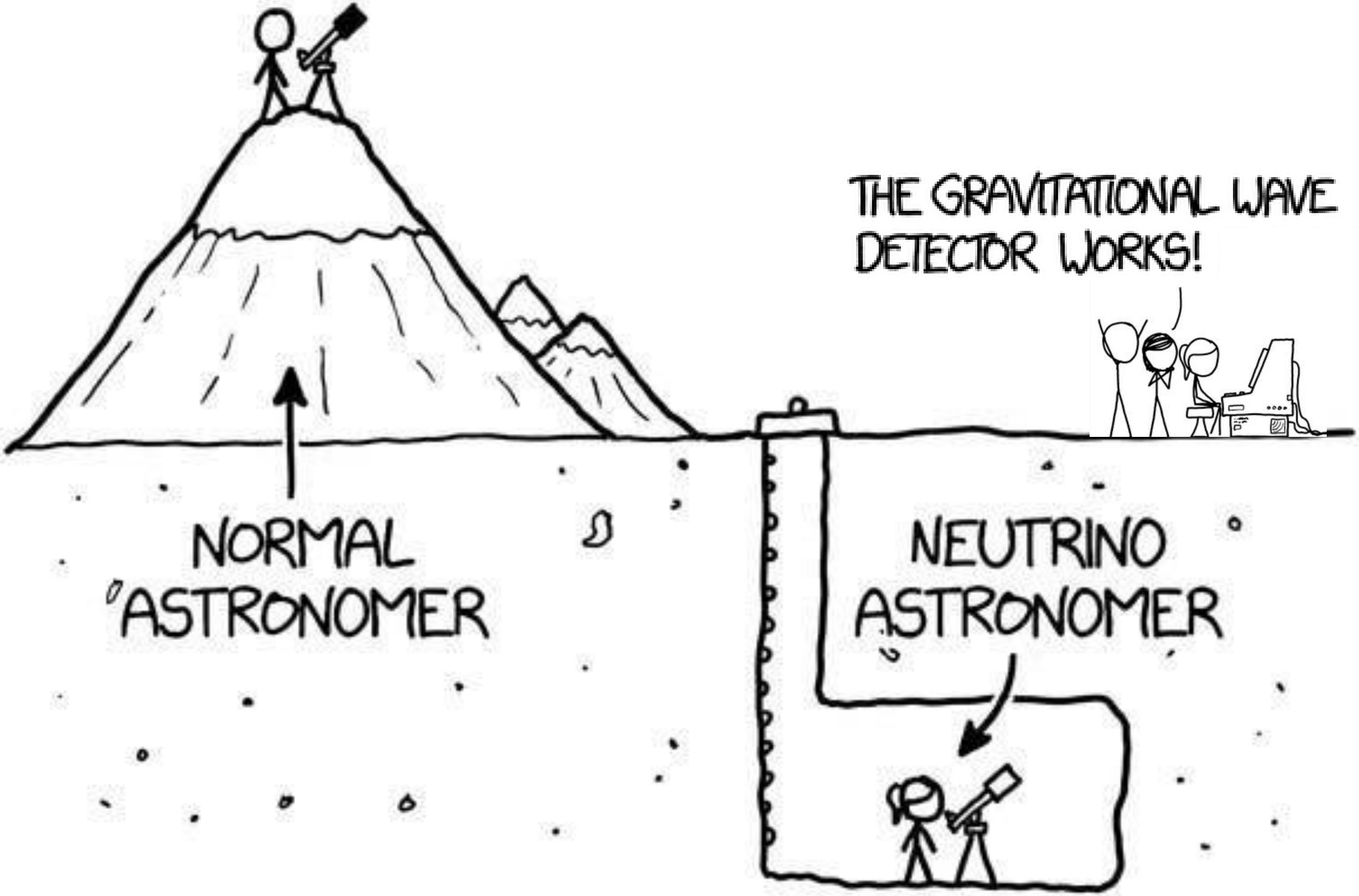
Hyper-Kamiokande Looks to the Heavens

Mark Vagins
Kavli IPMU, UTokyo

Towards the Detection of Diffuse Supernova Neutrinos Workshop

MITP, Mainz September 19, 2024

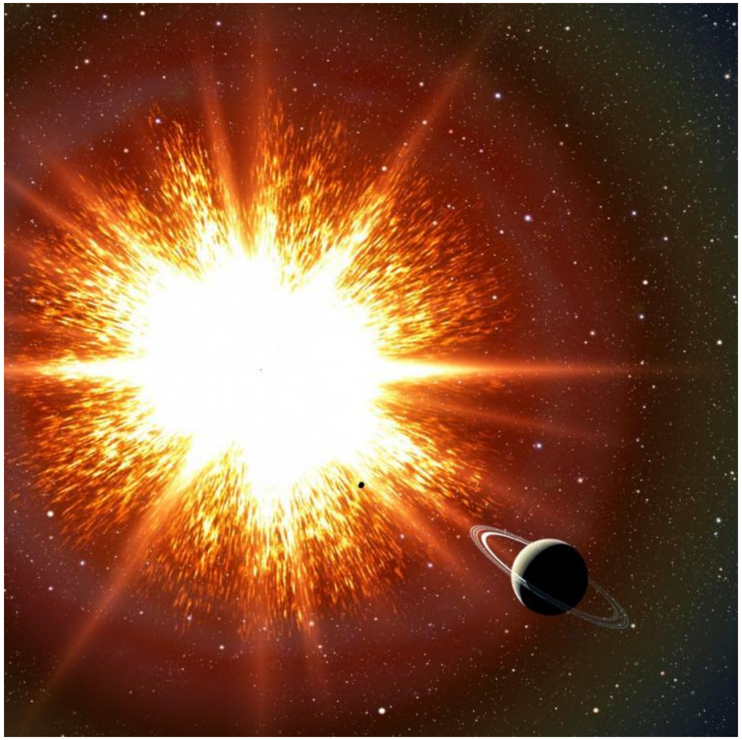
Multimessenger astronomy in a nutshell…

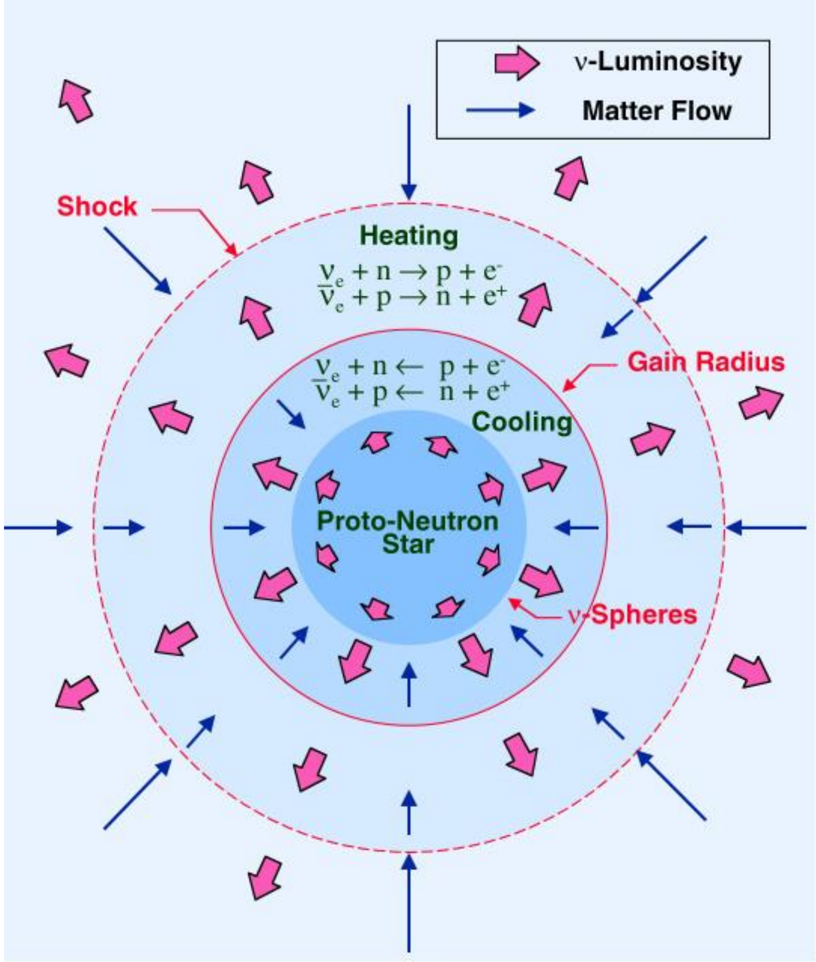


[image adapted from xkcd]

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.

