TAIWAN BRIDGES

Institute of Physics, Academia Sinica, Taiwan

April 24, 2026

The Story of the Kamioka Underground Research Facilities

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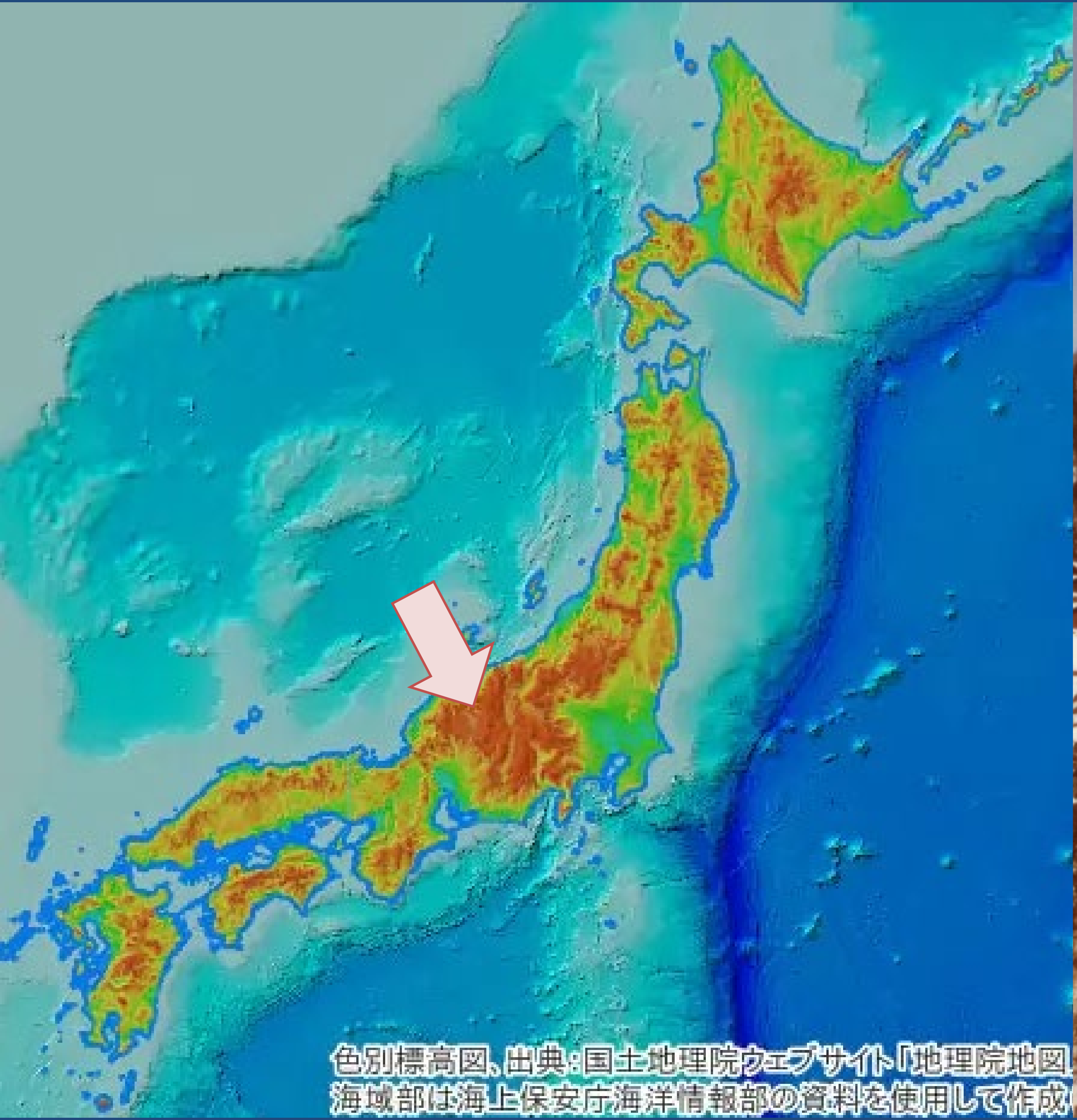
Outline

- *Where is Kamioka?*
- *Neutrinos*
  - *Kamiokande*
  - *Super-Kamiokande*
  - *KamLAND*
  - *Hyper-Kamiokande*
- *Gravitational waves*
  - *KAGRA*
- *Summary*

Where is Kamioka?



Neutrinos

Kamiokande

History before Kamiokande

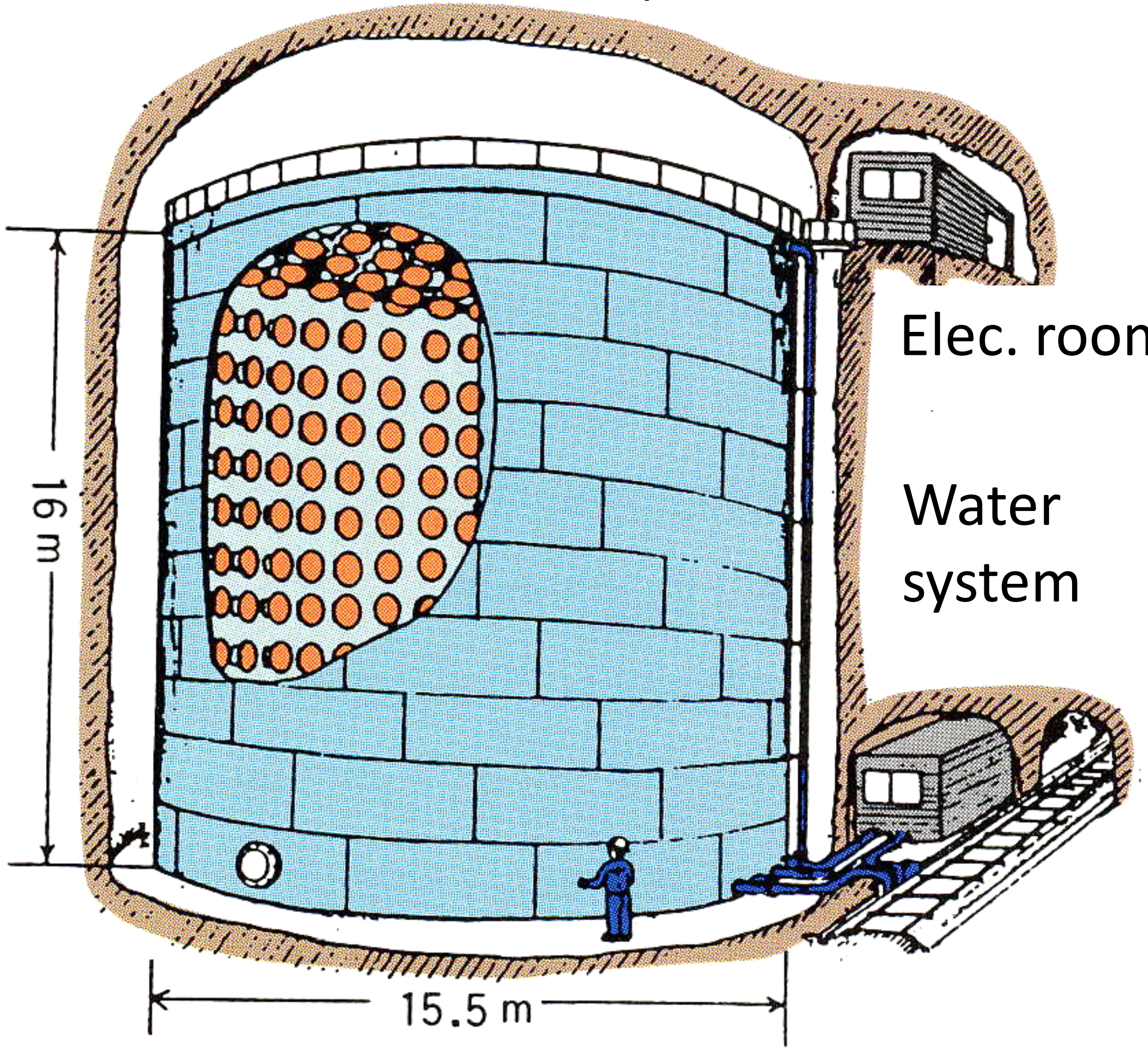
Prof. Koshiba had a cosmic ray muon experiment in the underground of the Kamioka mine in the 1960's.

Kamioka Nucleon Decay Experiment (Kamiokande)

- ✓ In the 1970's, newly proposed Grand Unified Theories predicted that protons should decay with the lifetime of about 10^{30} years.
- ✓ Several proton decay experiments began in the early 1980's. One of them was Kamiokande.
- ✓ Physicists, both theoretical and experimental, thought that proton decay experiment is so important. Therefore, many people helped to realize the Kamiokande experiment. (The direct support by the government was not large.)

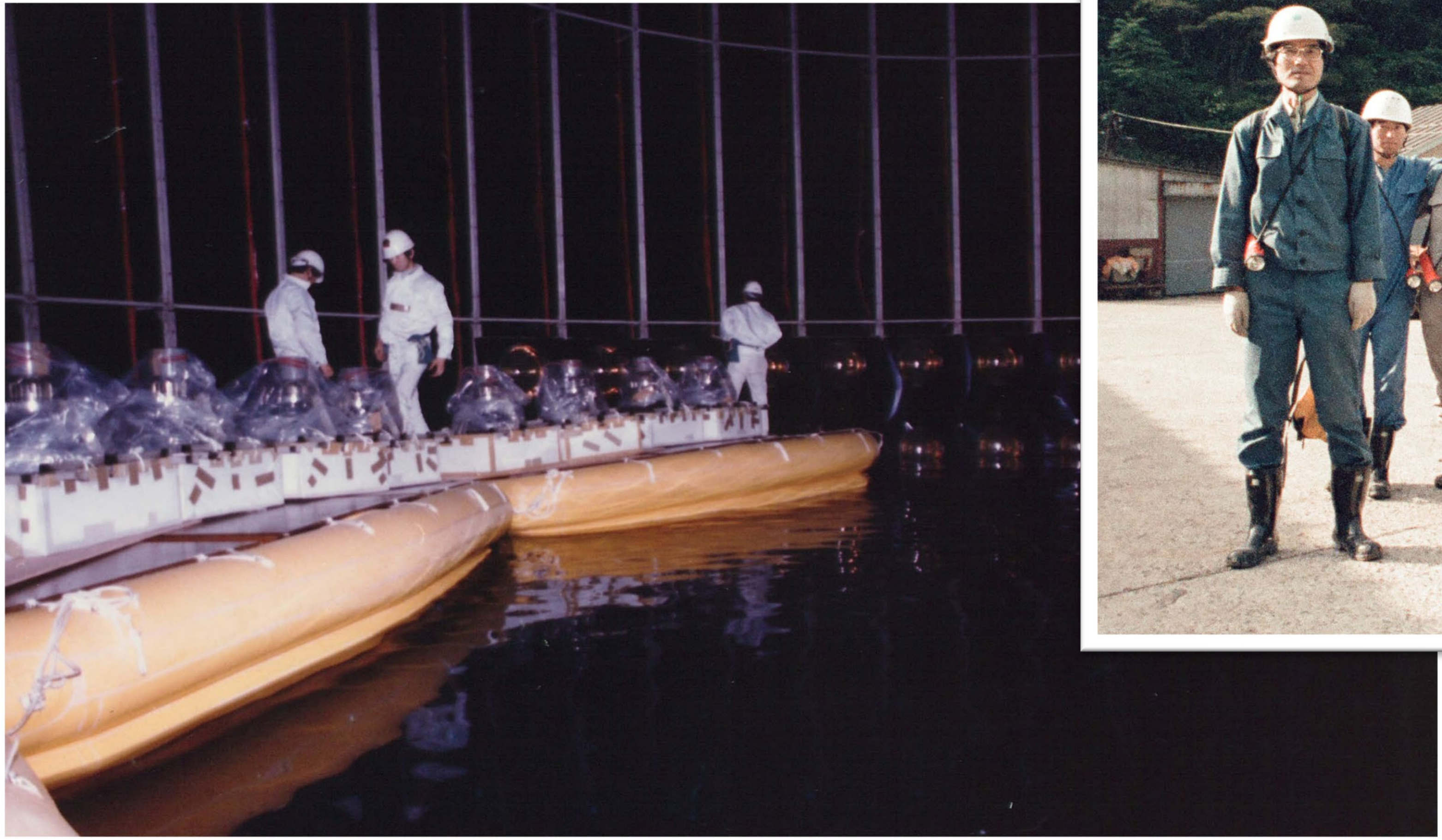
Kamiokande

(3000 ton water tank)



Construction of the Kamiokande detector (spring 1983)

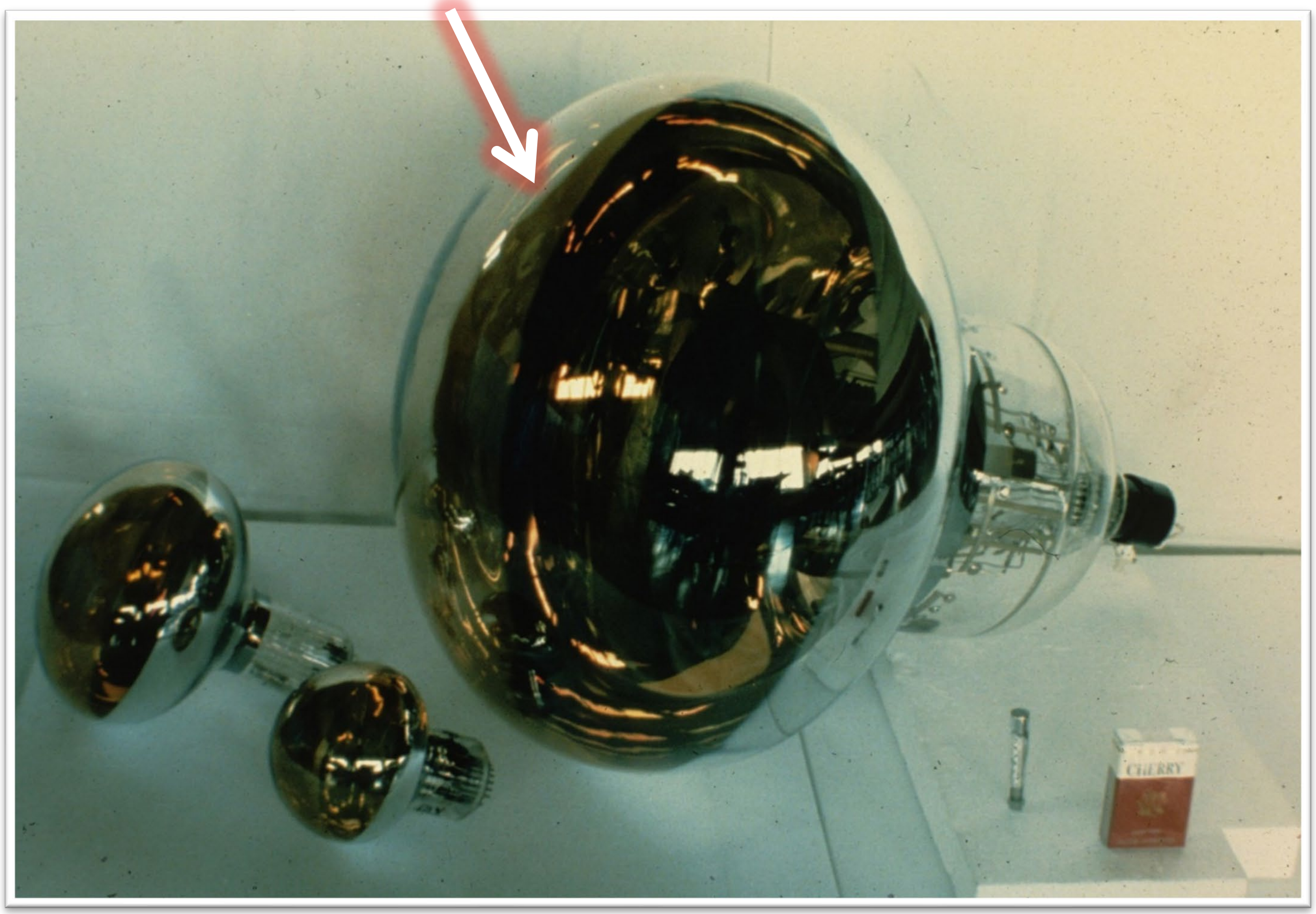
Kamiokande was a "small" experiment with about 10 collaborators during the construction.



