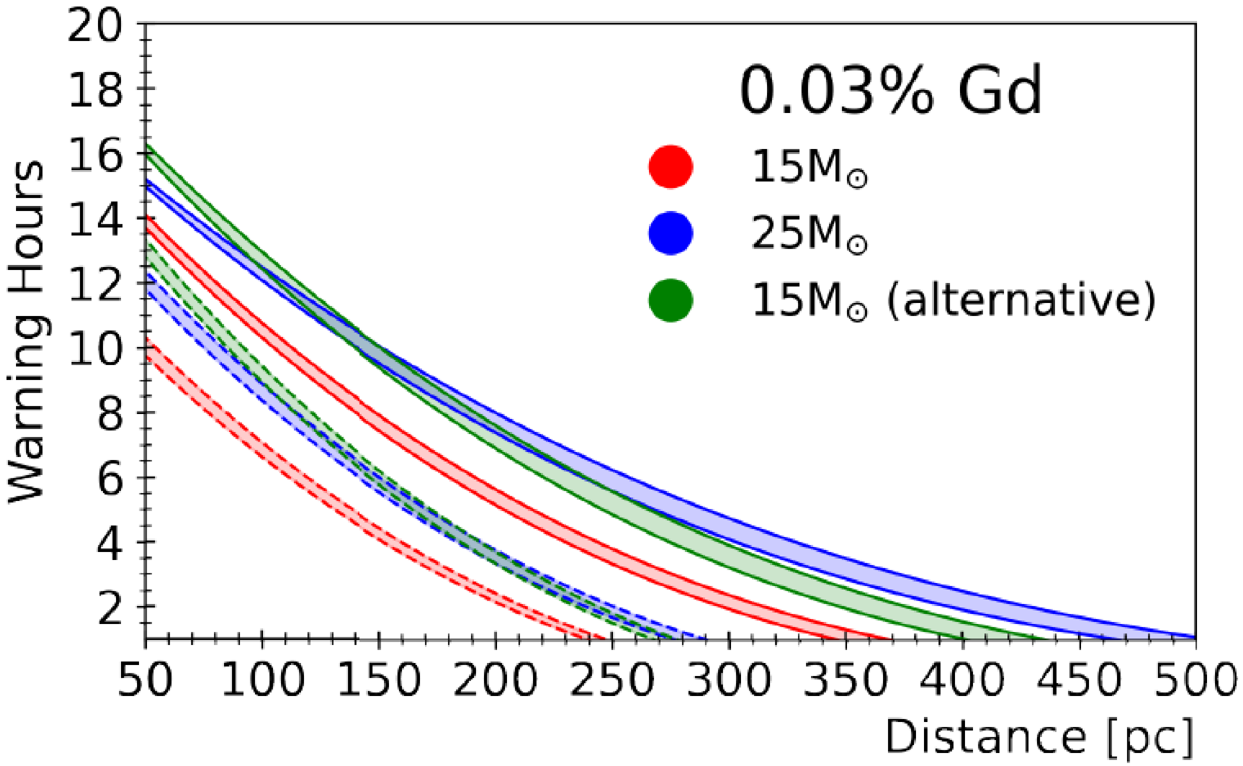


```
TYPE:          SK-SN Golden event
SUBMISSION_DATE:  2022/05/09 03:26:44 UT
MESG_REALITY: test
TRIGGER_NUMBER: SK_SN 1
EVENT_DATE: 19708 TJD;  129 DOY;  2022/05/09
EVENT_TIME: 10792.64 SOD {02:59:52.64} UT
N_EVENTS:   60135  (number_of_detected_neutrinos_events)
ENERGY_LIMIT: 7.0 MeV (Visible energy)
DURATION:   18.6 seconds
SRC_RA:     42.88d {02h 51m 31s} (J2000),
SRC_DEC:    34.23d {+34d 13m 47s} (J2000),
ERROR68:    0.66 [deg]
ERROR90:    0.97 [deg]
ERROR95:    1.13 [deg]
DISTANCE:   2.23 3.05 [kpc]  (min_max_assuming_as_SN1987A_like)
COMMENTS:   The EVENT_TIME corresponds to the detection time of
COMMENTS:   the first neutrino event at 2022/May/09 02:59:52 641948 [us] UT
```

Latency is currently on the order of minutes; reconstruction improvements ongoing with goal of <1 minute