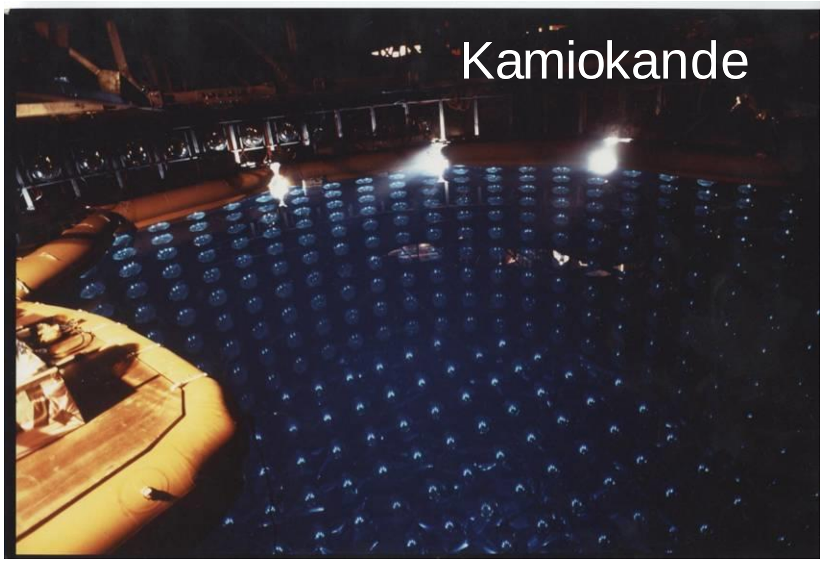


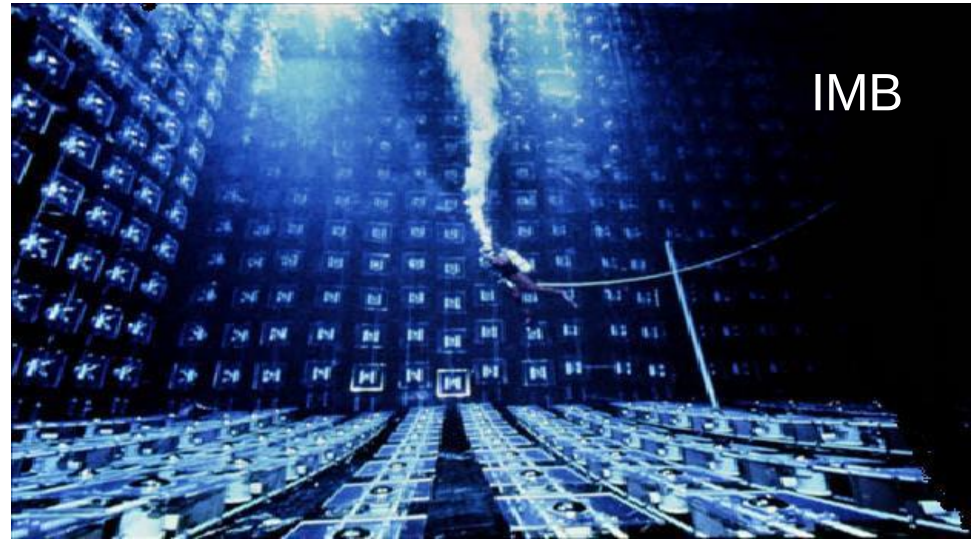


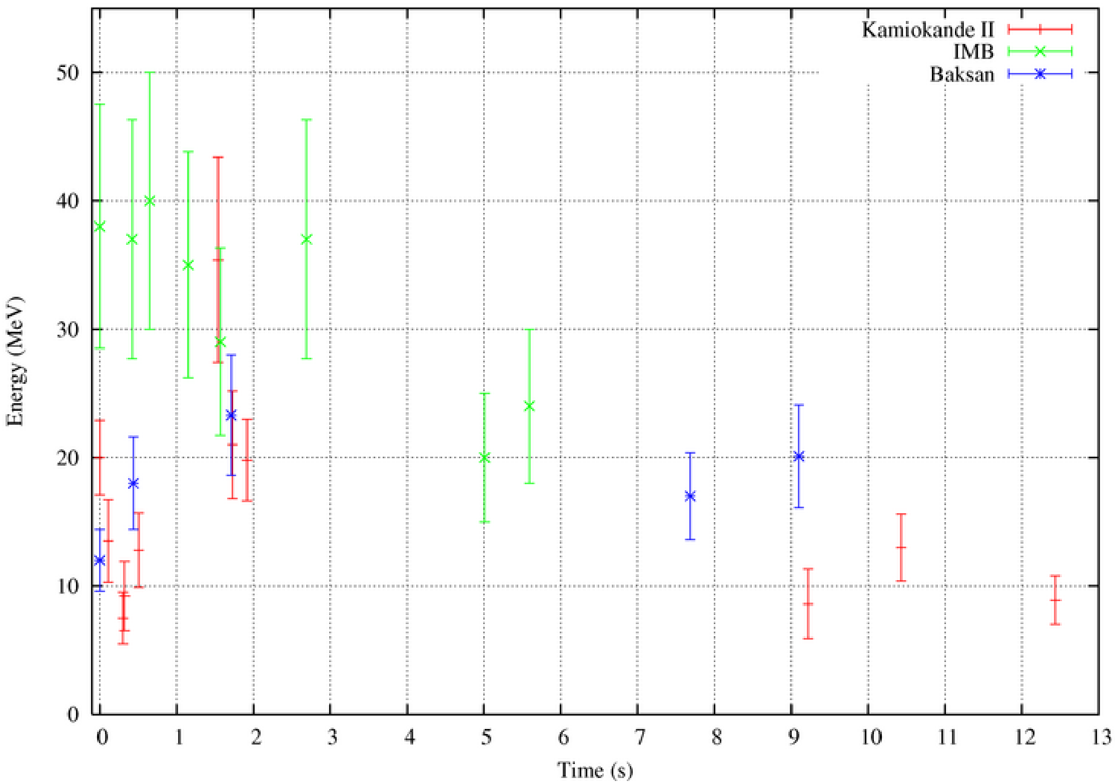
Neutrinos, and possibly gravitational waves, provide the only windows into core collapses' inner dynamics.

A long time ago, in a (neighbor) galaxy far, far away…

A long time ago, in a (neighbor) galaxy far, far away…


Kamiokande

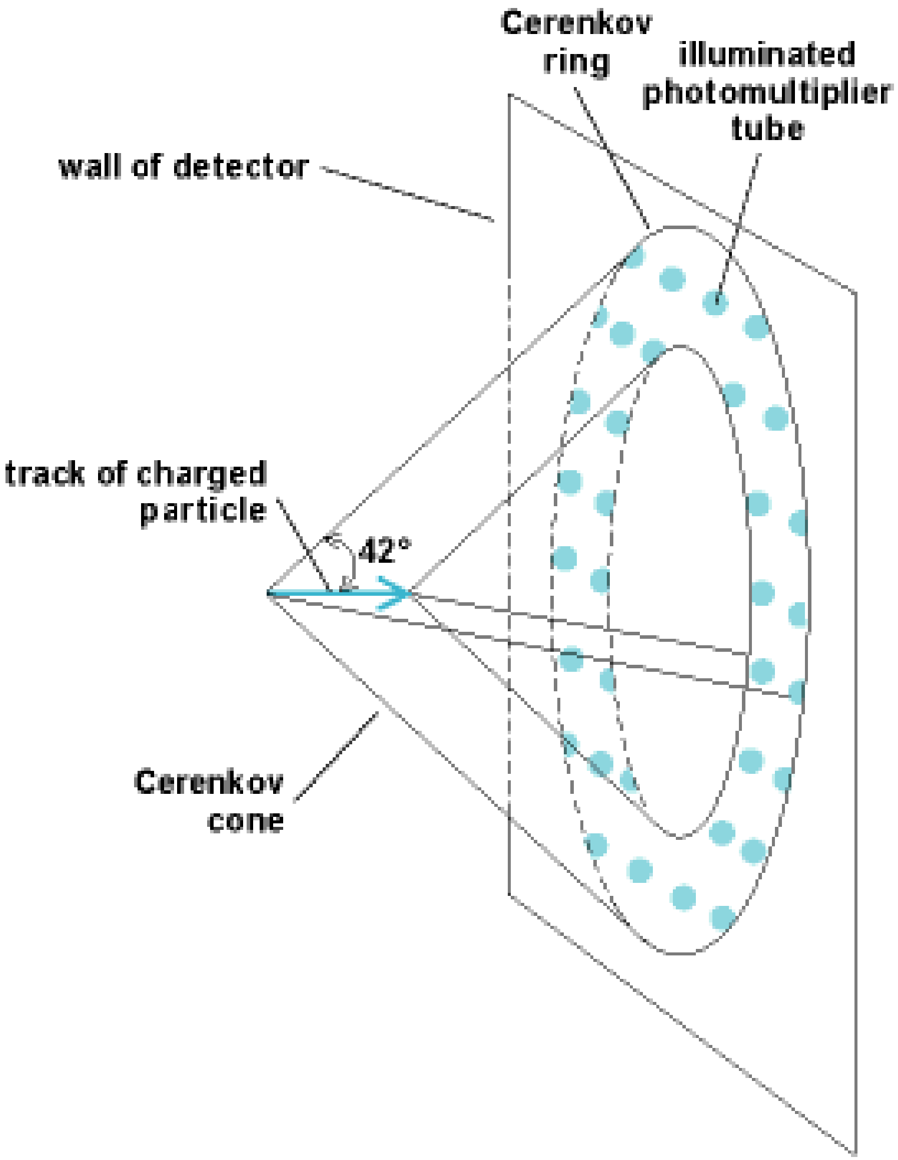

IMB

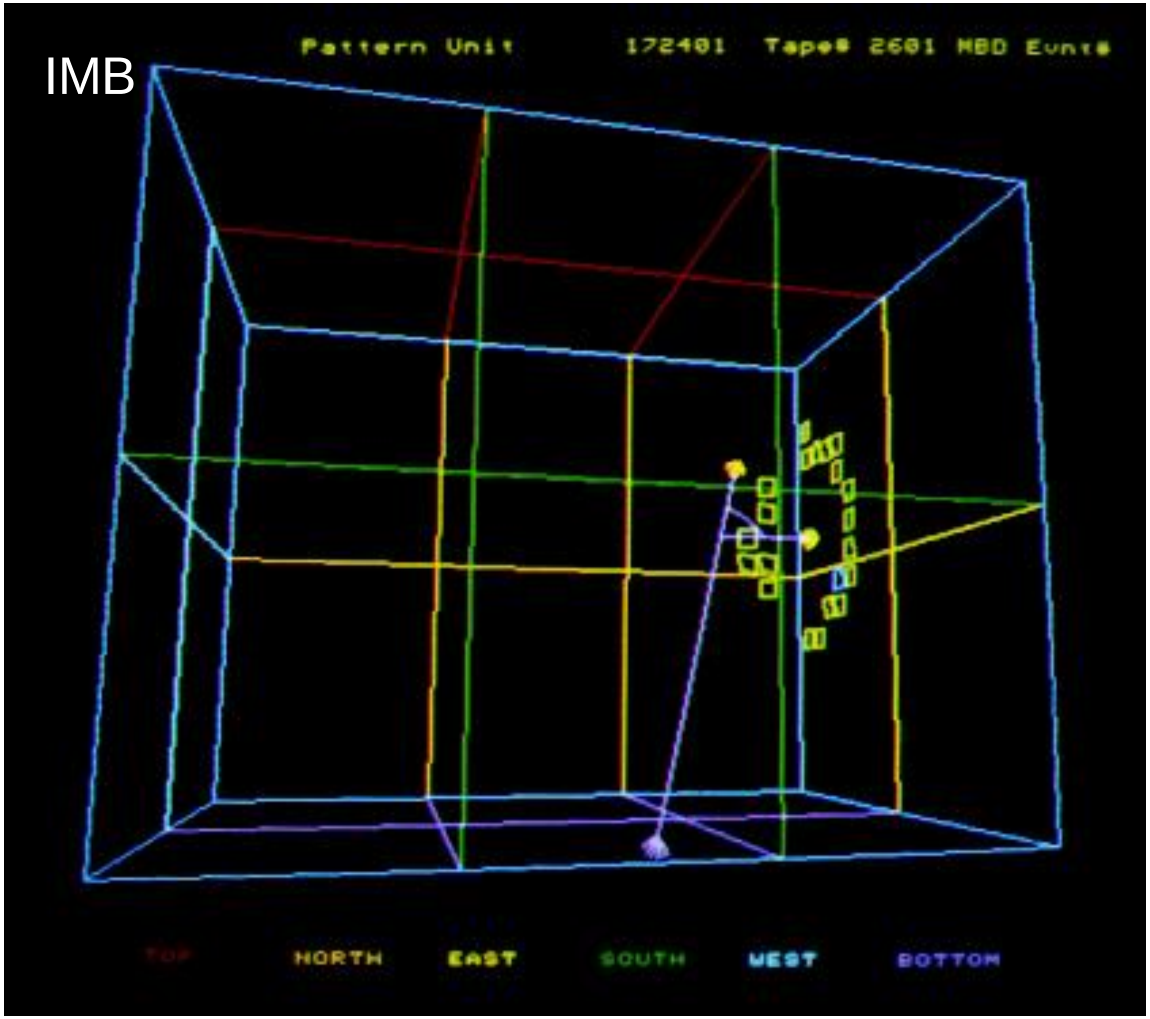

Kamiokande II
IMB
Baksan
Energy (MeV)
0
10
20
30
40
50
Time (s)
0
1
2
3
4
5
6
7
8
9
10
11
12
13

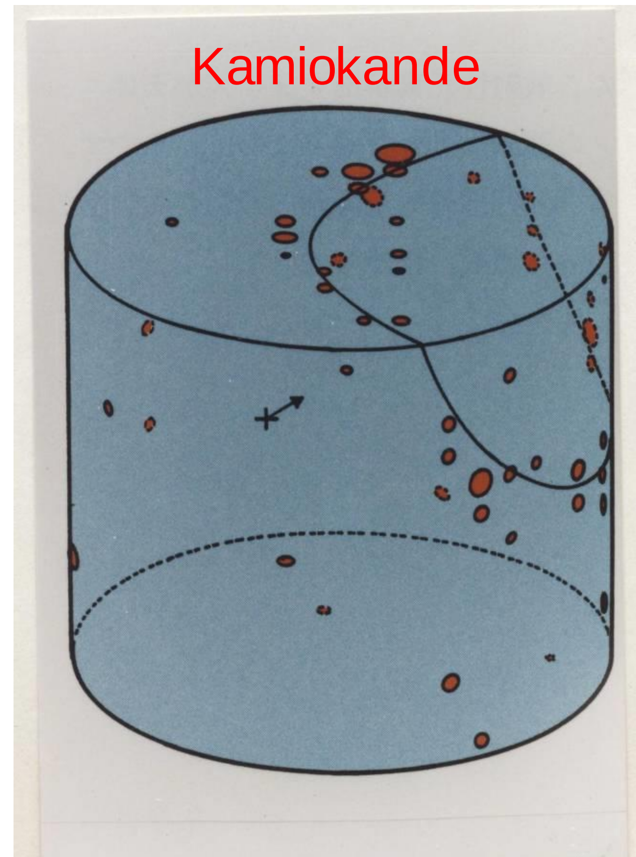

Baksan

Water Cherenkov detectors' principle of operation:

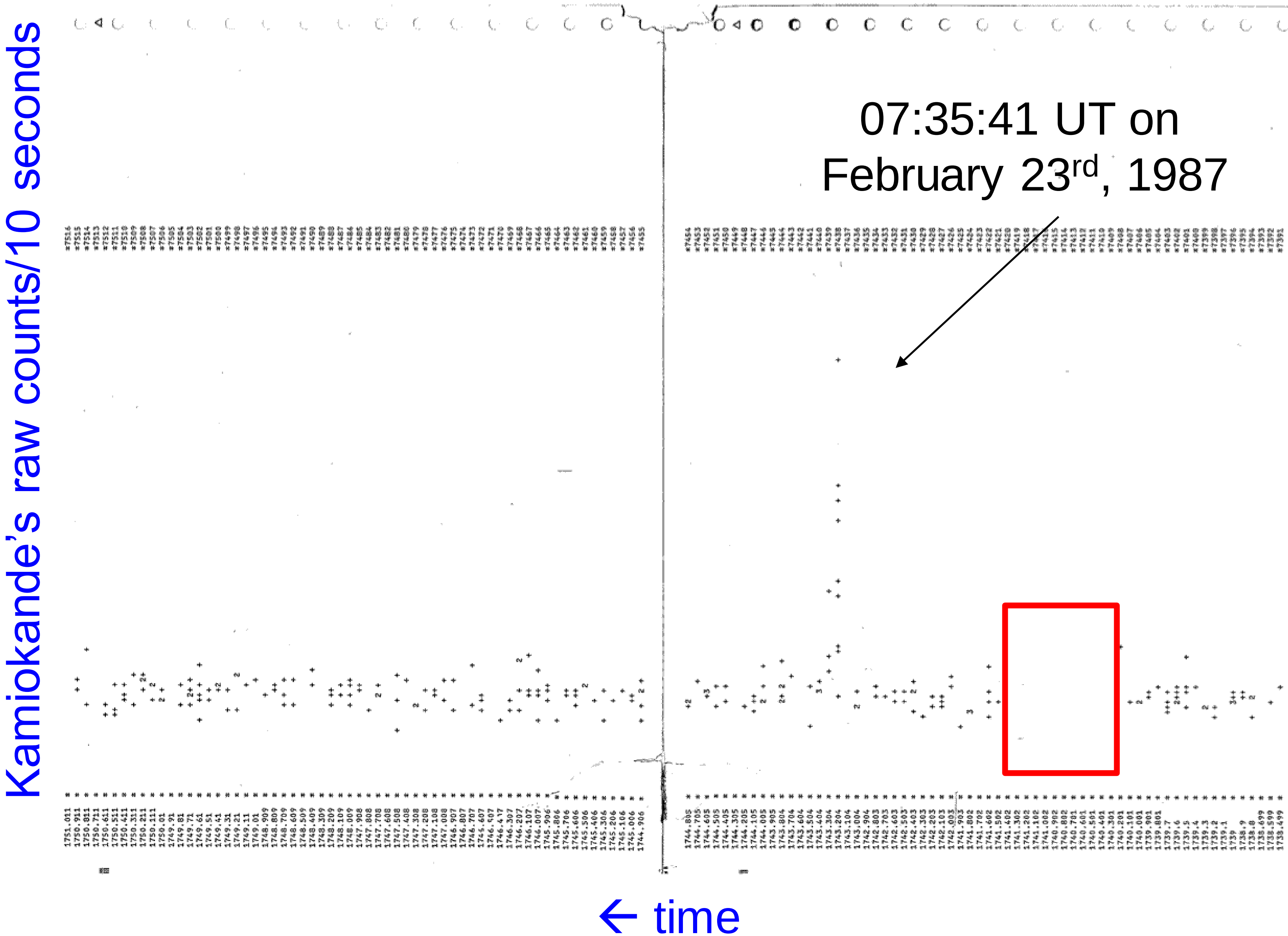
Relativistic charged particles make rings of light on the inner wall of the detector. The rings are then imaged by photomultiplier tubes.







Actual supernova neutrino events!


07:35:41 UT on
February 23rd, 1987
Kamiokande's raw counts/10 seconds
← time

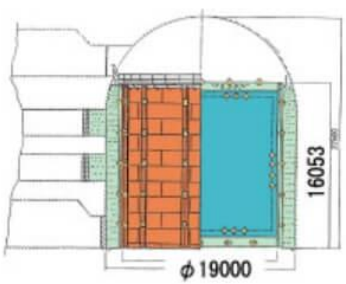
Kamiokande = Kamioka Nucleon Decay Experiment

Both IMB and Kamiokande had been built to discover proton decay based on SU(5) predictions.

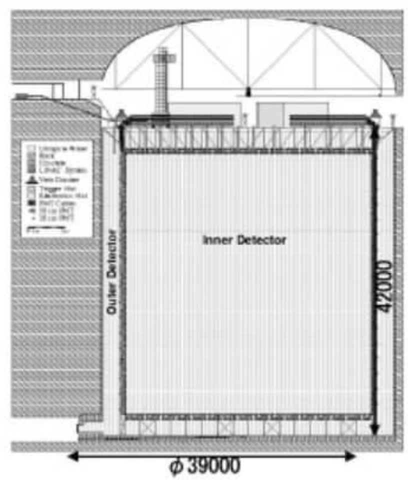
Super/Hyper-Kamiokande = Super/Hyper Kamioka Neutrino Detection Experiment

We're still looking for proton decay, but now neutrinos – atmospheric, solar, and supernova – are the undisputed stars of the show!

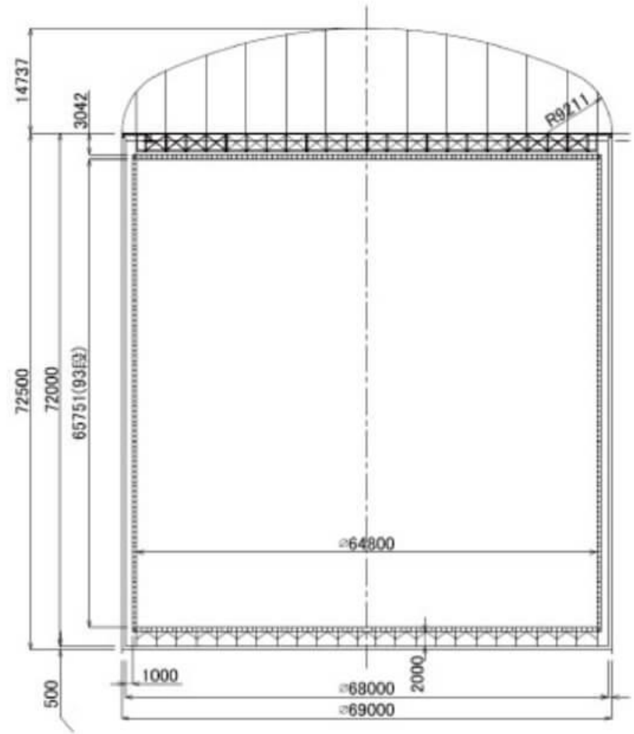
When collecting neutrinos, size definitely does matter!



Kamiokande
(1983-1996)



Super-Kamiokande
(1996-present)



Hyper-Kamiokande
(to be started in 2027)

3 kilotons → 50 kilotons → 258 kilotons

(1 kt fiducial) → (22.5 kt fiducial) → (178 kt fiducial)

HYPER-K COLLABORATION

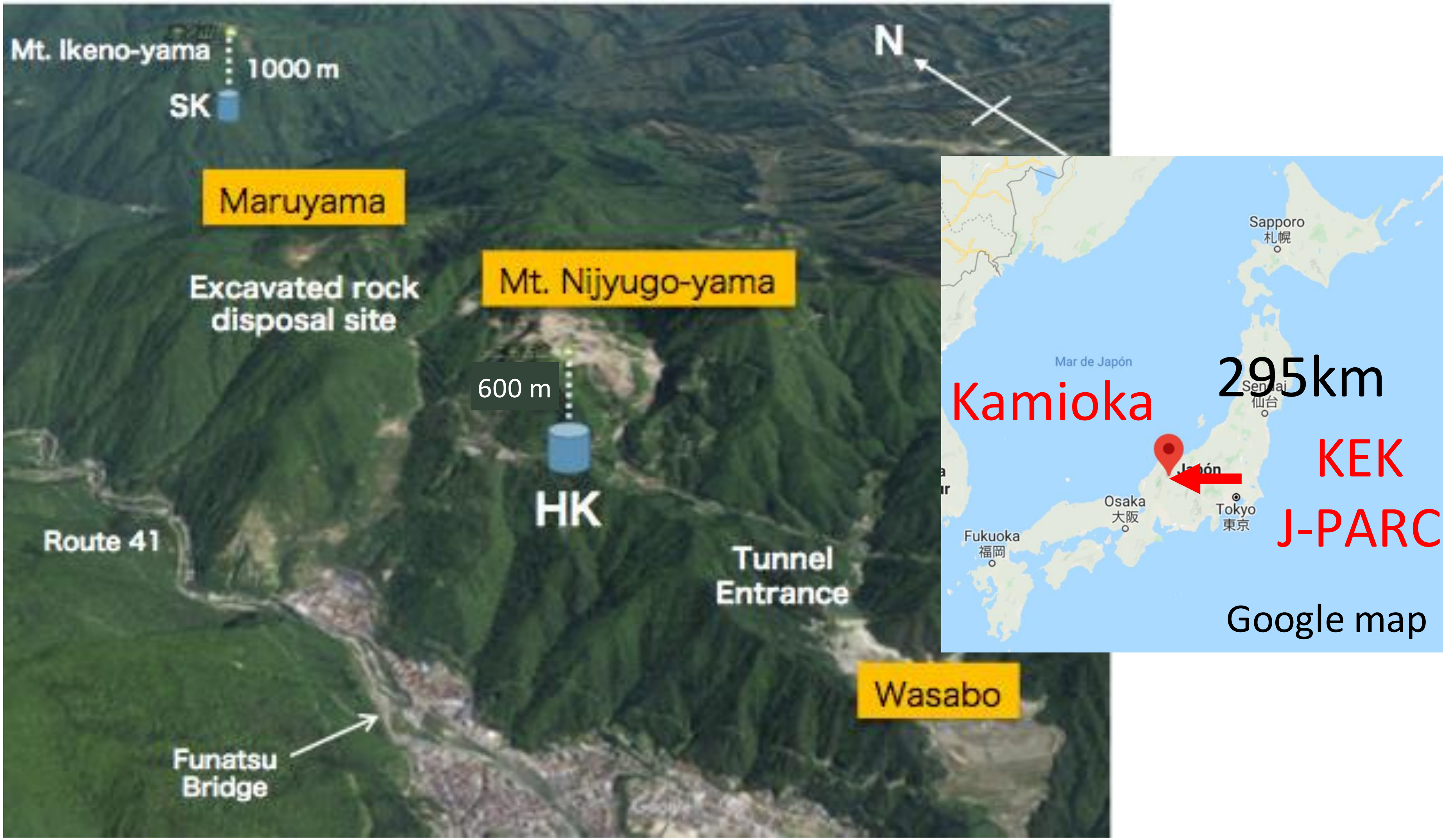
Broadening of the international collaboration

~600 collaborators (incl. 25% of Japanese), 22 countries, and 102 institutes.
Funding secured in several countries.