At the mine entrance

Didn’t observe proton decays, but…

Photomultiplier tube used in Kamiokande



Solar neutrinos (whose energies are about 1/100 of the proton decay signal) could be observed.

Prof. Koshiba proposed to improve the Kamiokande detector to observe solar neutrinos.

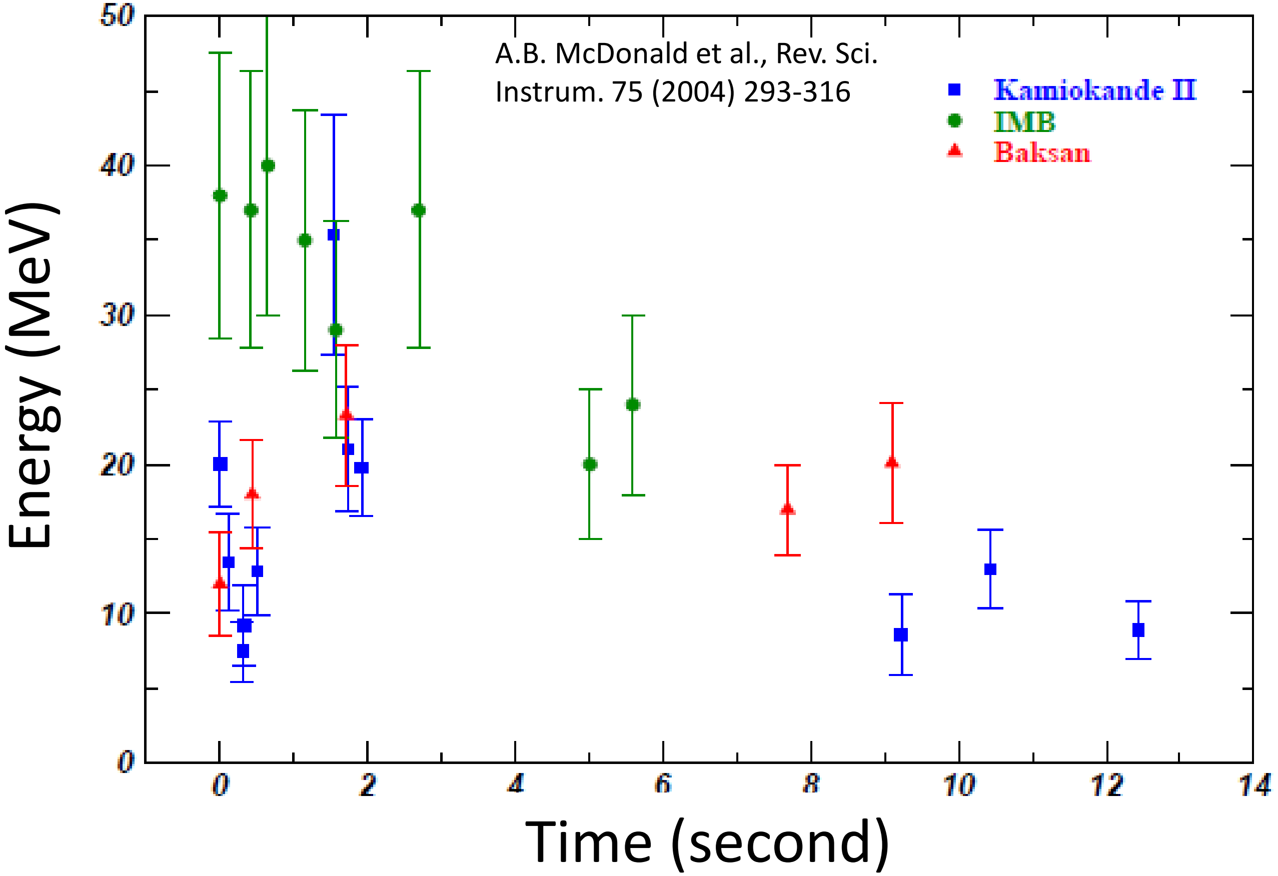
The observed flux by the Homestake experiment was about 30% of the expectation by the standard solar model.
(R. Davis Jr., D. S. Harmer and K. C. Hoffman PRL 20 (1968) 1205)

Supernova SN1987A

Feb. 1987
（Large Magellanic Cloud, 160,000 light-years)

Birth of neutrino astronomy

<u>*Total 24 neutrino events were observed by 3 detectors (Kamiokande, IMB-3 and Baksan)*</u>



➔ Understood the basic mechanism of the supernova explosion: When a massive star finished its life, the star collapse, a shock wave is generated, and the outside of the star explode !

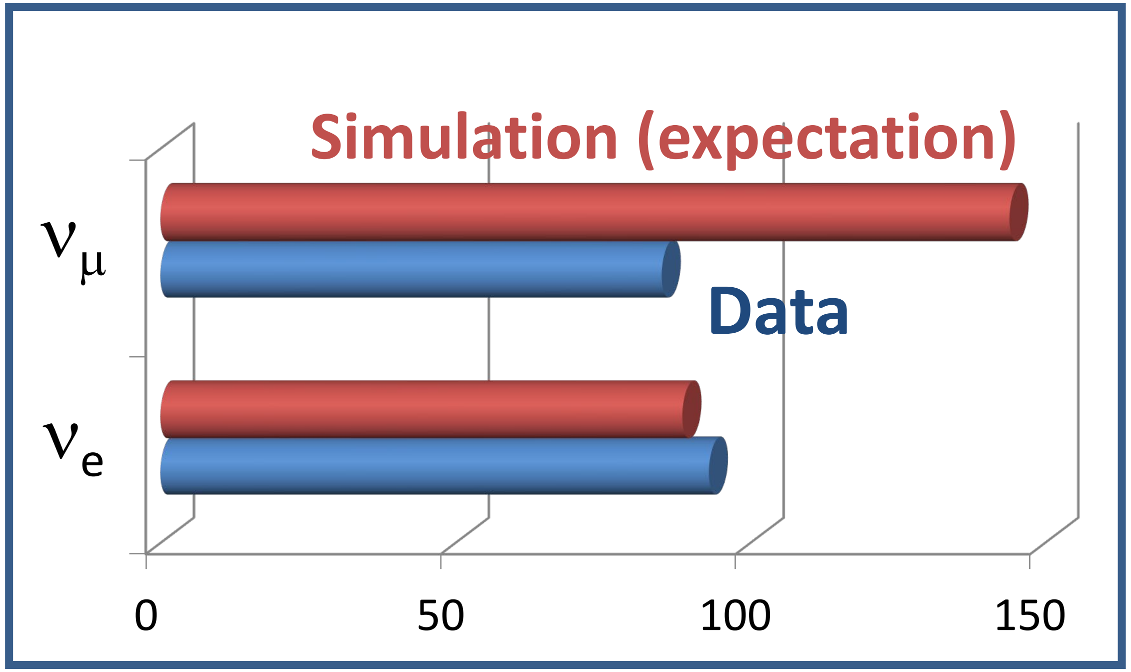
Prof. M. Koshiba
(Nobel prize 2002)

Prof. Kosiba said; "Many people say I am fortunate. However, at that time, neutrinos came to everywhere on the earth. Only people who prepared for them were able to observe them."

Other Kamiokande results

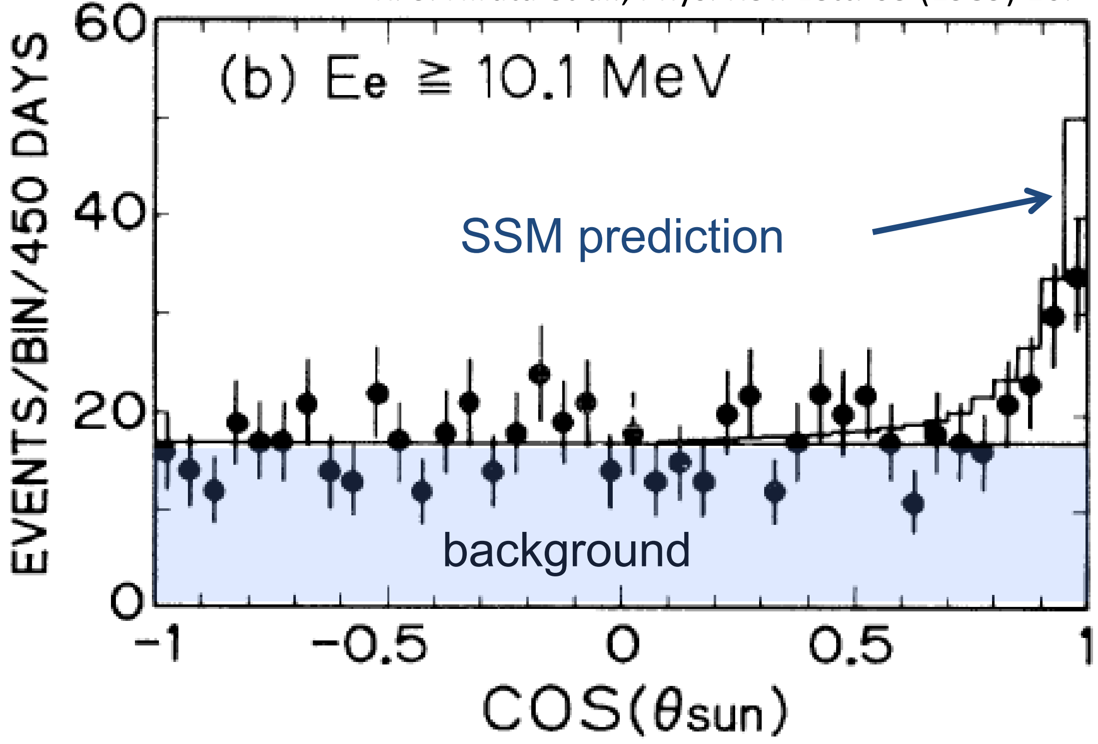
Missing atmospheric neutrinos (1988)

K. Hirata et al, Phys.Lett.B 205 (1988) 416.



Missing solar neutrinos (1989)

K. S. Hirata et al., Phys. Rev. Lett. 63 (1989) 16.



Observation of Supernova neutrinos (1987), missing atmospheric neutrinos (1988) and missing solar neutrinos (1989) suggested that neutrinos should be very important.
➔High expectations for Super-Kamiokande

Super-Kamiokande

Institute for Cosmic Ray Research in the late 1980's

"Scrap plan" of research institutes in National Universities

「附置研究所の現状分析」から

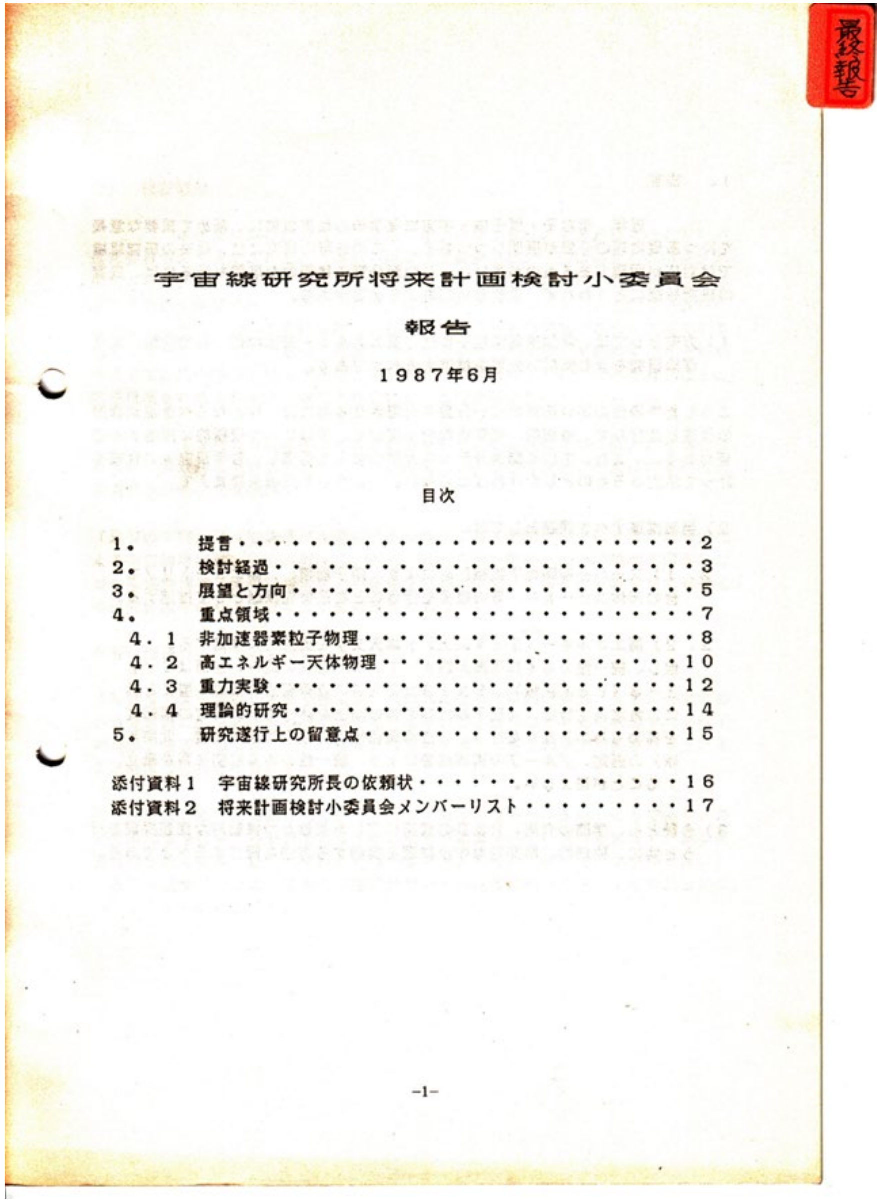
分野	大学	研究所		
人文社会	東京大学	社会科学研究所	A	1
		新聞研究所	A	1
		史料編さん所	A	2
	東京外国語大学	アジア・アフリカ言語文化研究所	B	
	東京大学	東洋文化研究所	D	
	京都大学	人文科学研究所	D	
化学	北海道大学	触媒研究所	A	1
	東北大学	非水溶液化学研究所	B	
物理	東京大学	宇宙線研究所	A	1
		原子核研究所	A	1
	名古屋大学	プラズマ研究所	A	2
	広島大学	理論物理学研究所	A	1
	東北大学	金属材料研究所	A	C

A1: Research institute that lacks a clear vision and requires a significant organizational restructuring.