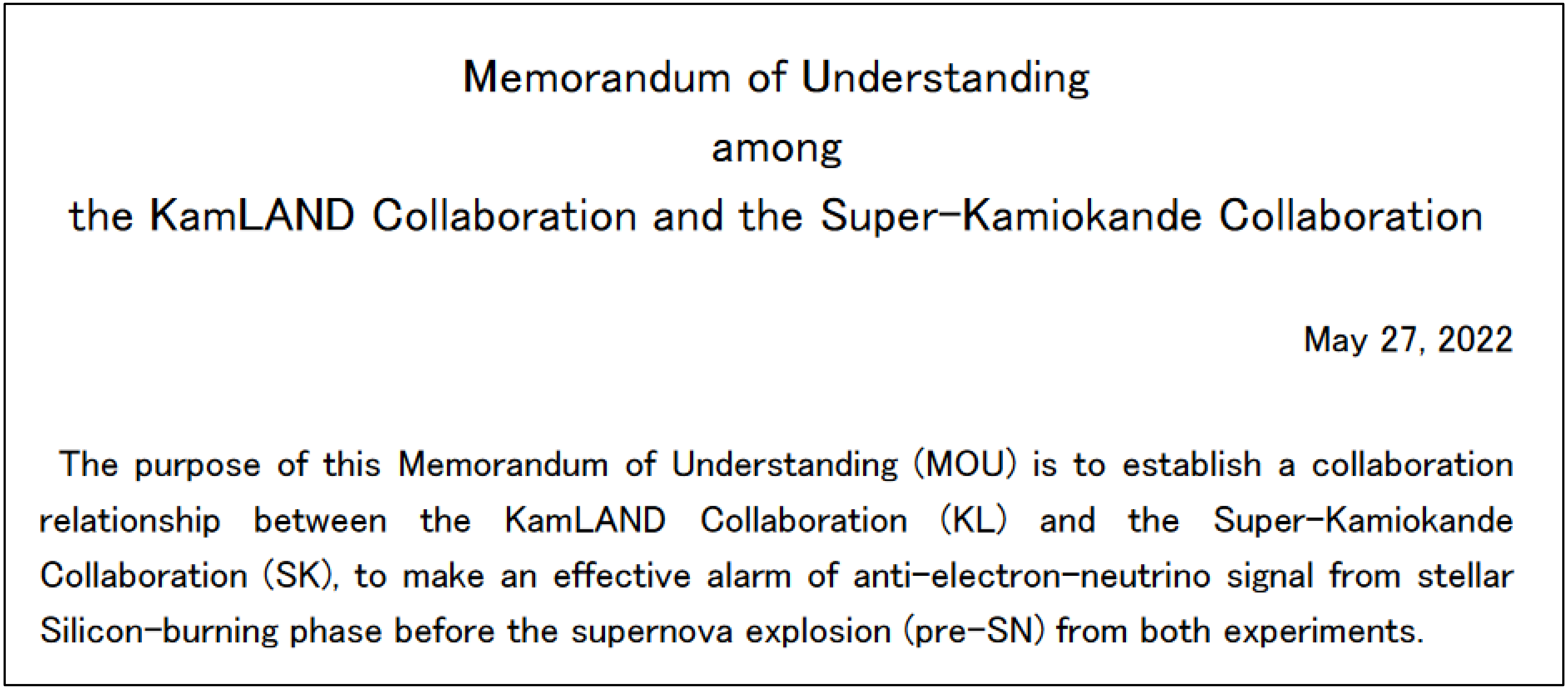
Pre-SN (Silicon Burning) Alert

For very nearby massive stars, gadolinium will allow Super-K to identify a star that is in its final stages of fusion and about to collapse. An online system - distinct from the SNWatch burst alarm - has been operational since October 2021.



Solid lines = normal neutrino mass hierarchy
Dashed lines = inverted neutrino mass hierarchy.
Baseline model (15 M☉ and 25 M☉) = Odrzywolek & Heger 2010
Alternative model (15 M☉ only) = Patton et al. 2017
The bands reflect variations in Japanese nuclear power reactor activity.

Pre-SN (Silicon Burning) Alert:
MOU Between KamLAND and Super-Kamiokande



Memorandum of Understanding

among

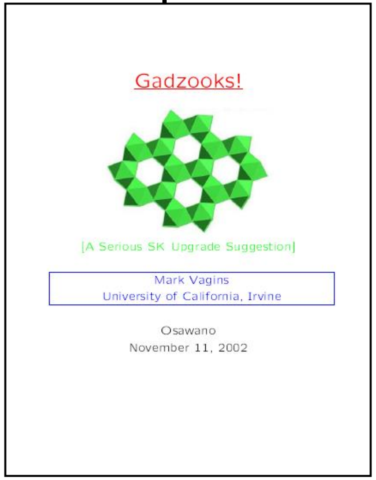
the KamLAND Collaboration and the Super-Kamiokande Collaboration

May 27, 2022

The purpose of this Memorandum of Understanding (MOU) is to establish a collaboration relationship between the KamLAND Collaboration (KL) and the Super-Kamiokande Collaboration (SK), to make an effective alarm of anti-electron-neutrino signal from stellar Silicon-burning phase before the supernova explosion (pre-SN) from both experiments.

What a Long, Strange Trip It's Been…

Gd Loading Of SK First Proposed



Gadzooks!