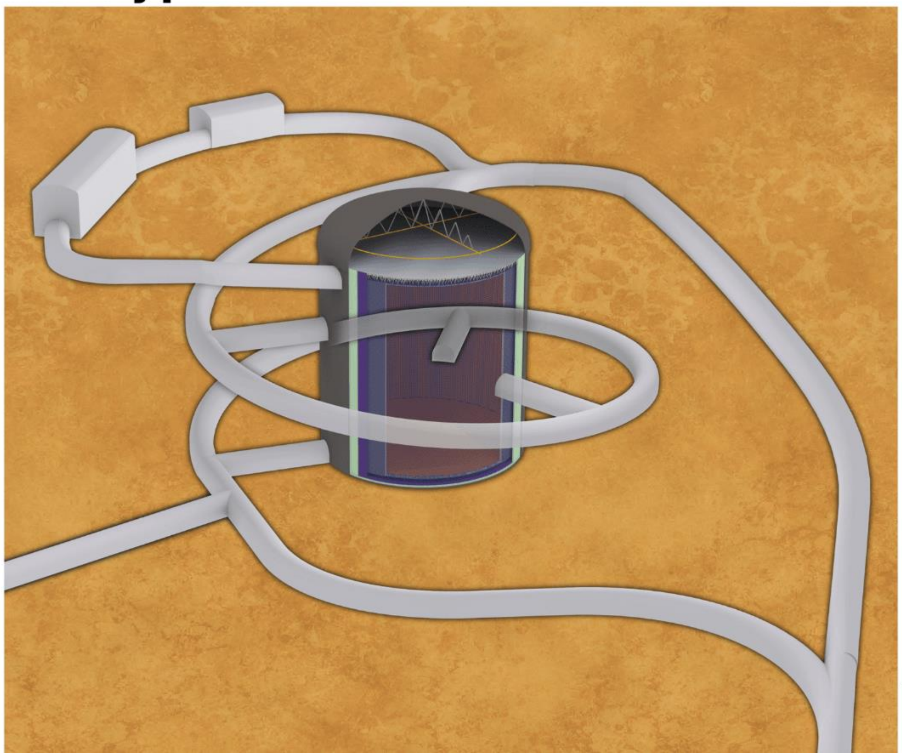
March 2023, 1st in-person Collaboration Meeting @ Toyama

Hyper-K Detector Location

- 8 km south of Super-K
- 295 km from J-PARC and 2.5 deg. off-axis beam (same as Super-K)
- 600 m rock overburden → 20 times SK's spallation rate



Schematic view of Hyper-Kamiokande detector



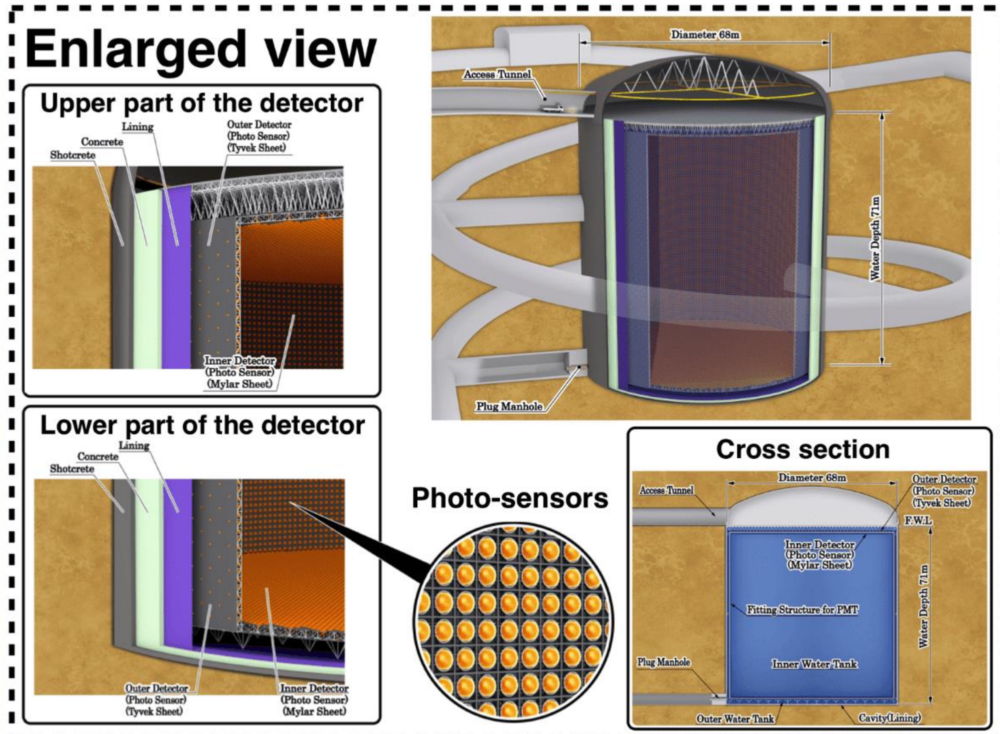
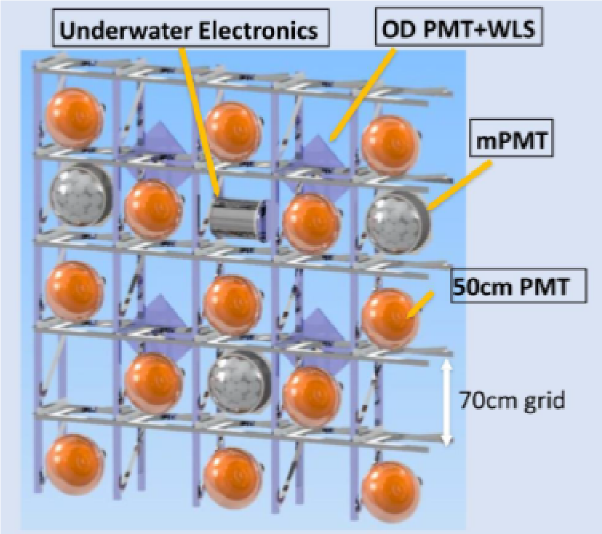
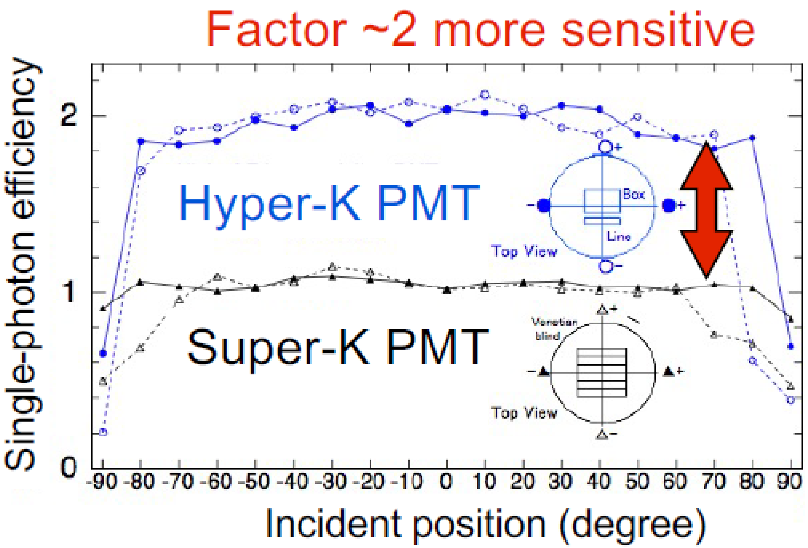


Photo-detection system

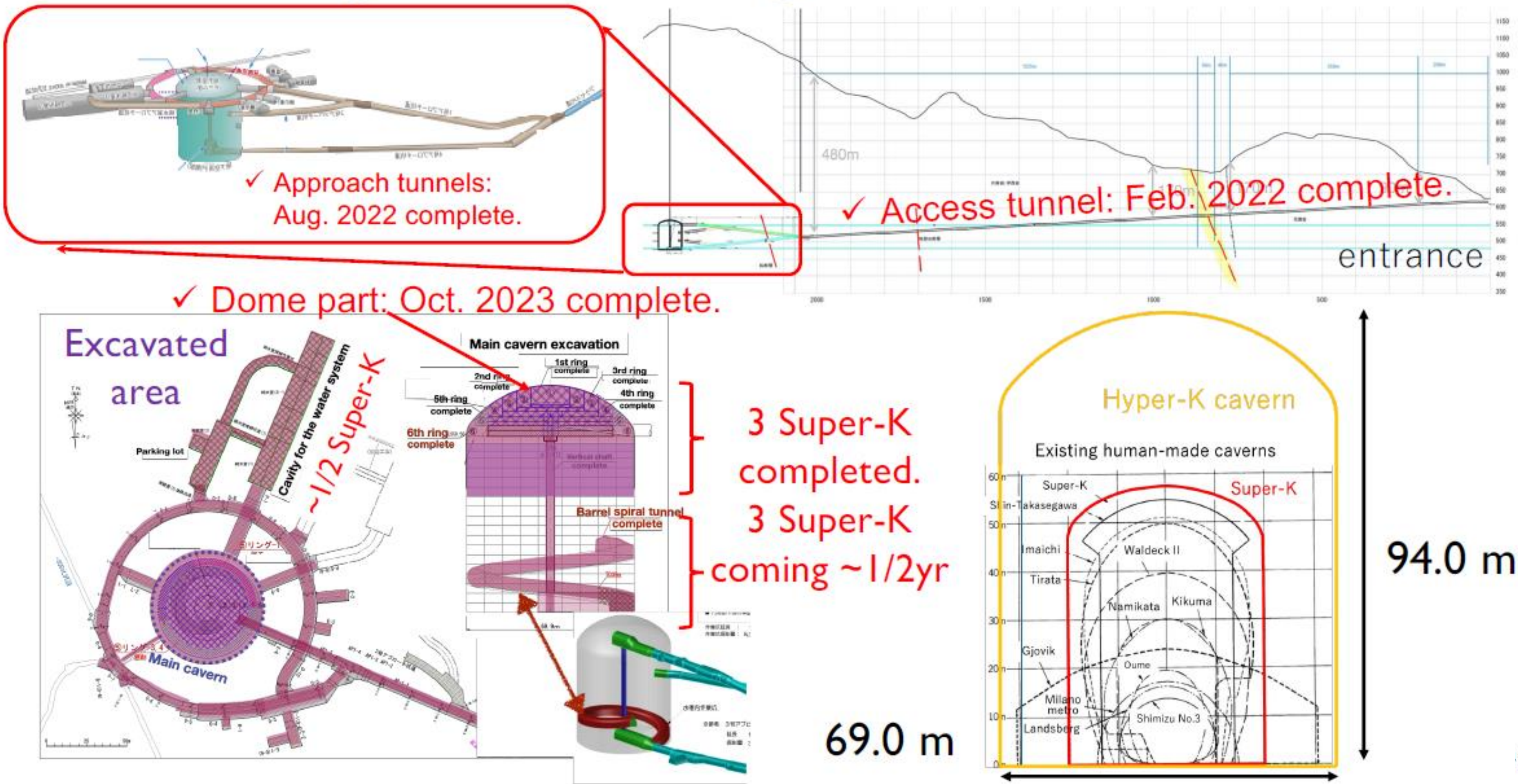
- Detailed design of the tank lining and photosensor support structure completed.