ICRR Future Project Planning Committee (1987)

- ✓ ICRR established the Future Project Planning Committee composed of members from outside ICRR.
- ✓ The committee concluded that the highest priority is to search for proton decays and studies of cosmic neutrinos, including solar neutrinos, in Super-Kamiokande.

- ✓ In addition, Super-Kamiokande was highly evaluated by the Science Council of Japan.
- ✓ In 1991, the construction of the Super-kamiokande was approved by the Japanese government. (The Japanese government directly supported the project.)


宇宙線研究所将来計画検討小委員会

報告

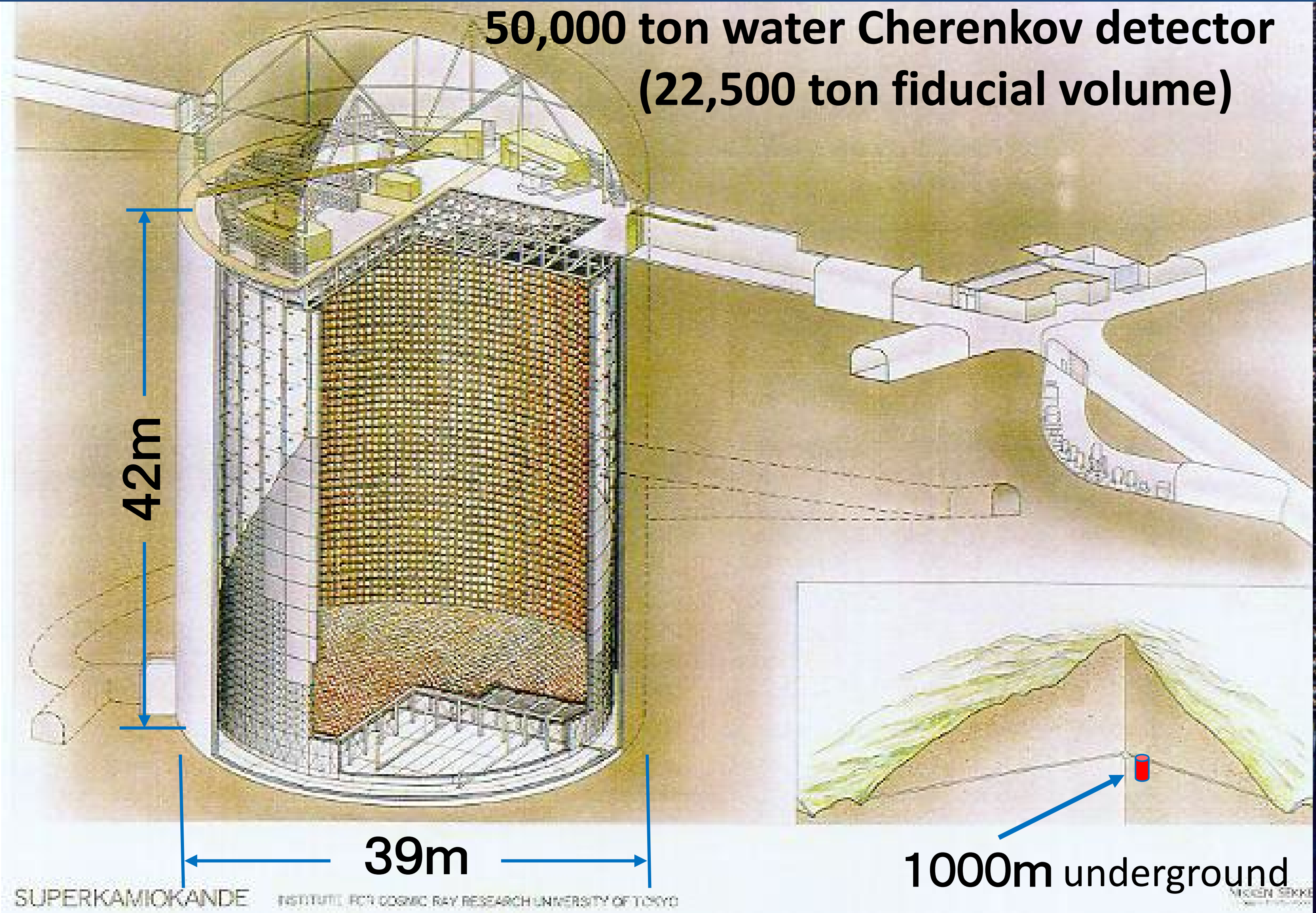
１９８７年６月

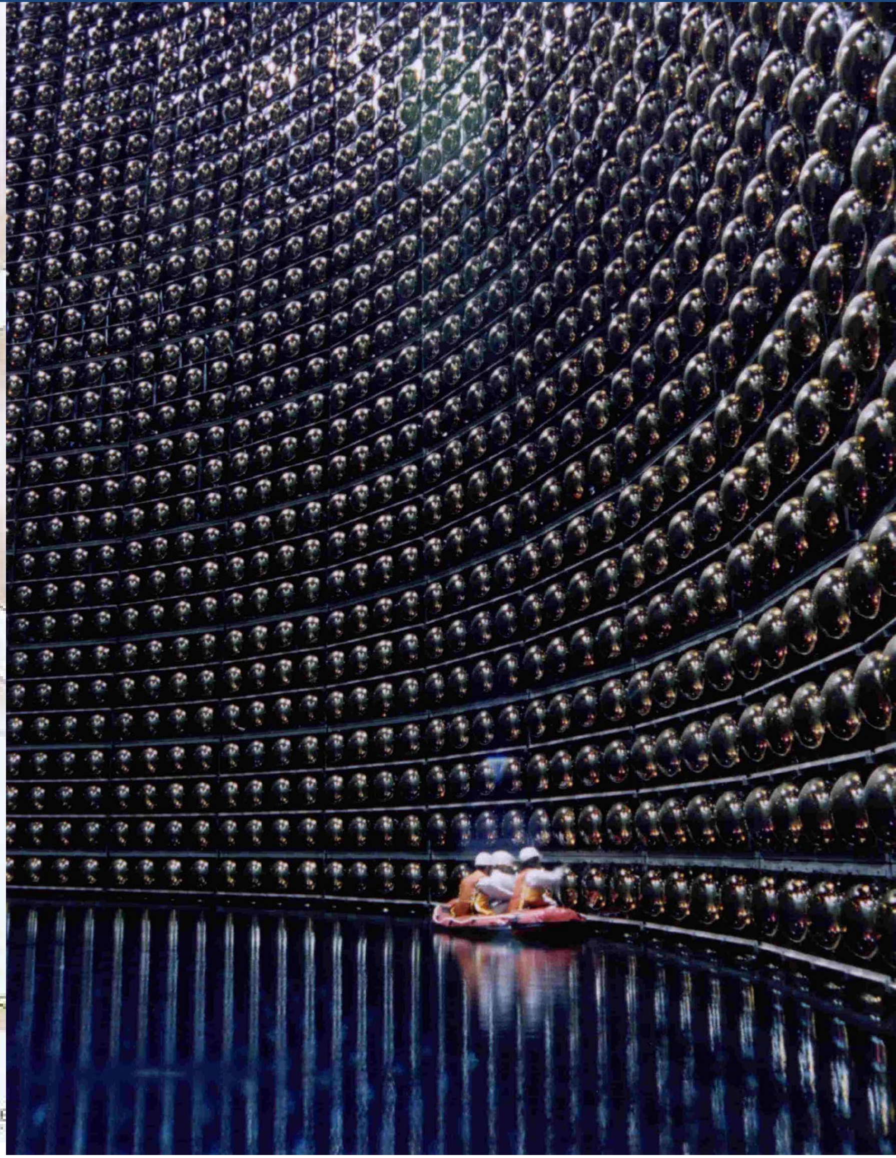
目次

-1-

Super-Kamiokande

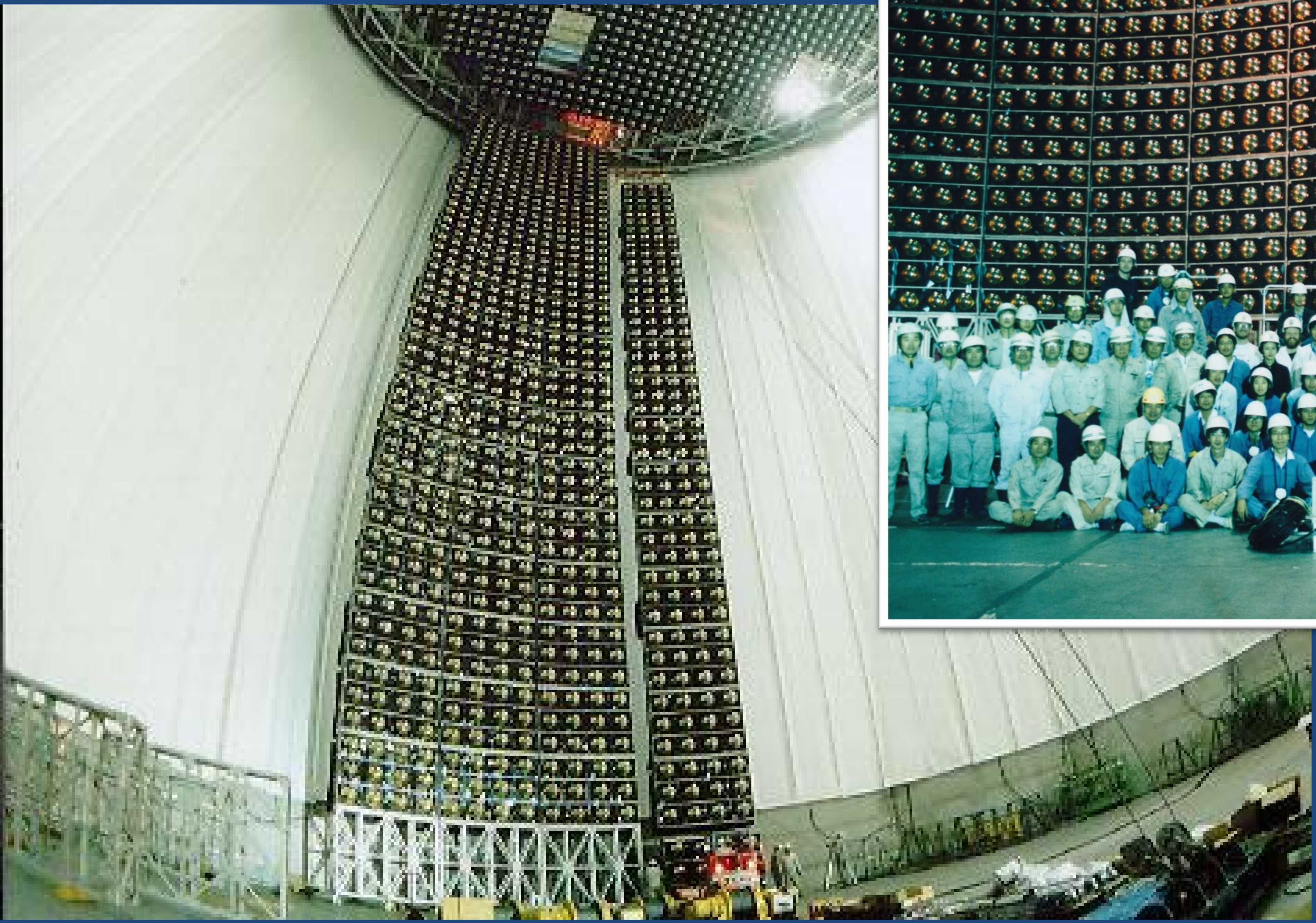
50,000 ton water Cherenkov detector
(22,500 ton fiducial volume)