[A Serious SK Upgrade Suggestion]

Mark Vagins
University of California, Irvine

Osawano
November 11, 2002

First Gd Loading Of SK

First Gadolinium Loading to Super-Kamiokande

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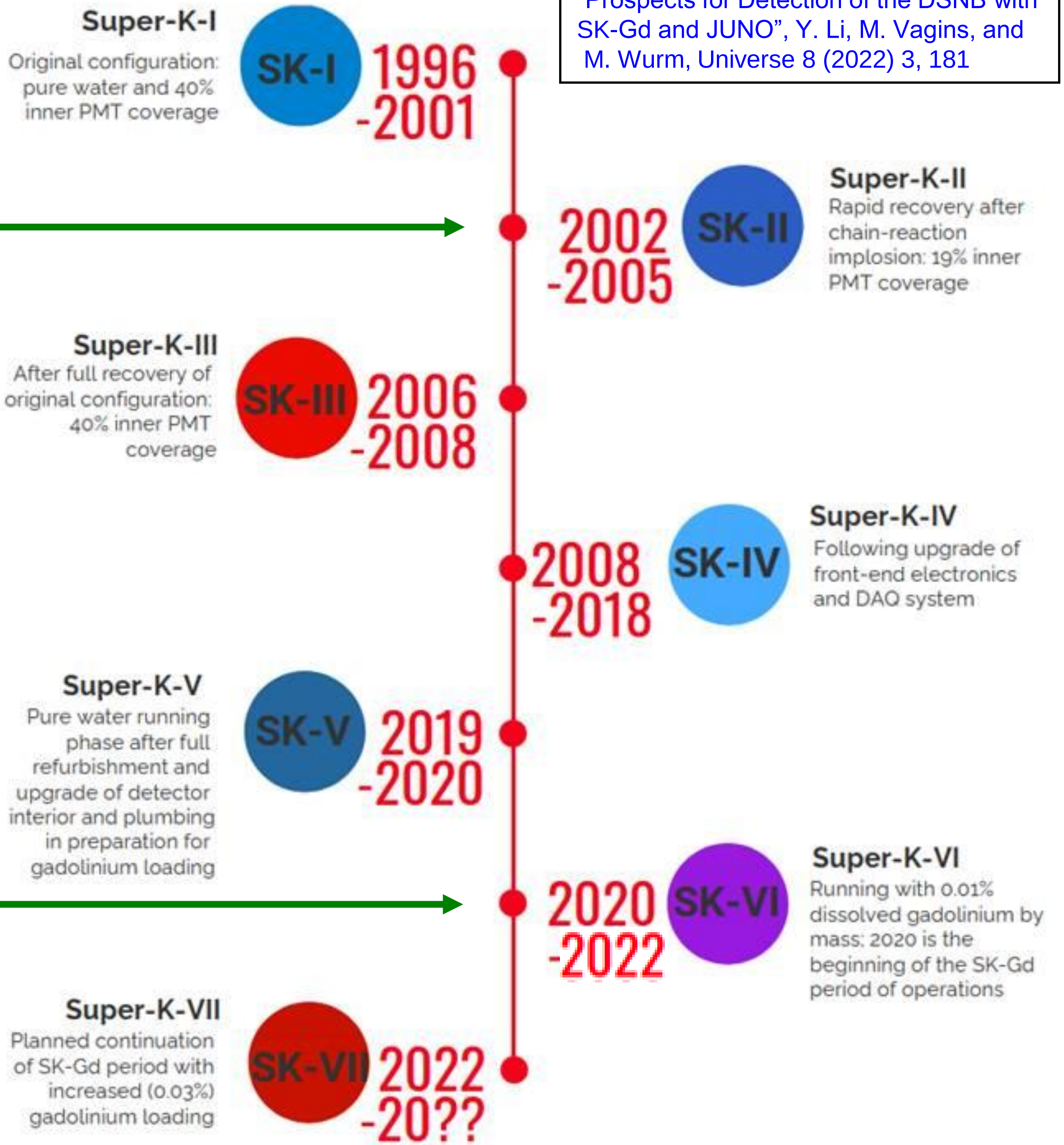
"Prospects for Detection of the DSNB with SK-Gd and JUNO", Y. Li, M. Vagins, and M. Wurm, Universe 8 (2022) 3, 181



Super-K-I
Original configuration: pure water and 40% inner PMT coverage

SK-I 1996 -2001

Super-K-II
Rapid recovery after chain-reaction implosion: 19% inner PMT coverage

SK-II 2002 -2005

Super-K-III
After full recovery of original configuration: 40% inner PMT coverage

SK-III 2006 -2008

Super-K-IV
Following upgrade of front-end electronics and DAQ system

SK-IV 2008 -2018

Super-K-V
Pure water running phase after full refurbishment and upgrade of detector interior and plumbing in preparation for gadolinium loading

SK-V 2019 -2020

Super-K-VI
Running with 0.01% dissolved gadolinium by mass: 2020 is the beginning of the SK-Gd period of operations

SK-VI 2020 -2022

Super-K-VII
Planned continuation of SK-Gd period with increased (0.03%) gadolinium loading

SK-VII 2022 -20??

While Super-Kamiokande waits for the next galactic supernova explosion - very nearby or otherwise - gadolinium now allows us to continuously collect SN ν's from explosions halfway across the universe.

For the past two years we have been taking data with what is essentially a completely new SK enriched with 0.01% Gd, positively impacting many physics topics. The next phase - utilizing three times as much Gd - has just begun, with its concentration being increased at this very minute.

SK is looking to have evidence of the world's first diffuse supernova neutrino signal within the next few years!