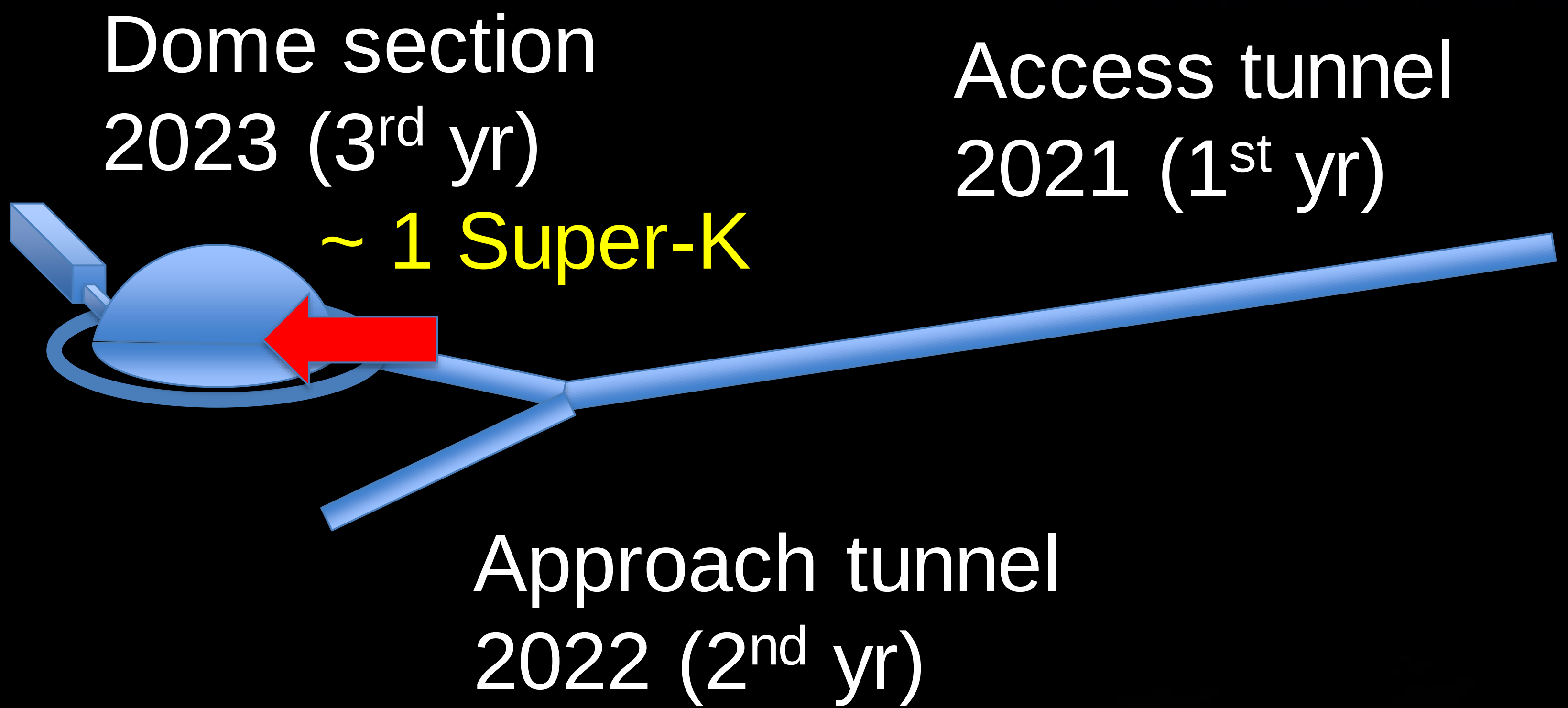


- New features of 50 cm PMT (B&L-dynode) include
  - High QE, T resolution, pressure tolerance (x2 better than Super-K)
  - dark rate reduction, low radioactivity, cover development
  - long-term performance evaluation already in Super-K
  - ➔ 20 000 of 50 cm PMTs from Japan

Excavating the world's largest human-made cavern



Construction history



Approved as a project in April 2020, Hyper-Kamiokande rock excavation is proceeding on schedule. All access tunnels have been dug, as well as the 69-meter-wide by 21-meter-tall dome, and the cavernous (1st) water system room.

Approved as a project in April 2020, Hyper-Kamiokande rock excavation is proceeding on schedule. All access tunnels have been dug, as well as the 69-meter-wide by 21-meter-tall dome, and the cavernous (1st) water system room.

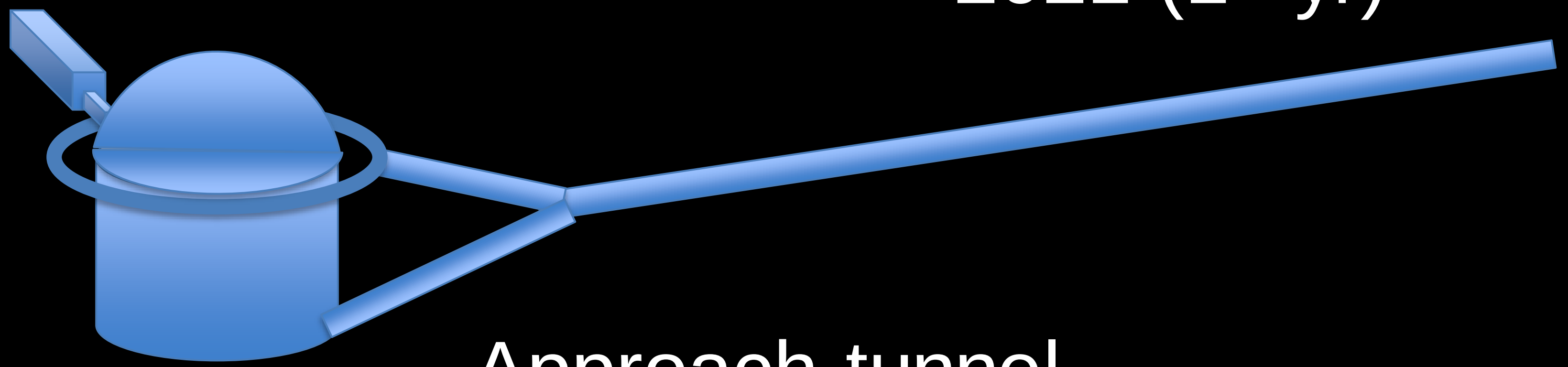
Barrel excavation is now rapidly proceeding and should be completed within 2024.

PMT production for Hyper-K is also underway

Screening of ~20,000 50-cm tubes is being conducted both at Hamamatsu and Kamioka

>10,000 PMTs already delivered to Kamioka

Construction plan



Dome section
2023 (3rd yr)

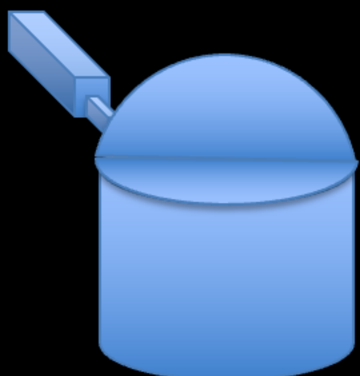
Access tunnel
2021 (1st yr)

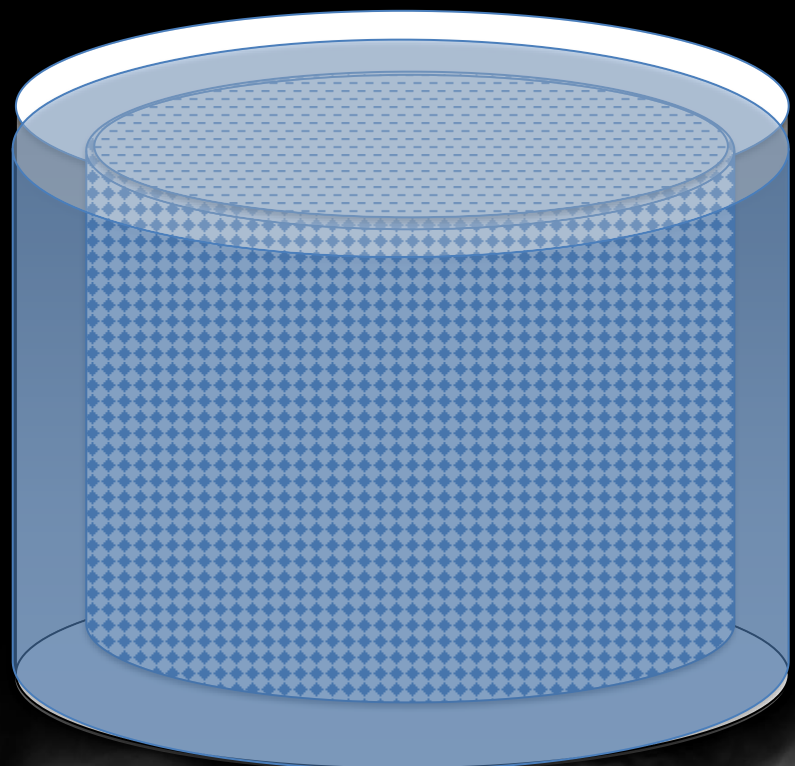
Approach tunnel
2022 (2nd yr)

Cylindrical sec.
2024 (4th yr)
~5 Super-K

Construction plan

Photosensor installation
2026 (6^{th} yr)