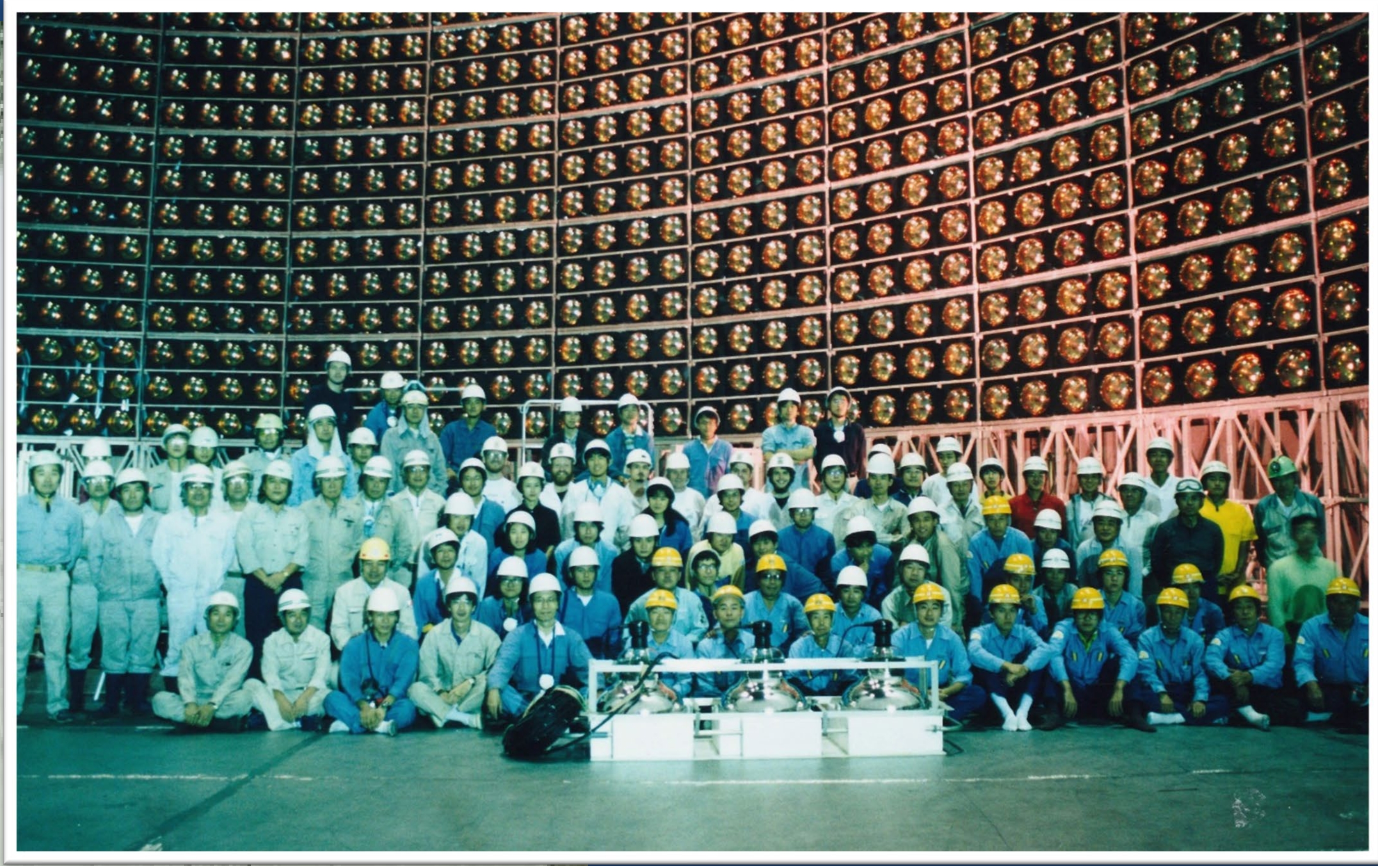




~230 collaborators

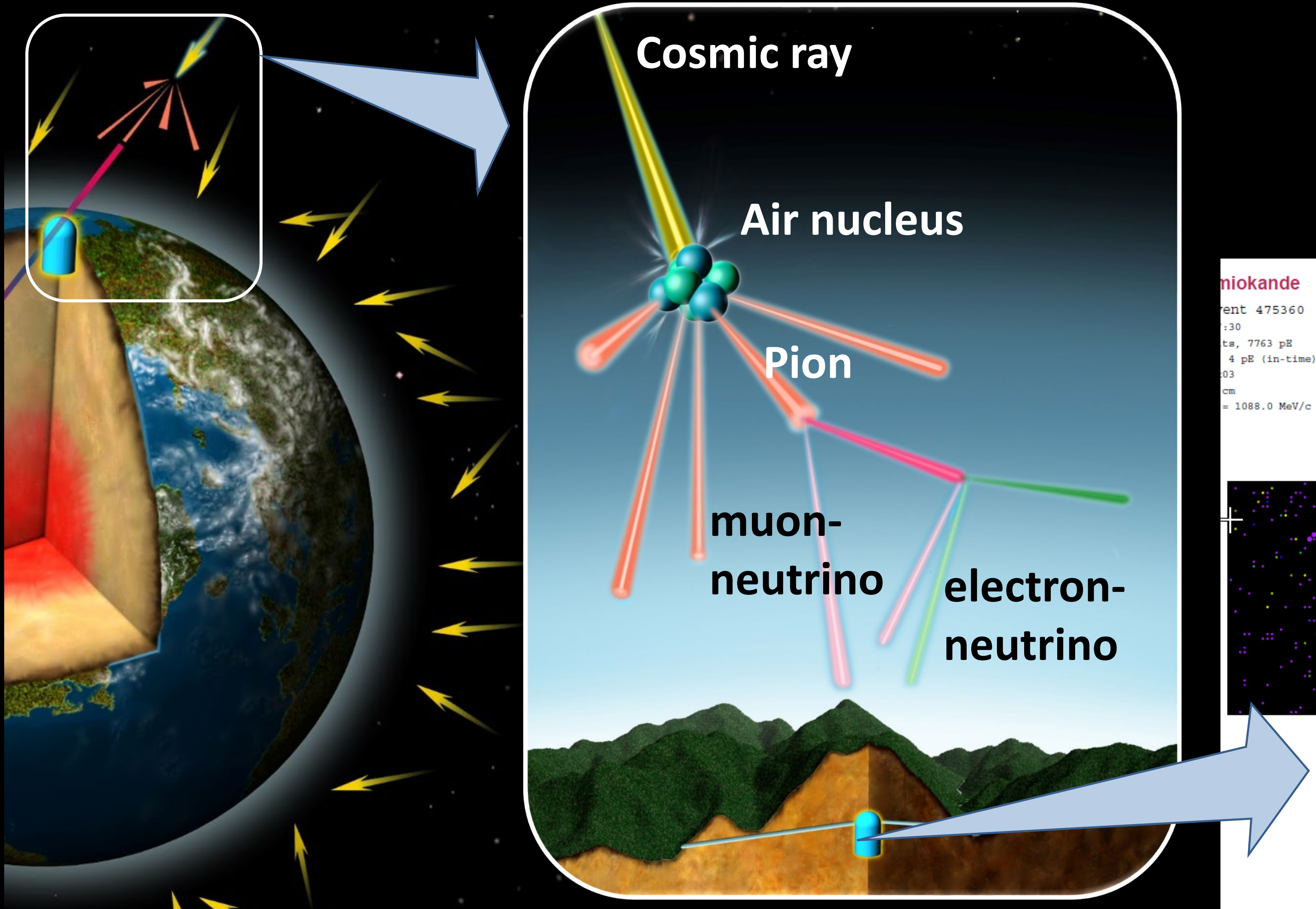
Construction of Super-Kamiokande (1995)



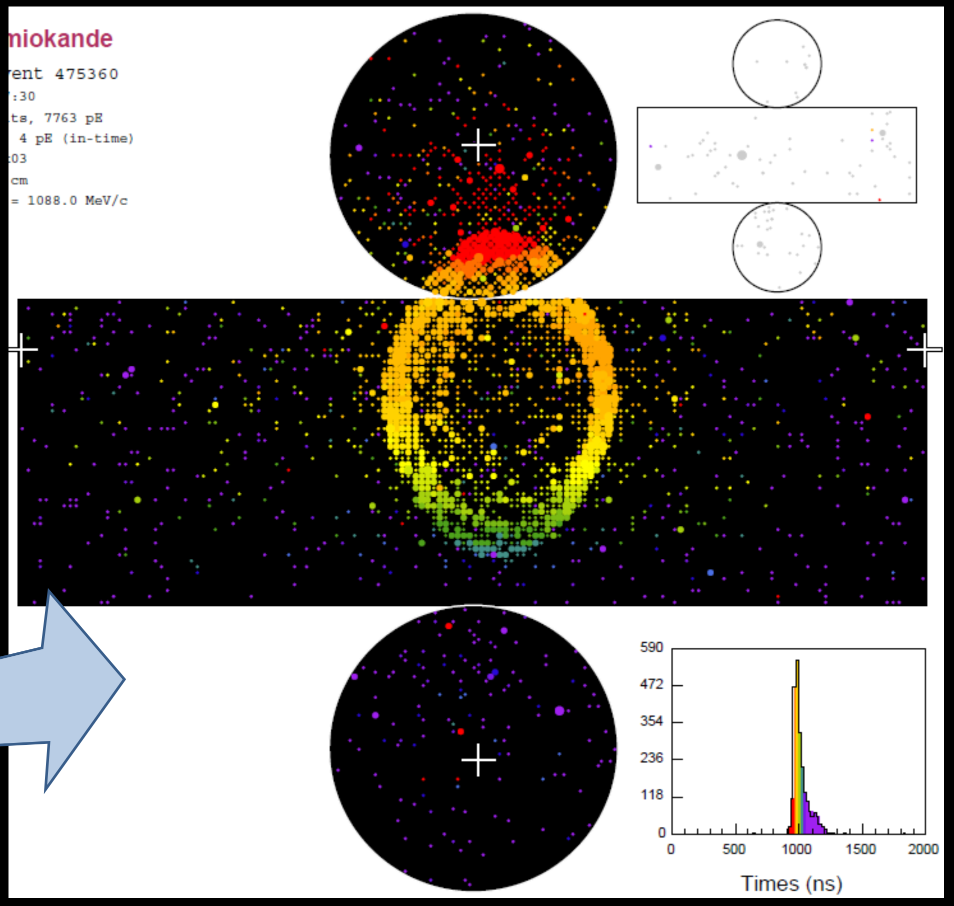


Many collaborators worked in underground for the construction of Super-K. (Much larger facility)

Atmospheric neutrinos

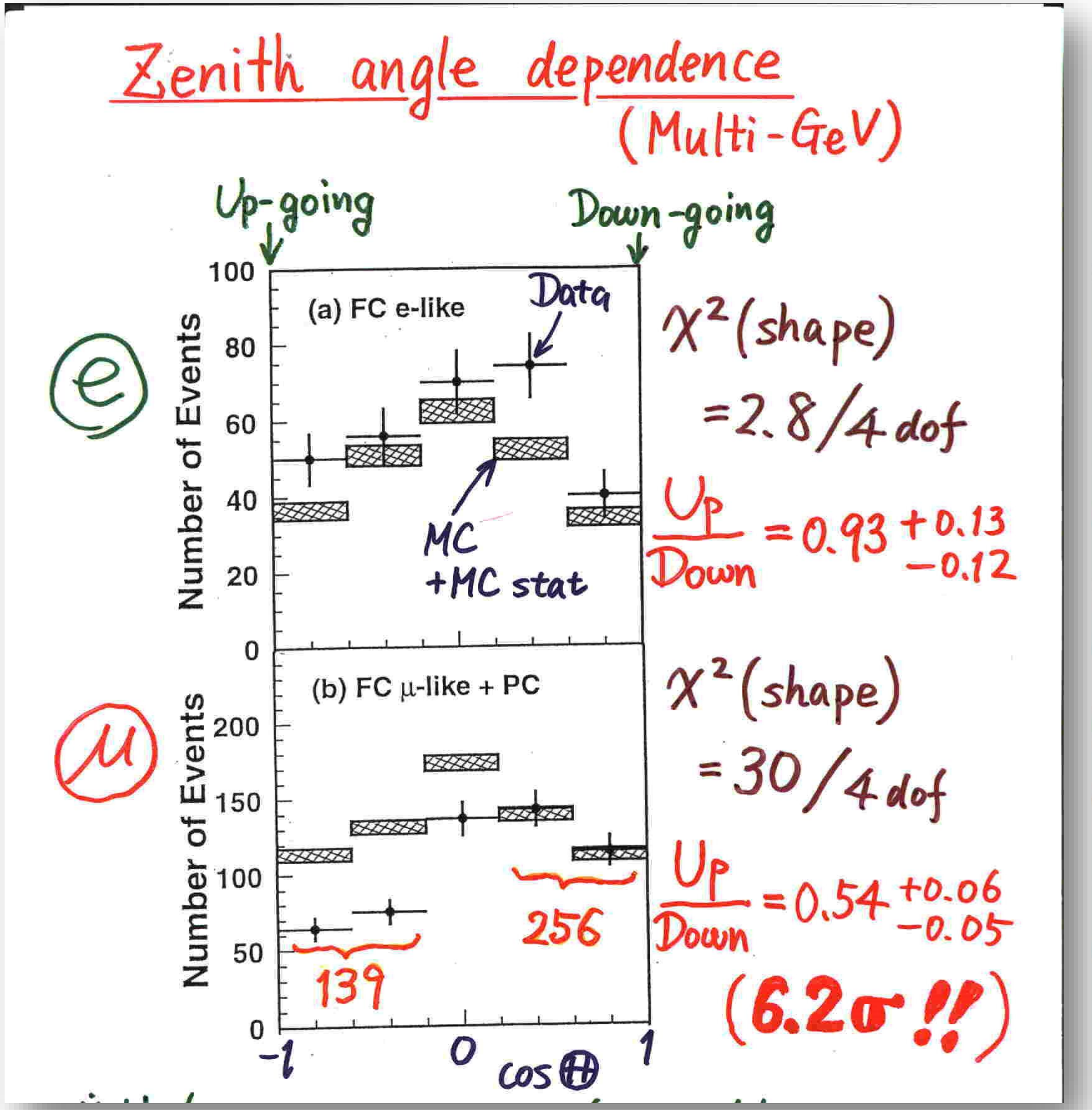


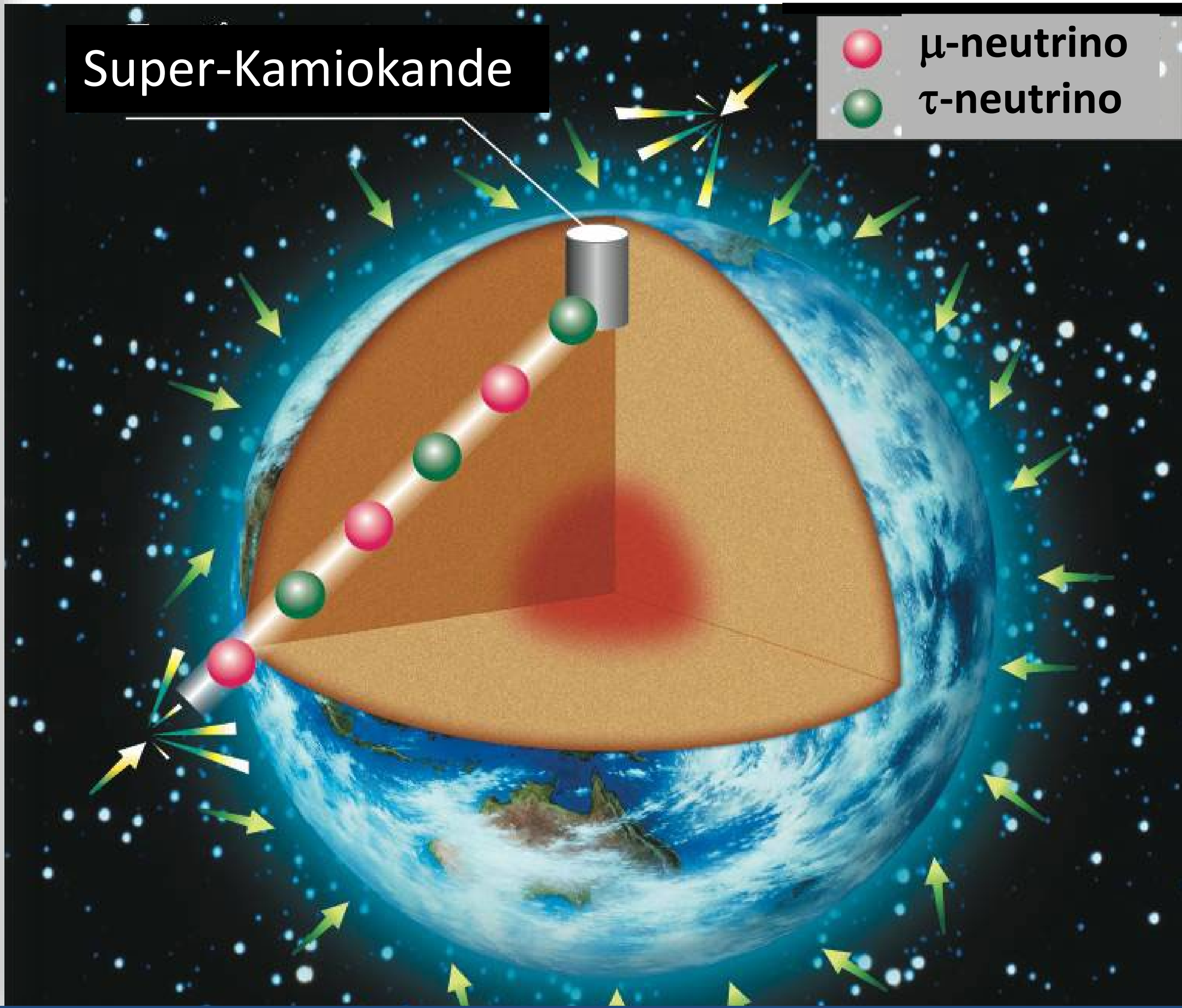
Atmospheric neutrino event observed in Super-K



Evidence for neutrino oscillations (Super-Kamiokande @Neutrino 1998)

Y. Fukuda et al., PRL 81 (1998) 1562





Super-K as the far detector in accelerator-based long-baseline neutrino oscillation experiments

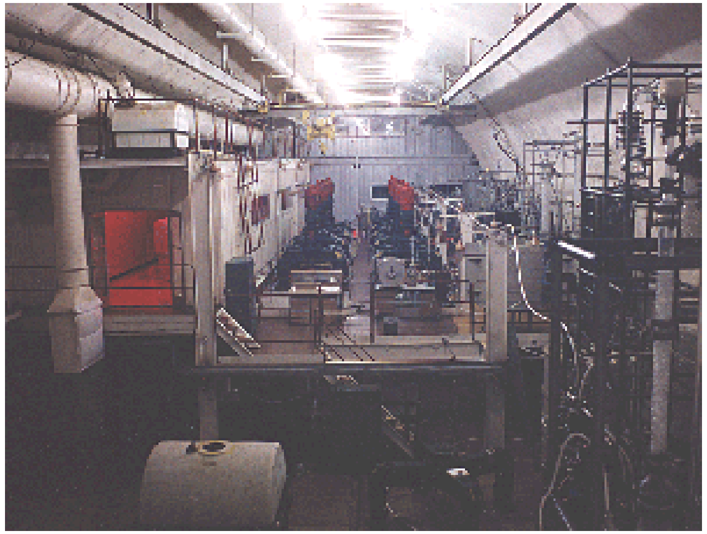
K2K

- Confirmed neutrino oscillation with the accelerator beam

T2K

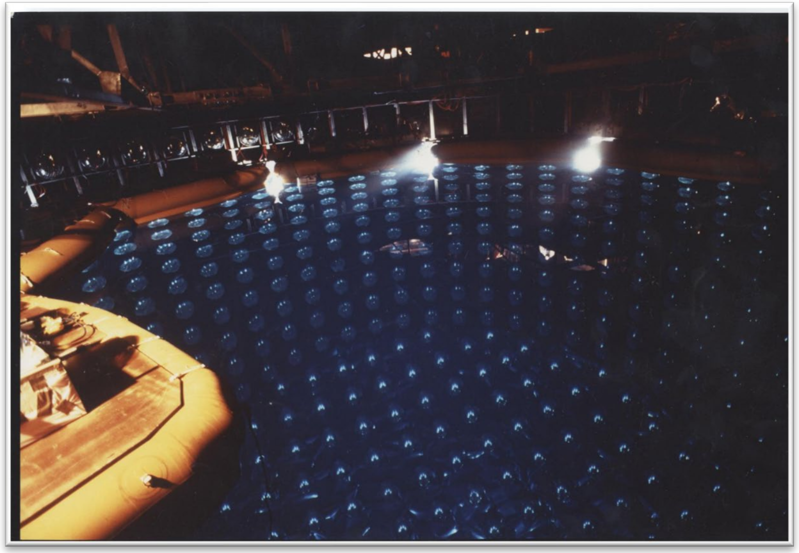
- Discovered $\nu_\mu \rightarrow \nu_e$ oscillation (3rd oscillation channel).
- Studies of $\nu_\mu \rightarrow \nu_e$ and anti-$\nu_\mu \rightarrow$ anti-ν_e (CP violation).

Solar neutrino problem

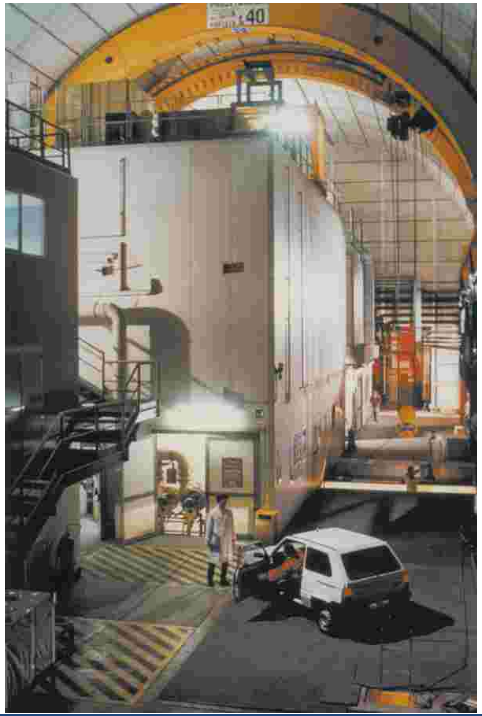


SAGE

Homestake



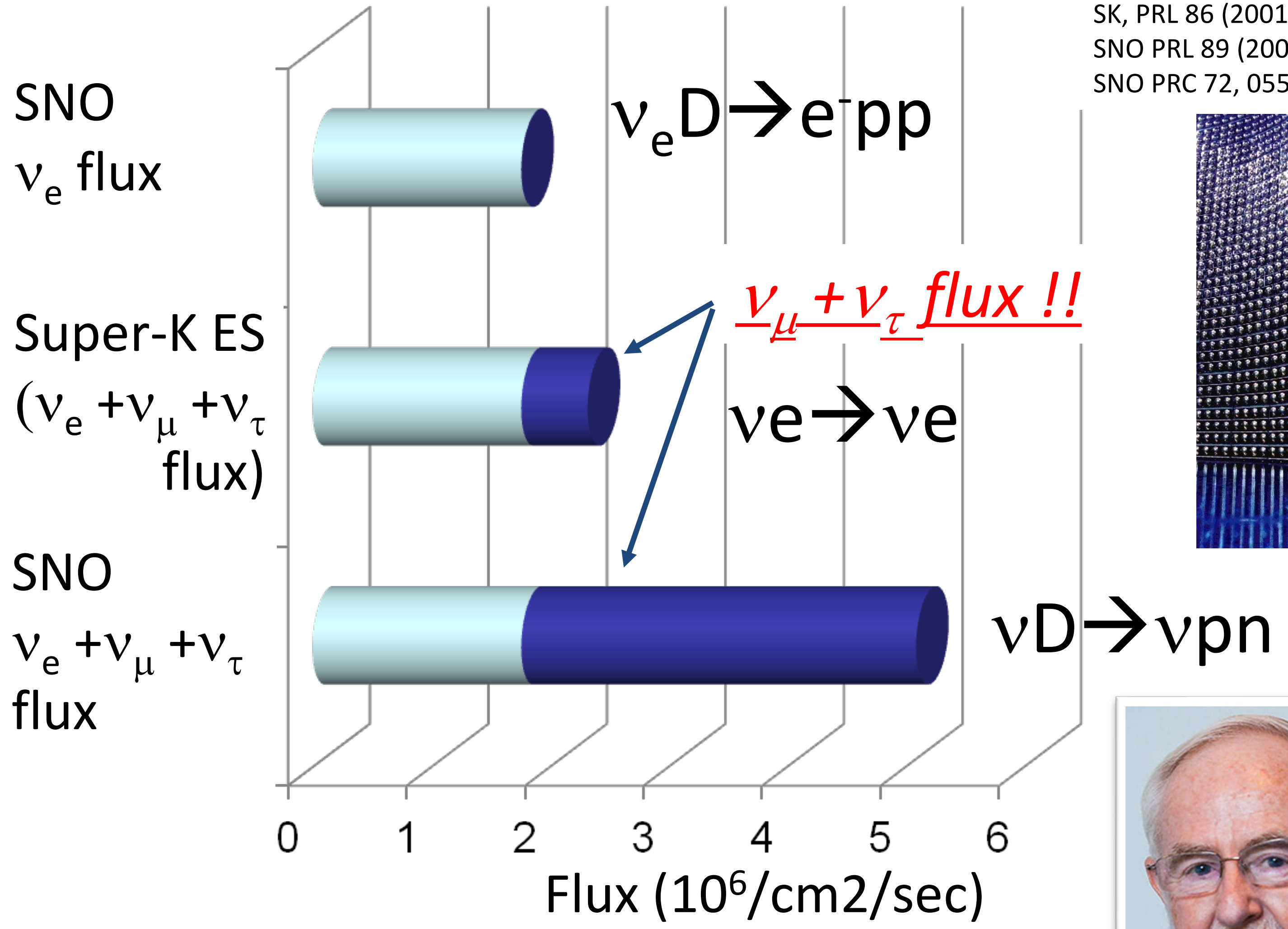
Kamiokande



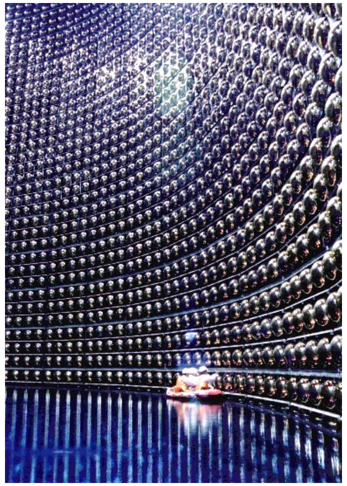
Gallex/GNO

- ✓ In the 20th century, several experiments observed solar neutrinos.
- ✓ These solar neutrino experiments found that the numbers of observed neutrino events were significantly fewer than expected.
- ✓ We did not know why the solar neutrinos were missing.

Solar neutrino oscillation (2001-2002)



SK, PRL 86 (2001) 5651
SNO PRL 89 (2002) 011301
SNO PRC 72, 055502 (2005)



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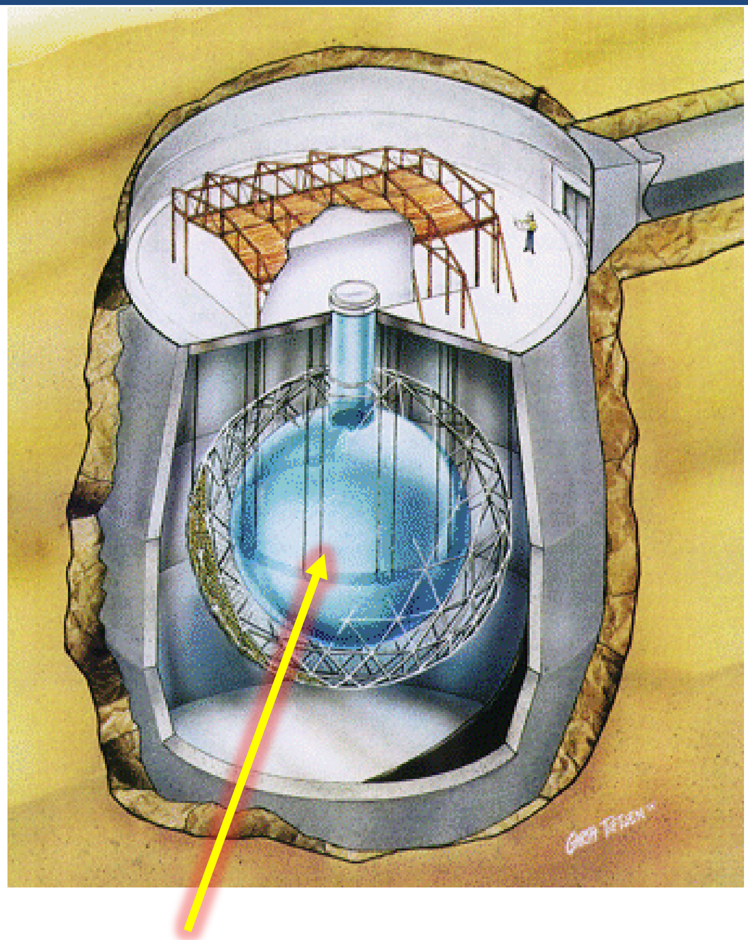
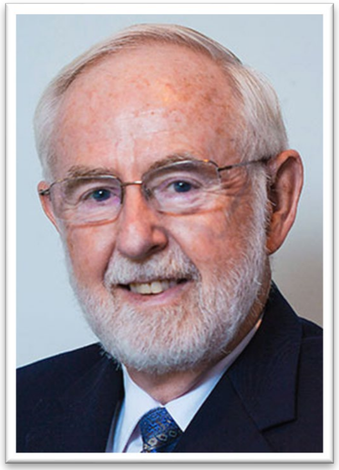