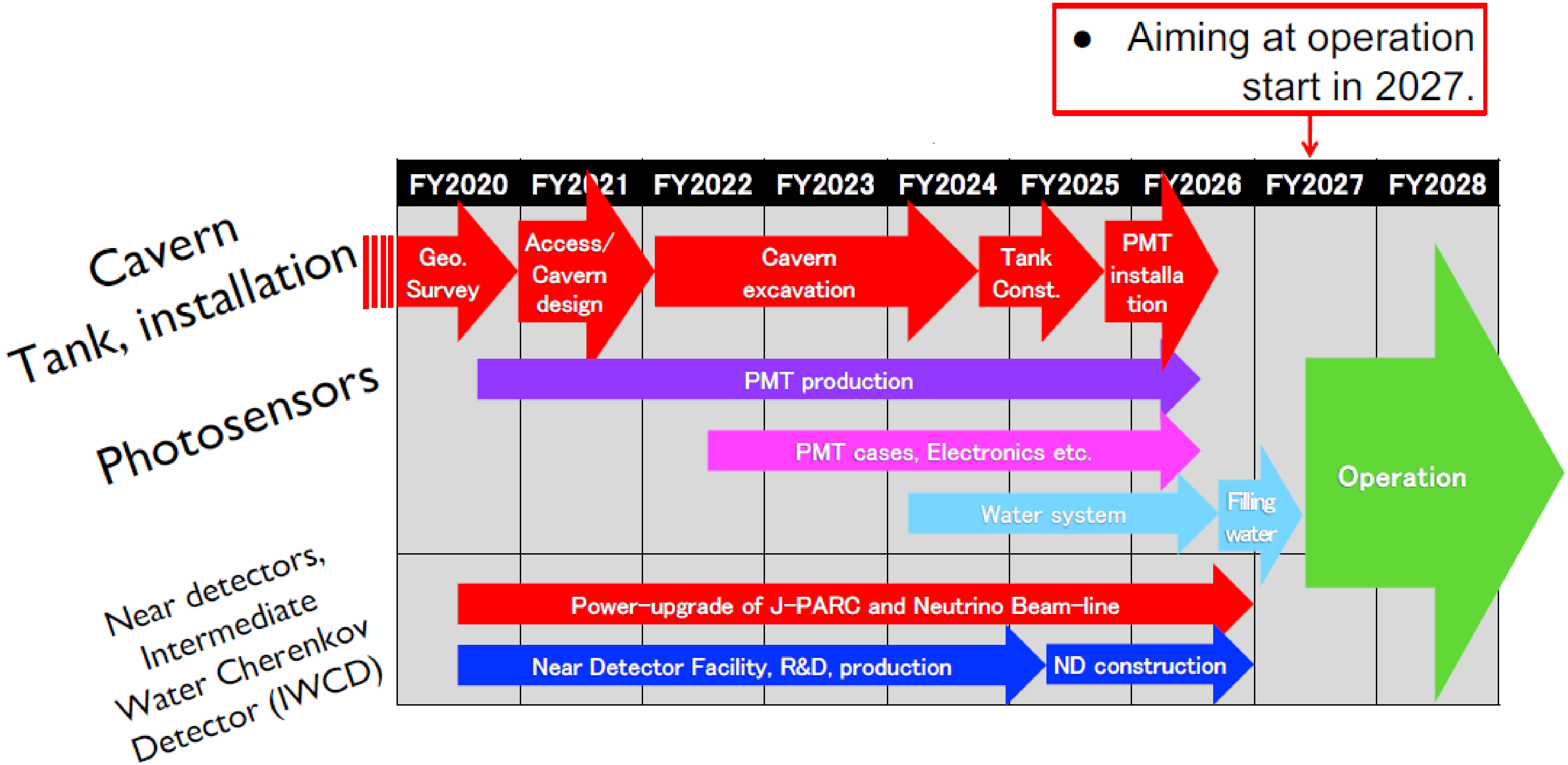




Stainless lining
2025 (5^{th} yr)

Water
Filling
&
DAQ
start
2027

Construction Schedule



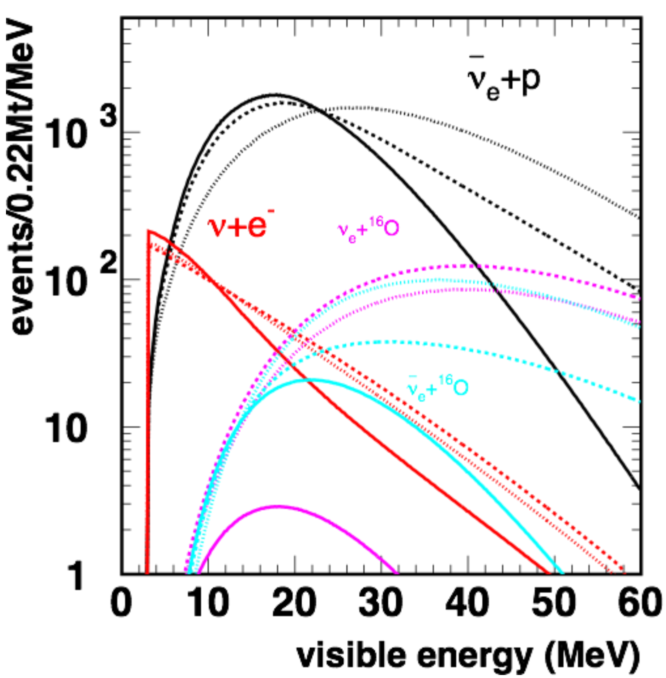
(Japan FY starts April 1st → FY2027 starts in April 2027)

Astrophysics: Supernova ν in Hyper-K

Main detection channels

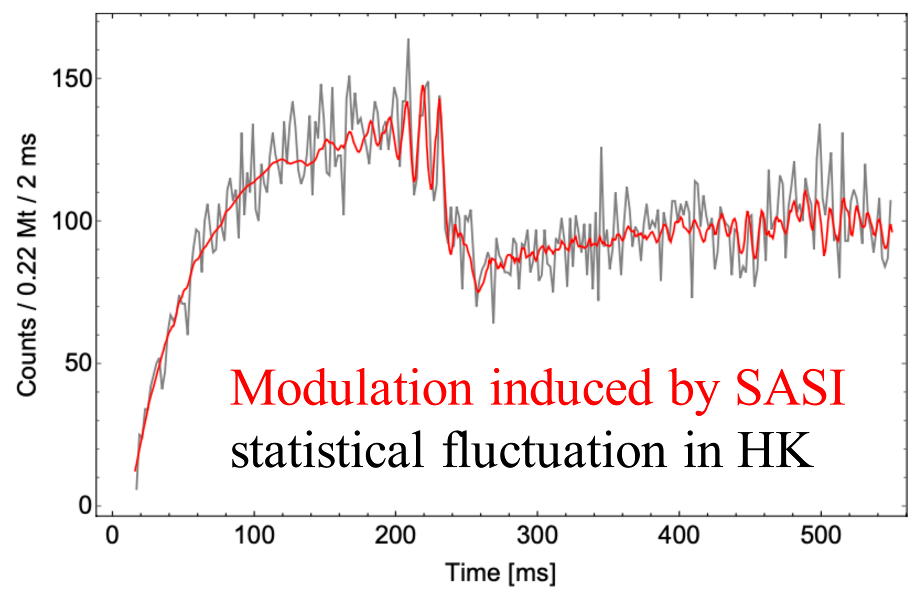
Inverse beta decay	$\overline{\nu}_e + p \rightarrow e^+ + n$	E > 1.8 MeV
ν-e scattering	$\nu + e^- \rightarrow \nu + e^-$	
ν_e ^{16}O CC	$\nu_e + {}^{16}\mathrm{O} \rightarrow e^- + {}^{16}\mathrm{F}^{(*)}$	E > 15 MeV
$\overline{\nu}_e$ ^{16}O CC	$\overline{\nu}_e + {}^{16}\mathrm{O} \rightarrow e^+ + {}^{16}\mathrm{N}^{(*)}$	E > 11 MeV

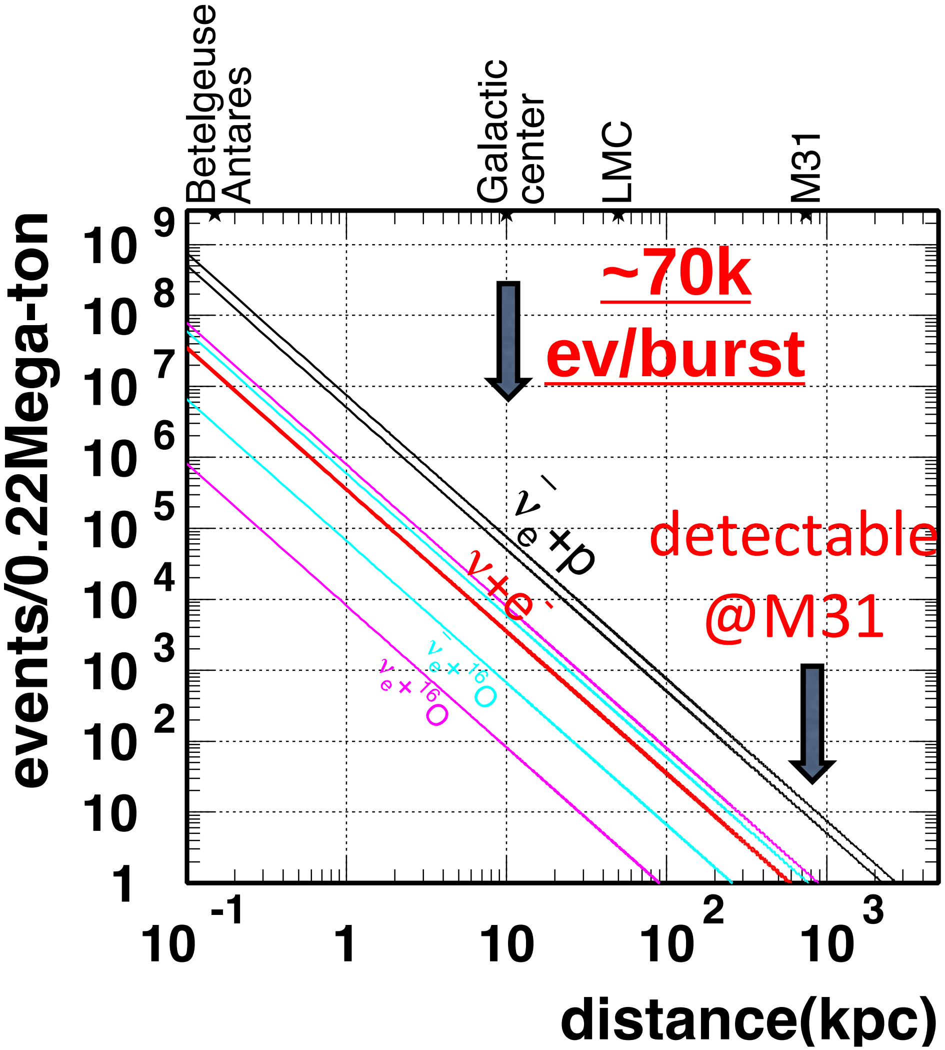
Total energy spectrum

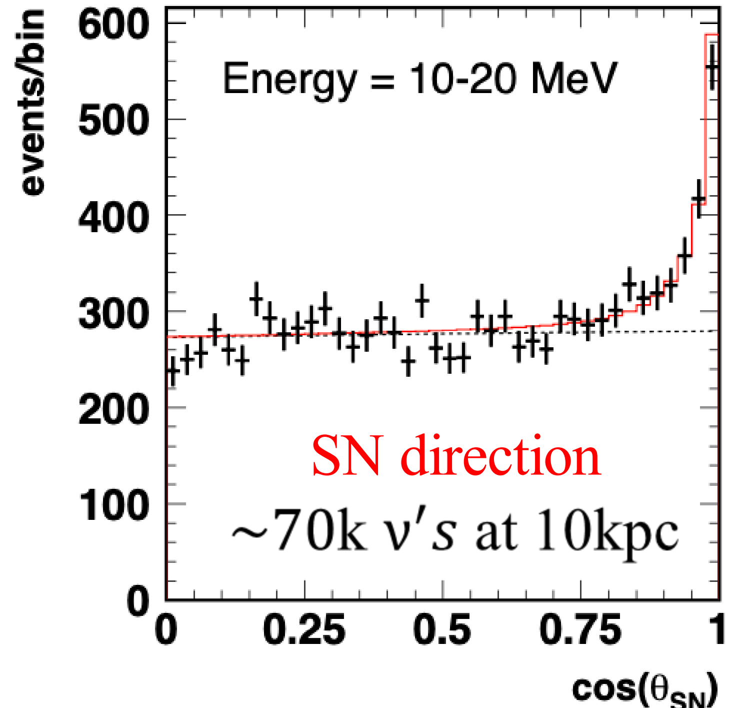


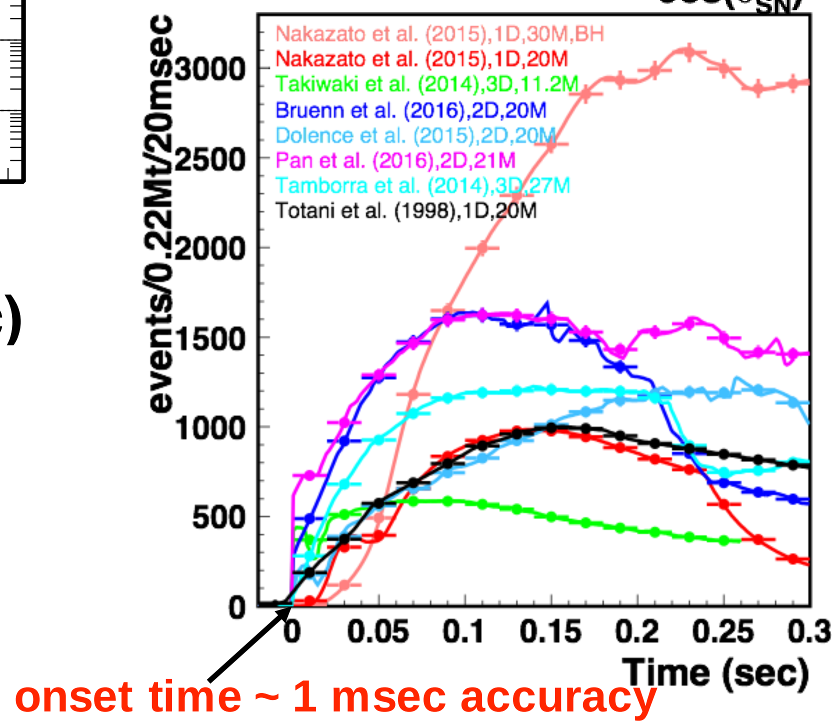
Time modulation of event rate

galactic supernova at 10 kpc (our r_{gal}= 8 kpc)