SNO 1000 ton of heavy water (D_2O) detector

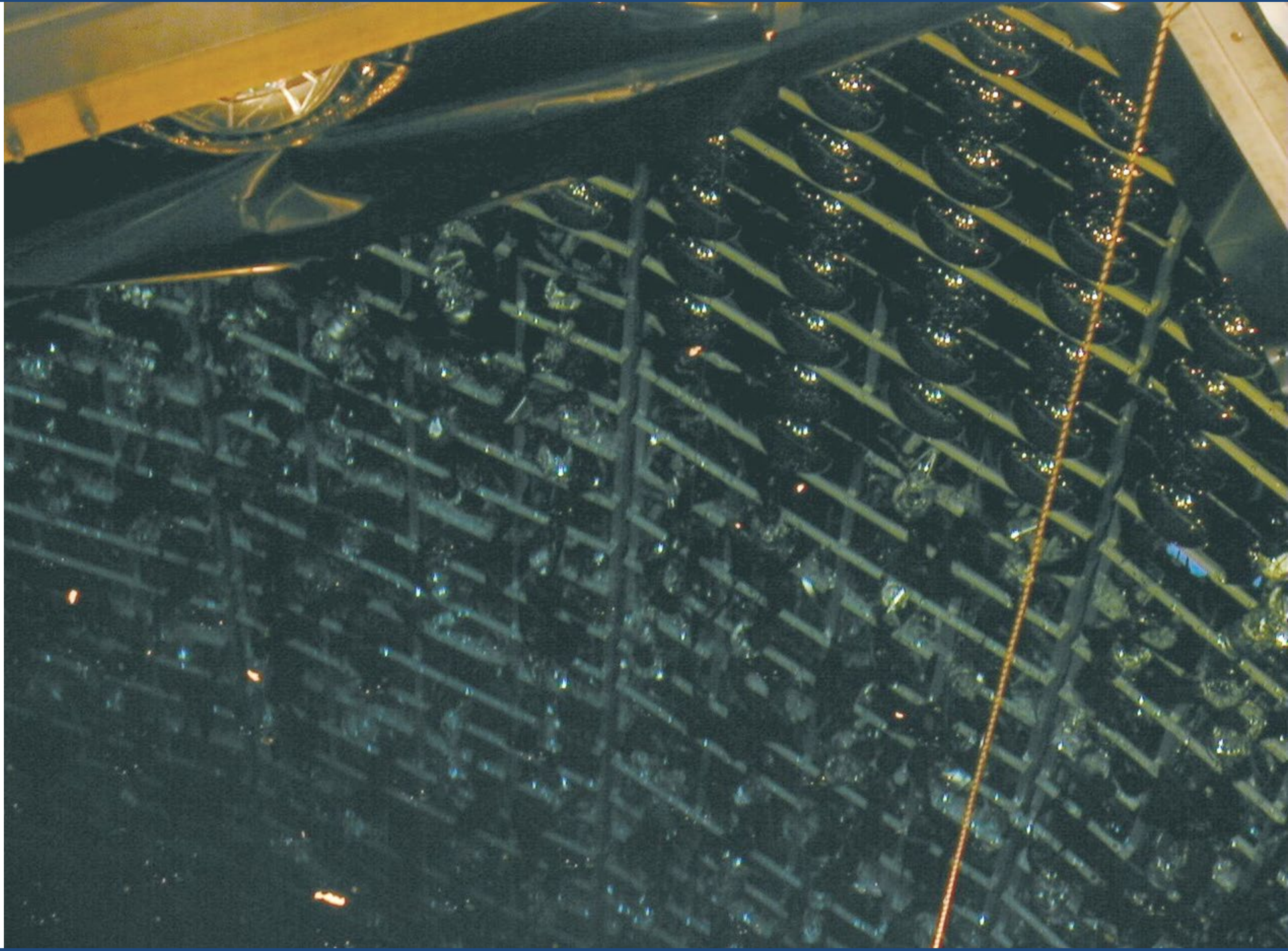
Neutrino oscillation: electron neutrinos to the other neutrinos.



Art McDonald
Photo: K. MacFarlane. Queen's University /SNOLAB

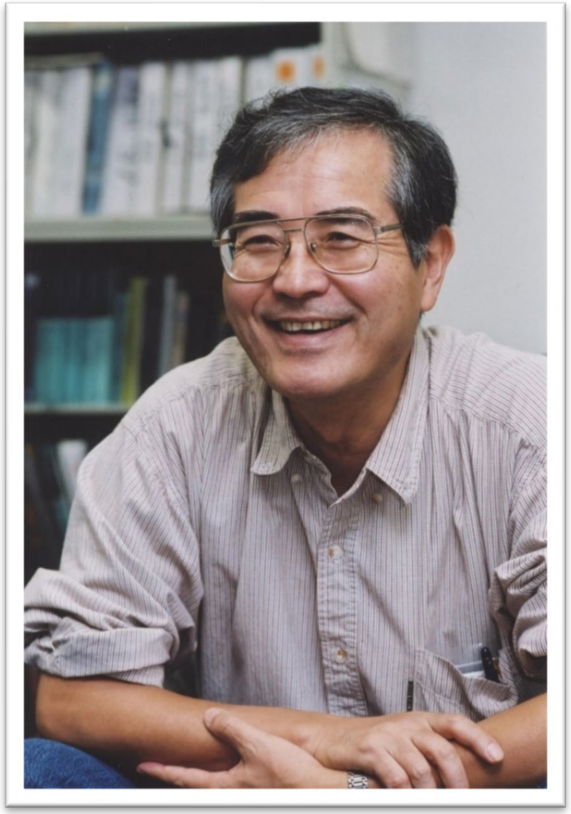
Accident on Nov. 12, 2001

On November 12, 2001, after completing the repairs of Super-K and while filling pure water into the Super-K tank, more than half of the photomultiplier tubes (PMTS) broke in an instant.



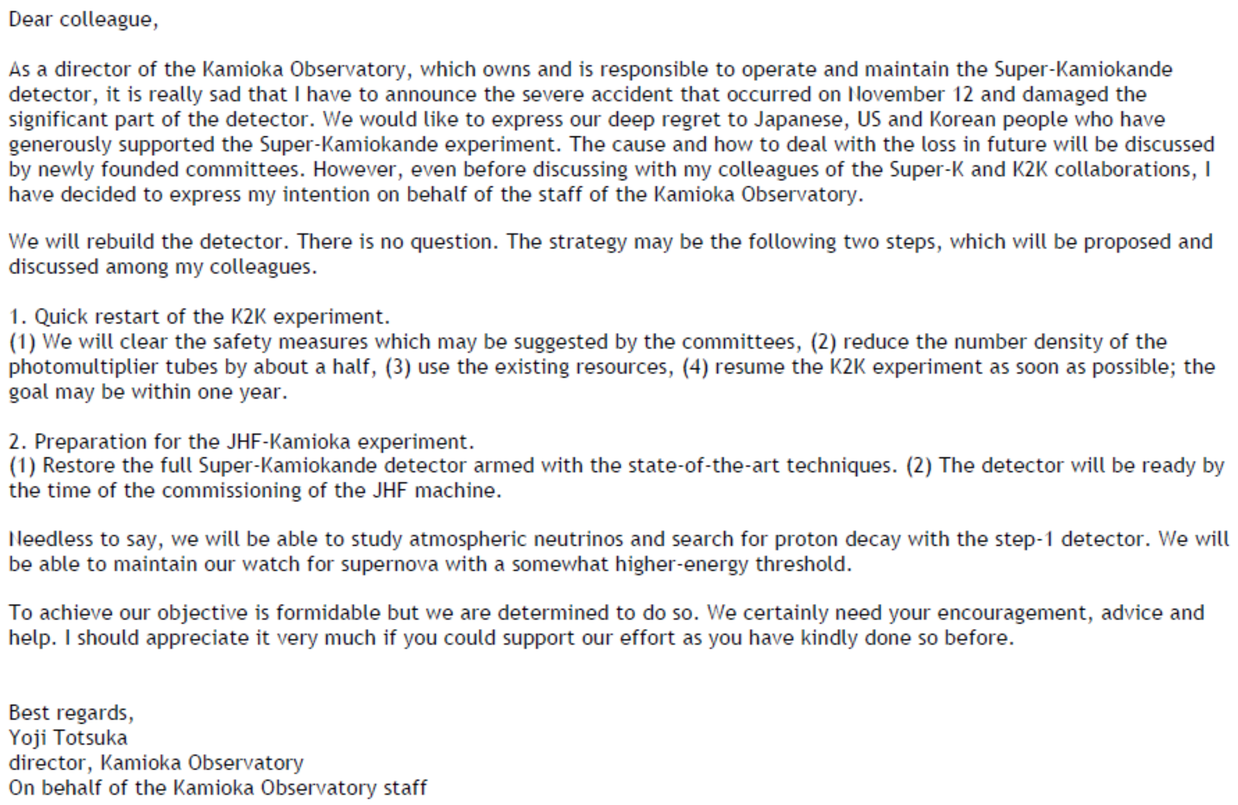
Inside of Super-K, soon after the accident.

Next day



Message from Prof. Yoji Totsuka (website of the Kamioka Observatory)

Yoji Totsuka


Dear colleague,

As a director of the Kamioka Observatory, which owns and is responsible to operate and maintain the Super-Kamiokande detector, it is really sad that I have to announce the severe accident that occurred on November 12 and damaged the significant part of the detector. We would like to express our deep regret to Japanese, US and Korean people who have generously supported the Super-Kamiokande experiment. The cause and how to deal with the loss in future will be discussed by newly founded committees. However, even before discussing with my colleagues of the Super-K and K2K collaborations, I have decided to express my intention on behalf of the staff of the Kamioka Observatory.

We will rebuild the detector. There is no question. The strategy may be the following two steps, which will be proposed and discussed among my colleagues.

1. Quick restart of the K2K experiment.
(1) We will clear the safety measures which may be suggested by the committees, (2) reduce the number density of the photomultiplier tubes by about a half, (3) use the existing resources, (4) resume the K2K experiment as soon as possible; the goal may be within one year.

2. Preparation for the JHF-Kamioka experiment.
(1) Restore the full Super-Kamiokande detector armed with the state-of-the-art techniques. (2) The detector will be ready by the time of the commissioning of the JHF machine.

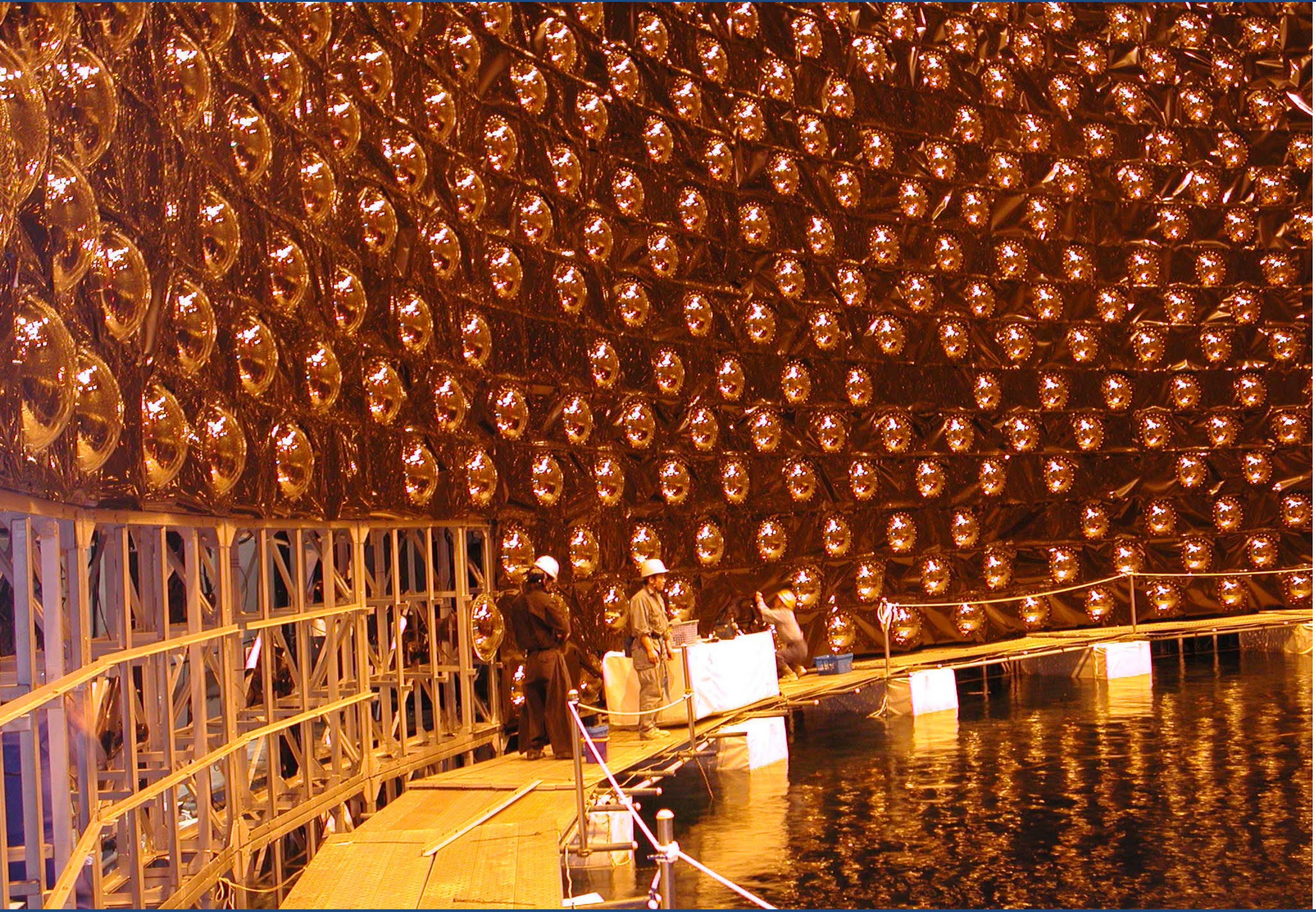
Needless to say, we will be able to study atmospheric neutrinos and search for proton decay with the step-1 detector. We will be able to maintain our watch for supernova with a somewhat higher-energy threshold.

To achieve our objective is formidable but we are determined to do so. We certainly need your encouragement, advice and help. I should appreciate it very much if you could support our effort as you have kindly done so before.

Best regards,
Yoji Totsuka
director, Kamioka Observatory
On behalf of the Kamioka Observatory staff

The next day, Professor Yoji Totsuka, who was the leader of Super-K, announced to the world on the website, "We will rebuild the detector. There is no question (on this decision).“
Thanks to the quick and clear decision-making in the midst of the crisis, we were able to move forward together toward the recovery with the support of many people. I am truly grateful to him. I believe that this is what leadership is all about.

(Partial) Reconstruction of Super-Kamiokande (2002)



Thanks to the strong leadership and strong support by various people, including UTokyo and MEXT, Super-Kamiokande collaboration was able to reconstruct the detector with the survived photomultiplier tubes (PMTS) in 2002 (photo).

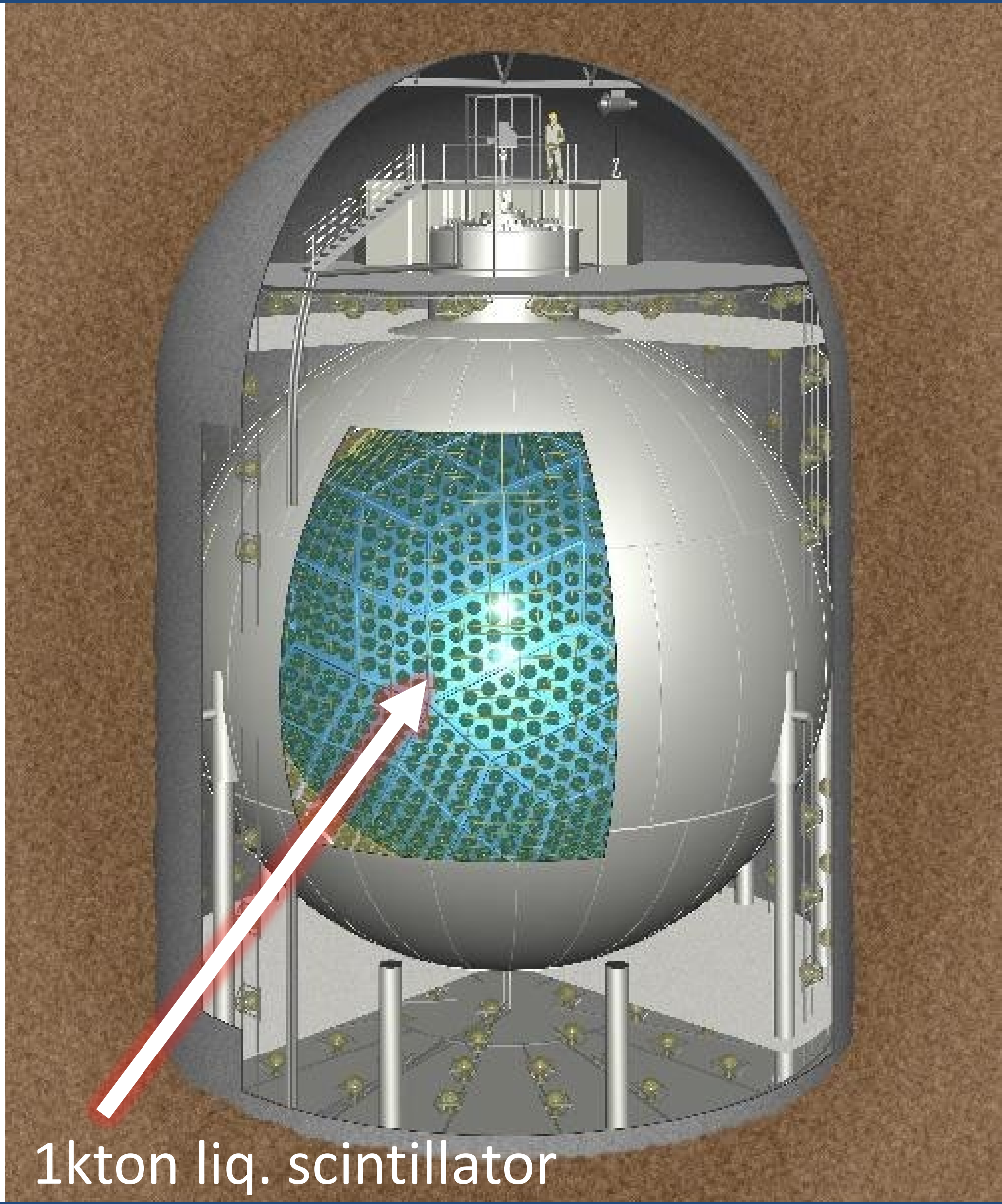
Finally, in 2006, Super-K was fully recovered to the original configuration with 11,000 PMTs.

KamLAND

History of KamLAND

A.Suzuki, Proc. Of Neutrino 1998, Nucl. Phys. B (Proc. Suppl.) 99 (1999) 171.
Atsuto Suzuki, JPSJ, 55 (2000) 594 (in Japanese)

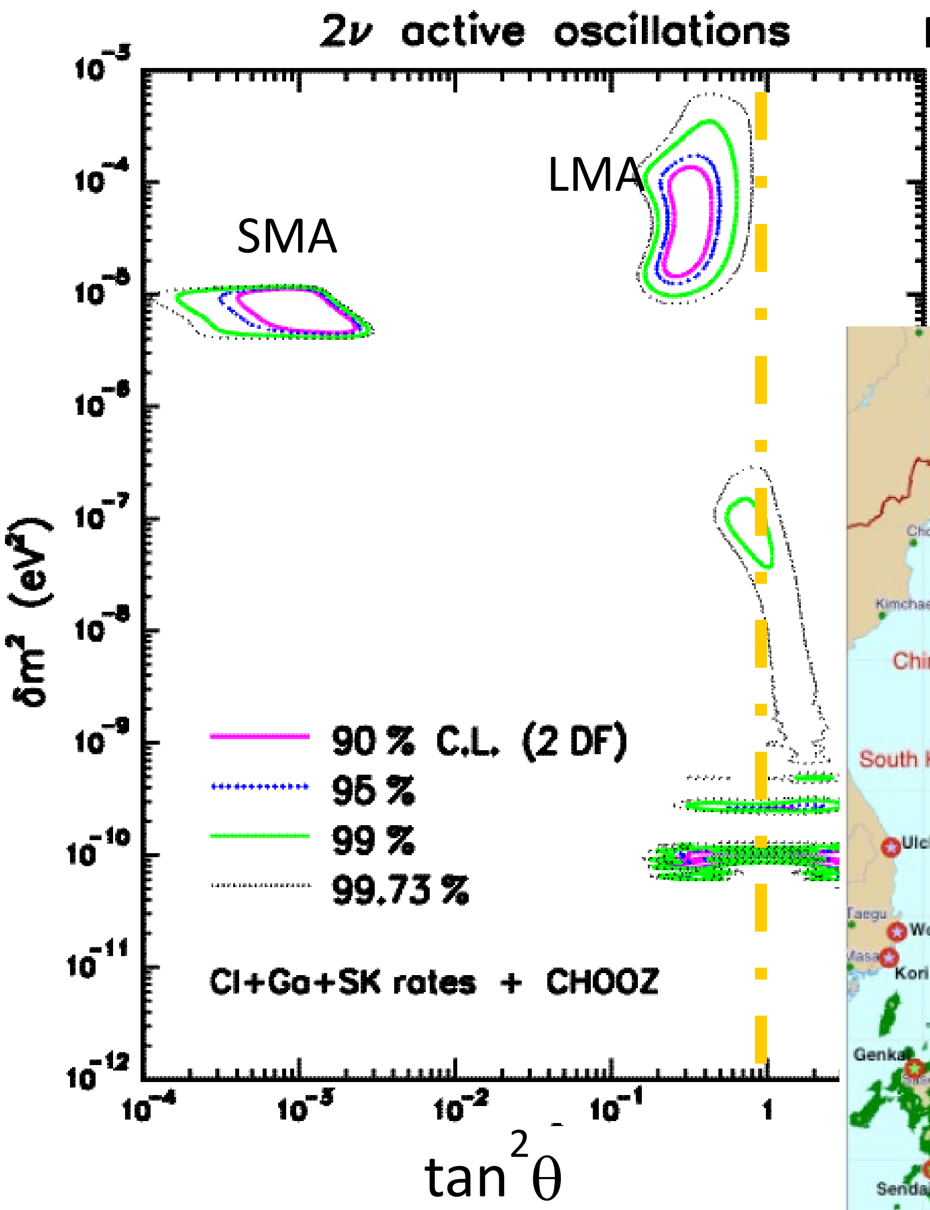
- ✓ The Kamiokande collaboration did not have any plan to use the Kamiokande cavity/facility after the start of the Super-Kamiokande experiment. (They are too busy for the Super-Kamiokande experiment.)
- ✓ Atsuto Suzuki had an idea to use the Kamiokande cavity/facility for a new experiment. The R&D for the new experiment was started in 1993(?). The KamLAND experiment was proposed in 1994.
- ✓ Atsuto Suzuki moved to Tohoku University and was also asked to reform "bubble chamber analysis facility" to a new organization on neutrino physics. He created "Research Center for Neutrino Science" in Tohoku University.
- ✓ The construction of KamLAND was approved in 1997.



KamLAND reactor oscillation experiment

- ✓ Before 2000, there were 2 (or 4 depending how you count) neutrino-oscillation solutions to the solar neutrino problem: Small Mixing Angle (SMA) solution and Large Mixing Angle (LMA) solution.
- ✓ In early 2000's, there were many nuclear power stations around KamLAND at the distance of about 180 km.

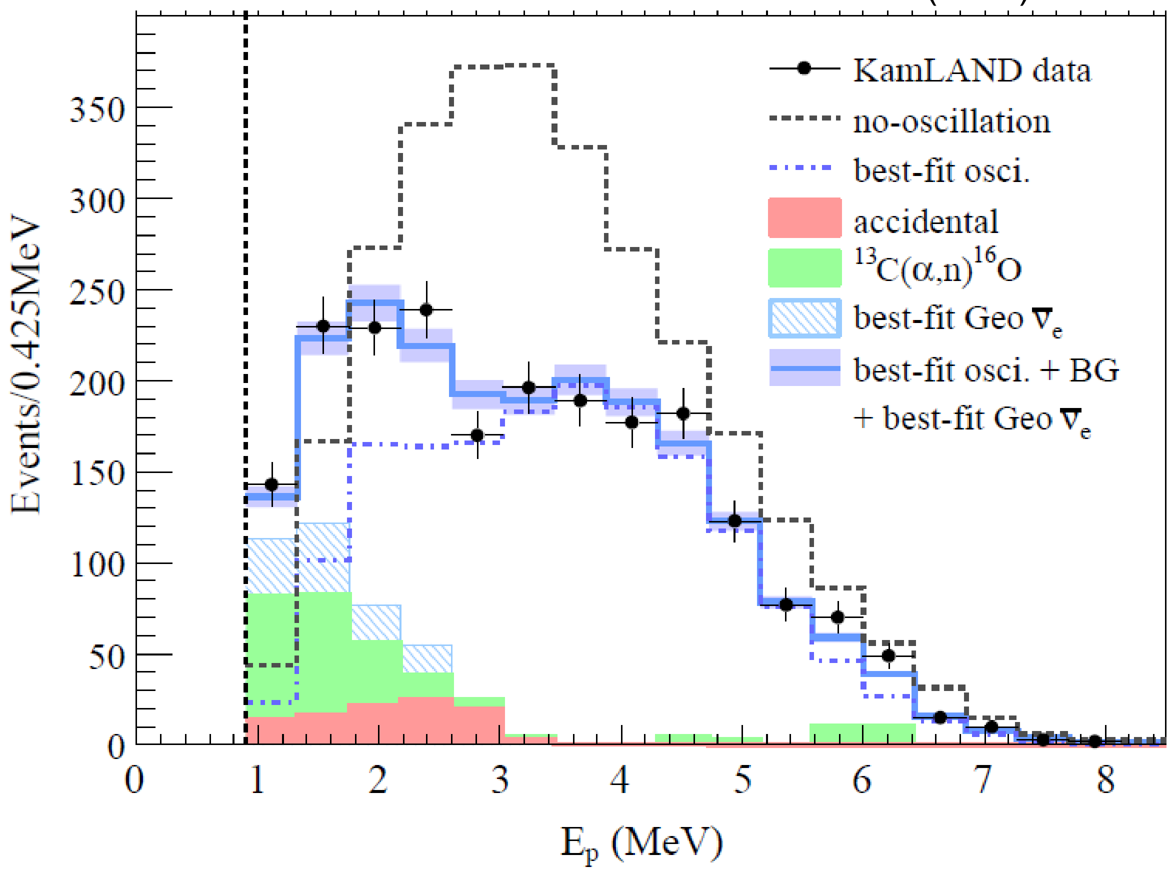
➔ Long baseline reactor neutrino osc. experiment that can test Large Mixing Angle solution.



Fogli et al.