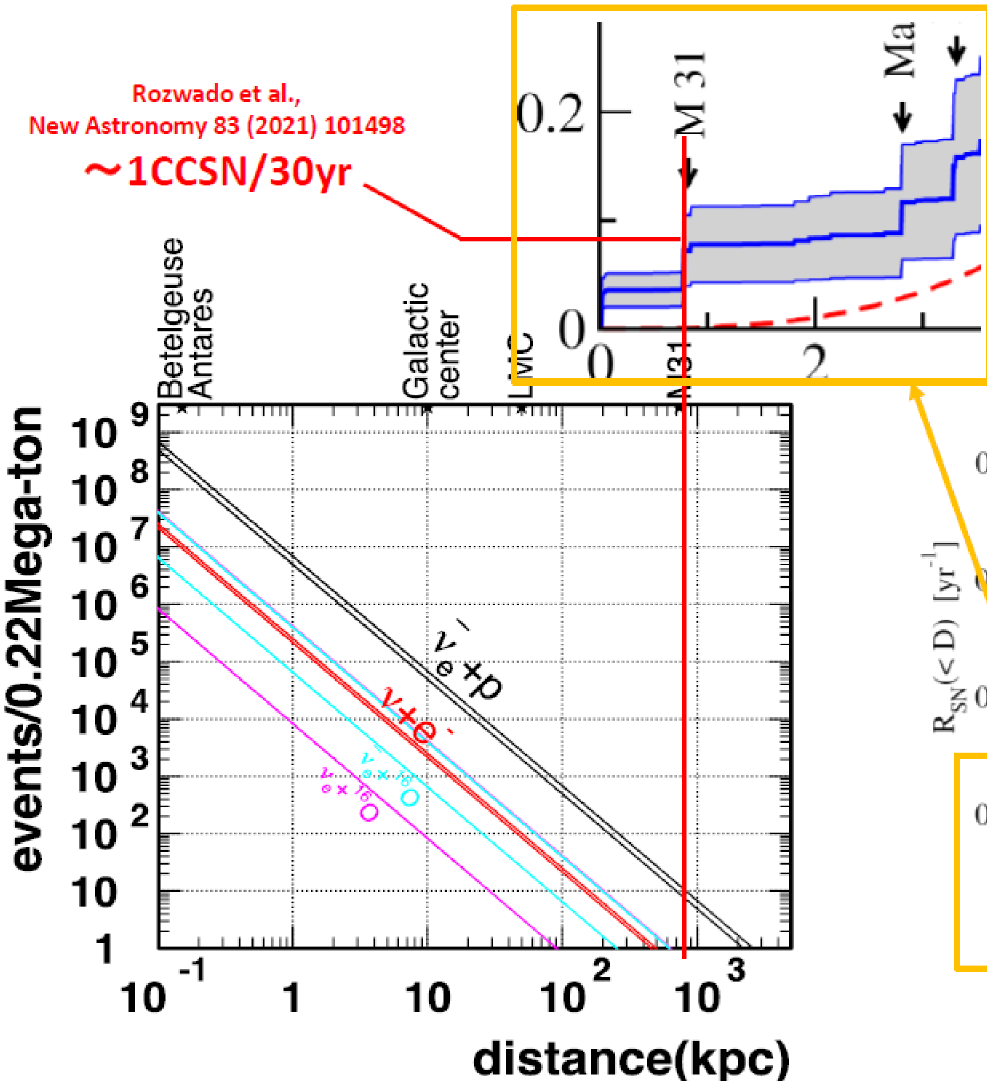
~70k events/burst

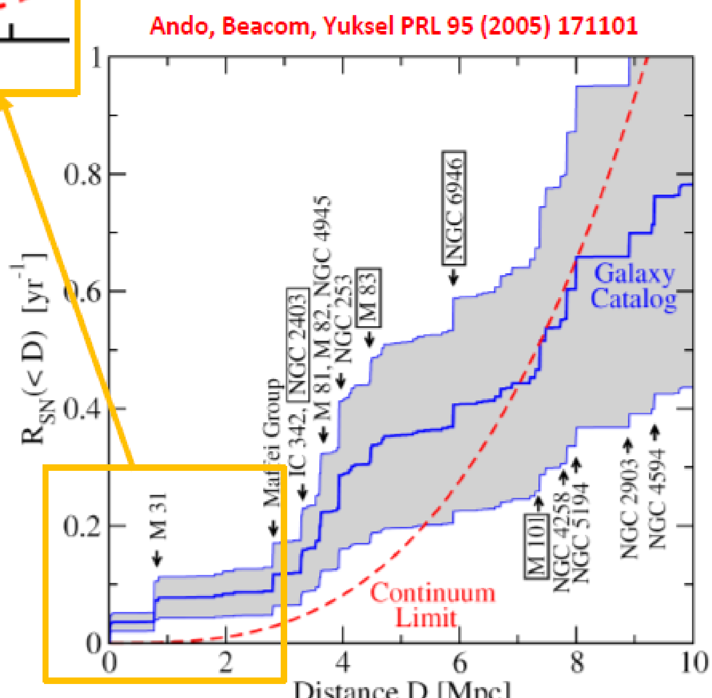
- explosion mechanism,
- BH/NS formation,
- alert with 1° pointing

Supernova Neutrino Detection

Heart of the multi-messenger astronomy with HK: 8.4 times larger effective mass than SK

- 100% detection of CCSNe at M31/M33
- Real time follow up may be possible due to limited number of corresponding galaxies.

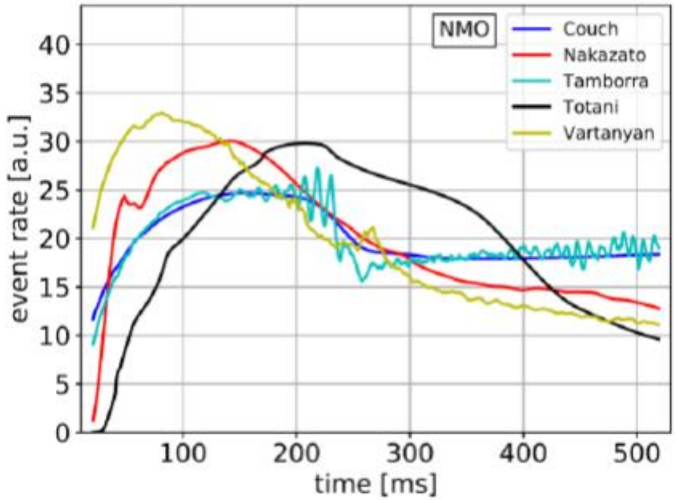


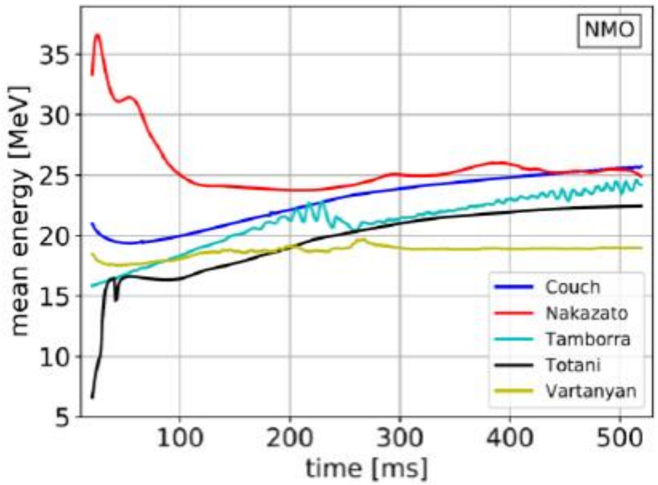


Supernova Model Discrimination

HK Collab., ApJ 916:15, 2021

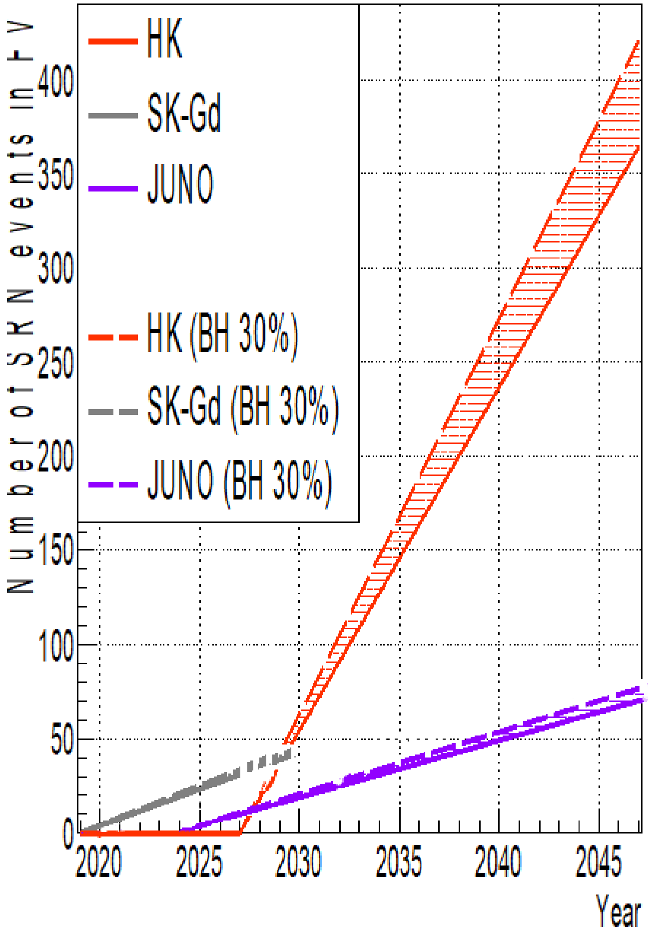
- To understand explosion mechanism, need to compare observation with simulations.
- 5 representative models are compared by using energy & time of events detected 20-520ms after core bounce.
  - Full detector simulation
  - Unbinned likelihood
- Model discrimination is surely possible at LMC (50kpc).





Model	Normal Mass Ordering		
	$N_{10\ \mathrm{kpc}}$	d_{100}	d_{300}
Totani	20021	141 kpc	82 kpc
Nakazato	17978	134 kpc	77 kpc
Couch	27539	166 kpc	96 kpc
Vartanyan	10372	102 kpc	59 kpc
Tamborra	25025	158 kpc	91 kpc

Expected number of DSNB events in HK



Conditions

SK-Gd (22.5 kton H_2O + Gd)

Low energy threshold : 10 MeV
neutron tagging by Gd-loading

Started data-taking in 2020

Aim for the first discovery

JUNO (20 kton LS)

Low energy threshold : 12 MeV

Start data-taking in 2025

Hyper-K (187 kton H_2O)

Energy threshold : 16 MeV?

Start data-taking in 2027

Aim for the precise flux and energy spectrum measurement

~4 events/yr in HK w/ H tag

- Stellar collapse
- Star formation rate
- Heavy element synthesis

Adding gadolinium to HK is being preserved as a future upgrade option → >10 DSNB events/yr

So, will we *really* get gadolinium into Hyper-Kamiokande?

Gadolinium progress has sometimes seemed slow, but it's been steady.

After one of the sessions at Neutrino 2002 in Munich, John and I spent a couple of hours sitting in a subway station brainstorming ideas.

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

Search...
Help

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 $\bar{\nu}_e + p \to e^+ + n$ (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.

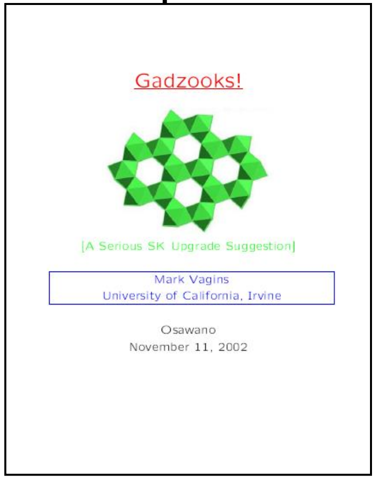
Comments: 4 pages, 1 figure, submitted to Phys. Rev Lett. Correspondence to beacom@fnal.gov, mvagins@uci.edu
Subjects: **High Energy Physics - Phenomenology (hep-ph)**; Astrophysics (astro-ph); High Energy Physics - Experiment (hep-ex); Nuclear Experiment (nucl-ex); Nuclear Theory (nucl-th)
Report number: 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 585 citations!]

What a Long, Strange Trip It's Been…

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

Gd Loading Of SK First Proposed


Gadzooks!

[A Serious SK Upgrade Suggestion]

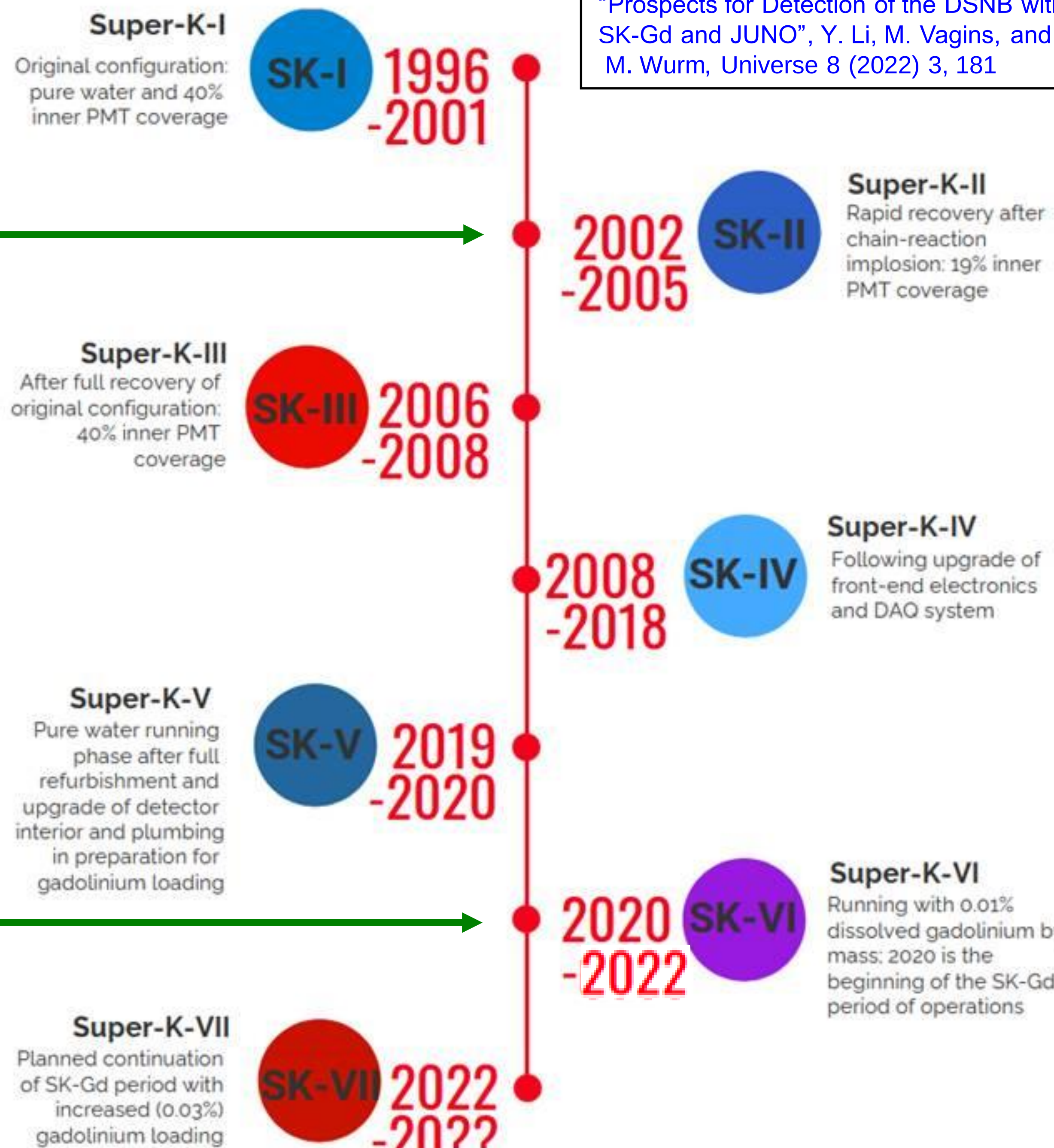
Mark Vagins
University of California, Irvine

Osawano
November 11, 2002

First Gd Loading Of SK


First Gadolinium Loading to Super-Kamiokande

K. Abe, C. Bronner, Y. Hayato, K. Hiraide, M. Ikeda, S. Imaizumi, J. Kameda, Y. Kanemura, Y. Kataoka, S. Miki, M. Miura, S. Moriyama, Y. Nagao, M. Nakahata, S. Nakayama, T. Okada, K. Okamoto, A. Orii, G. Pronost, H. Sekiya, M. Shiozawa, Y. Sonoda, Y. Suzuki, A. Takeda, Y. Takemoto, A. Takenaka, H. Tanaka, S. Watanabe, T. Yano, S. Han, T. Kajita, K. Okumura, T. Tashiro, J. Xia, G. D. Megias, D. Bravo-Berguno, L. Labarga, Ll. Marti, B. Zaldivar, B. W. Pointon, F. d. M. Blaszczyk, E. Kearns, J. L. Raaf, J. L. Stone, L. Wan, T. Wester, J. Bian, N. J. Griskevich, W. R. Kropp, S. Locke, S. Mine, M. B. Smy, H. W. Sobel, V. Takhistov, J. Hill, J. Y. Kim, I. T. Lim, R. G. Park, B. Bodur, K. Scholberg, C. W. Walter, L. Bernard, A. Coffani, O. Drapier, S. El Hedri, A. Giampaolo, M. Gonin, Th. A. Mueller, P. Paganini, B. Quilain, T. Ishizuka, T. Nakamura, J. S. Jang, J. G. Learned, L. H. V. Anthony, D. Martin, M. Scott, A. A. Sztuc, Y. Uchida, S. Cao, V. Berardi, M. G. Catanesi, E. Radicioni, N. F. Calabria, L. N. Machado, G. De Rosa, G. Collazuol, F. Iacob, M. Lamoureux, M. Mattiazzi, N. Ospina, L. Ludovici, Y. Maekawa, Y. Nishimura, M. Friend, T. Hasegawa, T. Ishida, T. Kobayashi, M. Jakkapu, T. Matsubara , T. Nakadaira, K. Nakamura, Y. Oyama, K. Sakashita, T. Sekiguchi, T. Tsukamoto, T. Boschi, J. Gao, F. Di Lodovico, J. Migenda, M. Taani, S. Zsoldos, Y. Kotsar, Y. Nakano, H. Ozaki, T. Shiozawa, A. T. Suzuki, Y. Takeuchi, S. Yamamoto, A. Ali, Y. Ashida, J. Feng, S. Hirota, T. Kikawa, M. Mori, T. Nakaya, R. A. Wendell, K. Yasutome, P. Fernandez, N. McCauley, P. Mehta, K. M. Tsui, Y. Fukuda, Y. Itow, H. Menjo, T. Niwa, K. Sato, M. Tsukada, J. Lagoda, S. M. Lakshmi, P. Mijakowski, J. Zalipska, J. Jiang, C. K. Jung, C. Vilela, M. J. Wilking, C. Yanagisawa, K. Hagiwara, M. Harada, T. Horai, H. Ishino, S. Ito, F. Kitagawa, Y. Koshio, W. Ma, N. Piplani, S. Sakai, G. Barr, D. Barrow, L. Cook, A. Goldsack, S. Samani, D. Wark, F. Nova, J. Y. Yang, S. J. Jenkins, M. Malek, J. M. McElwee, O. Stone, M. D. Thiesse, L. F. Thompson, H. Okazawa, S. B. Kim, J. W. Seo, I. Yu, A. K. Ichikawa, K. Nakamura, K. Nishijima, M. Koshiba, K. Iwamoto, Y. Nakajima, N. Ogawa, M. Yokoyama, K. Martens, M. R. Vagins, M. Kuze, S. Izumiyama, T. Yoshida, M. Inomoto, M. Ishitsuka, H. Ito, T. Kinoshita, R. Matsumoto, K. Ohta, M. Shinoki, T. Suganuma, J. F. Martin, H. A. Tanaka, T. Towstego, R. Akutsu, M. Hartz, A. Konaka, P. de Perio, N. W. Prouse, S. Chen, B. D. Xu, M. Posiadala-Zezula, D. Hadley, M. O'Flaherty, B. Richards, B. Jamieson, J. Walker, A. Minamino, K. Okamoto, G. Pintaudi, S. Sano, R. Sasaki (The Super-Kamiokande Collaboration)



Gd-H_2O: Everybody's Doing It, Man…

Name	Location	Main Goal	Water Volume	$Gd_2(SO_4)_3$ Loaded
EGADS	Kamioka	Gd R&D, SN Watch	200 tons	Since 2013
ANNIE	Fermilab	High-E Neutron Multiplicity	26 tons	Since 2019
Super-K-VI/VII	Kamioka	DSNB, SN Burst, PDK, ATM/Sol/LB ν	50 ktons	Since 2020/2
XENONnT Water Shield	Gran Sasso	Dark Matter Detection	700 tons	Since 2023
WCTE	CERN	IWCD/mPMT Demonstrator	50 tons	2024 (planned)
30-ton Test Tank	BNL	Nuclear Non-Proliferation Demonstrator	30 tons	2024 (planned)
BUTTON	Boulby	Underground Demonstrator	30 tons	2025(?)
Hyper-K-II(?)	Kamioka	DSNB, SN Burst, PDK, ATM/Sol/LB ν	258 ktons	203X(?)

So, while I go back to my sometimes odd life in Japan, please help support the idea of keeping SK with Gd running until we do eventually manage to get Gd into Hyper-Kamiokande.

After all, given just a few more years, SK should discover the DSNB flux!

Then, since what everyone here really dreams about is *spectral* DSNB information, having a Gd-loaded HK is by far the best bet.