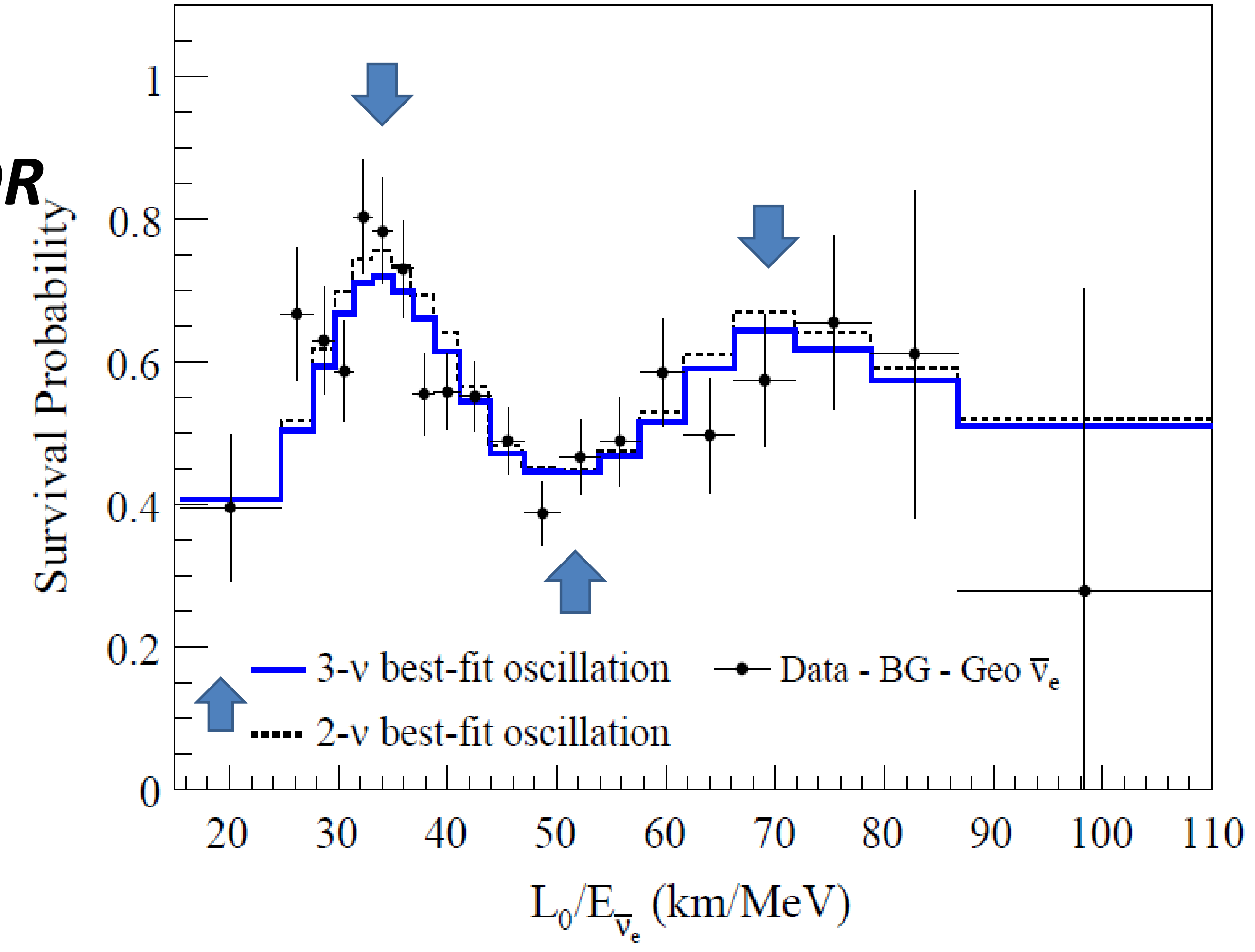
Really neutrino oscillations

KamLAND PRD 83 (2011) 052002



Energy spectrum of neutrinos from nuclear power stations observed in KamLAND.

OR



Really neutrino oscillations!

In addition, KamLAND observed geo-neutrinos for the first time.

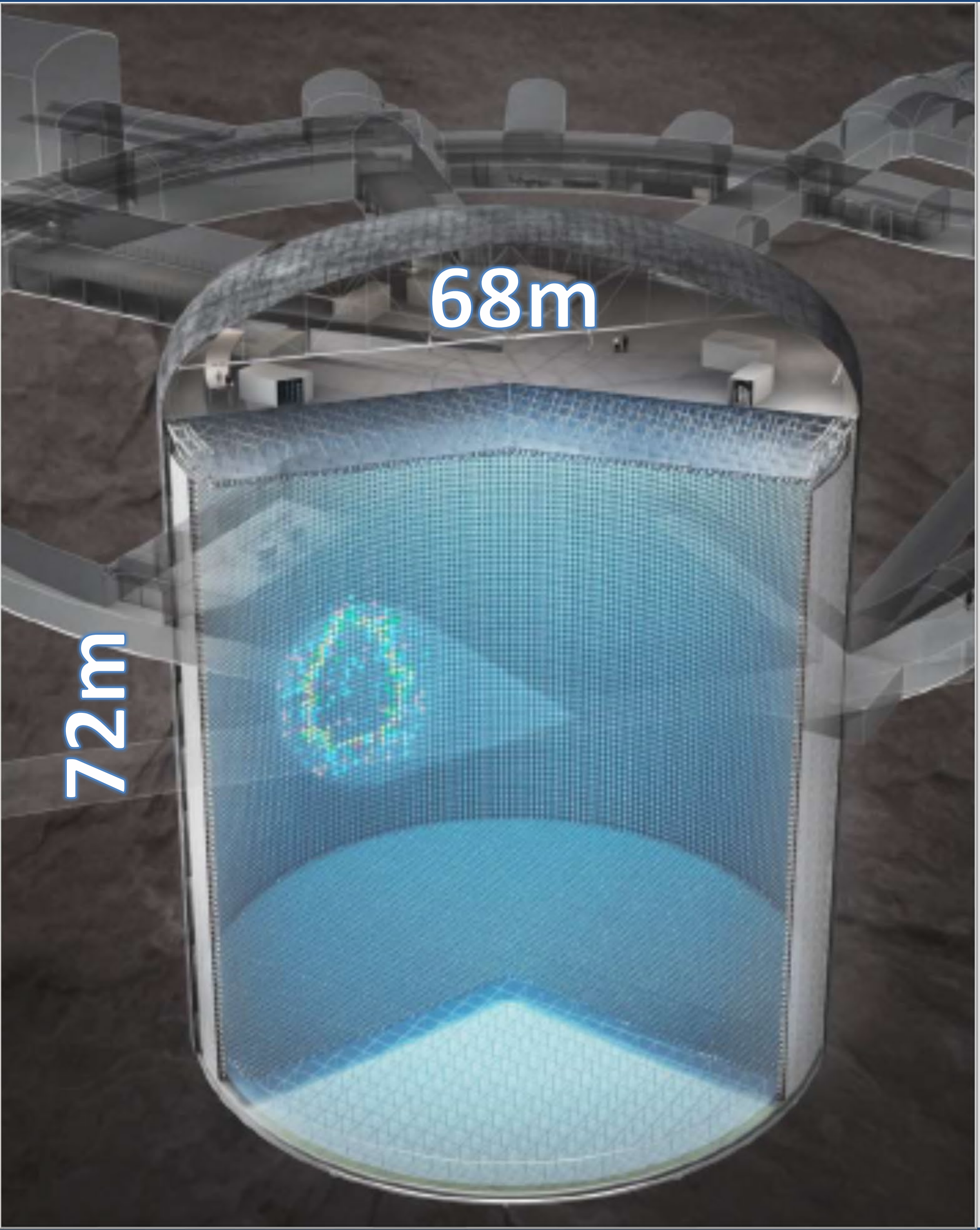
Hyper-Kamiokande

Neutrino physics

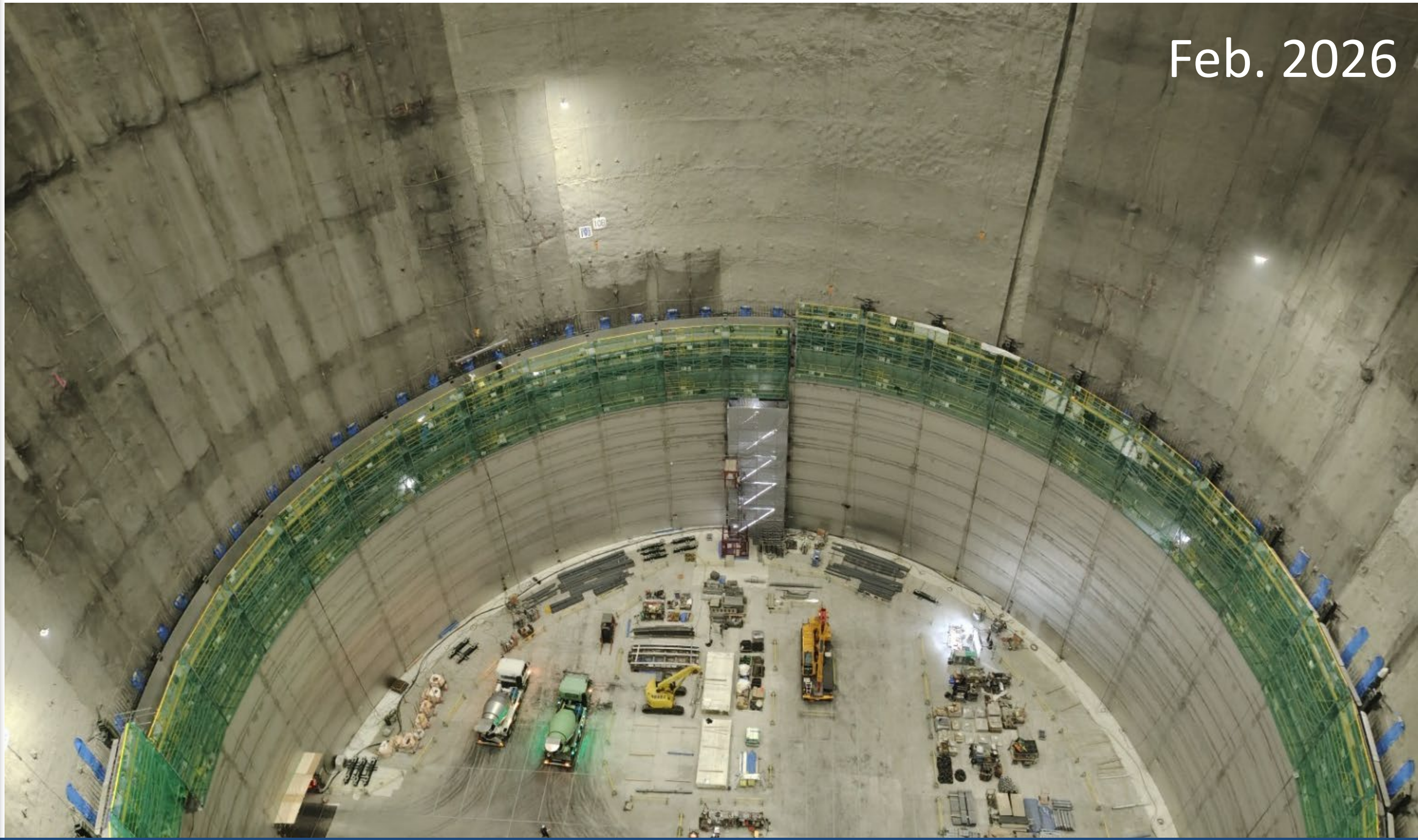
- Neutrino oscillations, namely the small neutrino mass, opened a window to study physics beyond the Standard Model of particle physics.
- It has been pointed out that neutrinos with very small mass might be the key to understand a fundamental question in the Universe; why the present Universe is dominated by matter (without any anti-matter) while, at the time of the Big Bang, the number of matter particles and antimatter particles must had been equal.

→ Next generation of neutrino facilities

Hyper-Kamiokande

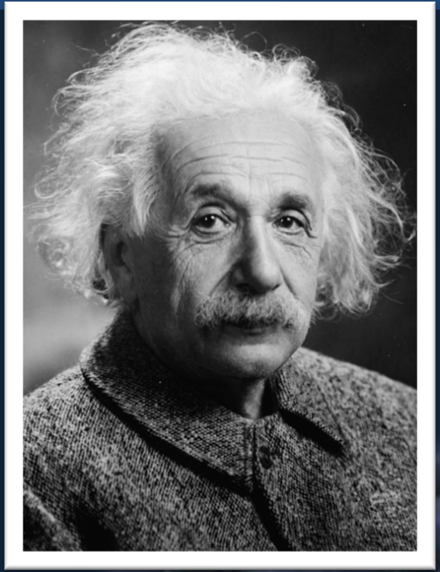


- Much larger facility with many important research topics in neutrino physics and astrophysics.
- ~650 collaborators from 23 countries.
- The experiment will start in ~2028!



Gravitational waves

Gravitational waves



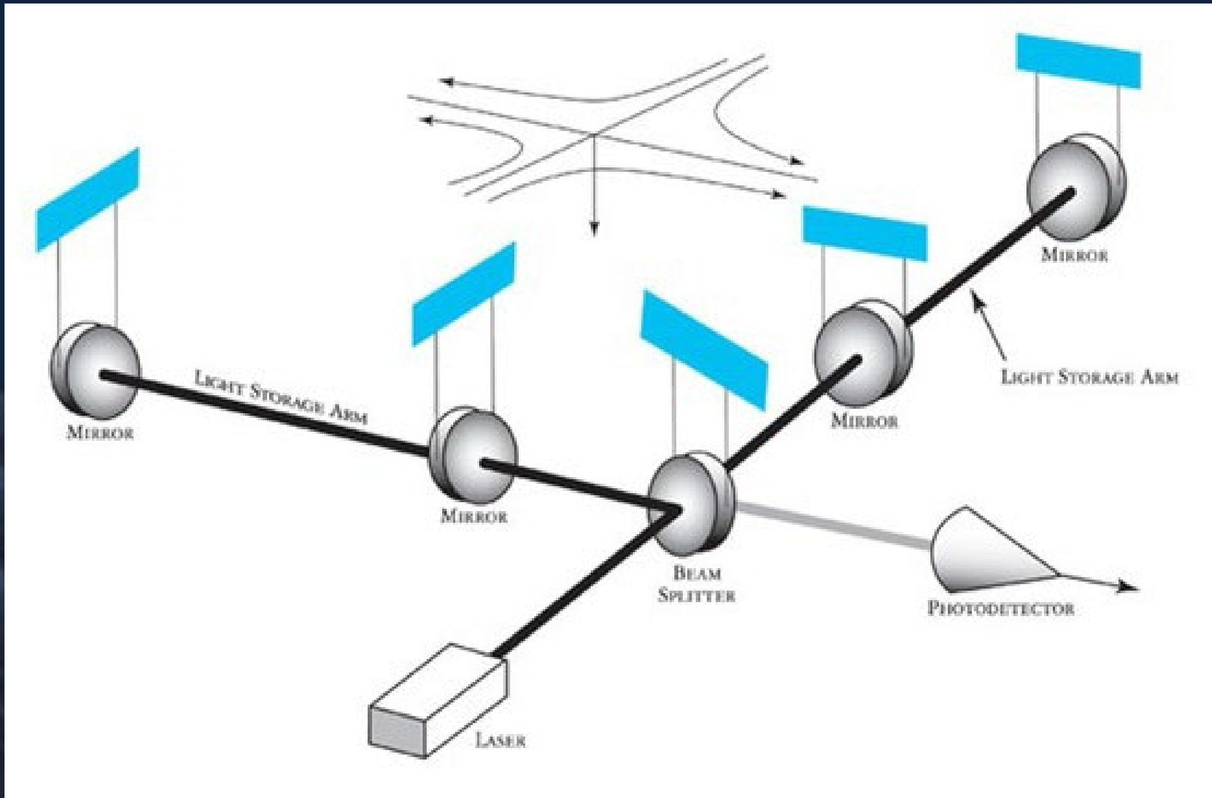
A.Einstein
(by Oren. J. Turner, Wikipedia)

A. Einstein predicted gravitational waves in 1916 based on his theory of general relativity.

(Image credit: K. Thorne (Caltech) and T. Carnahan (NASA GSFC))

Image of the gravitational wave emission from a binary black hole system. These back holes merge, creating a new heavier black hole.

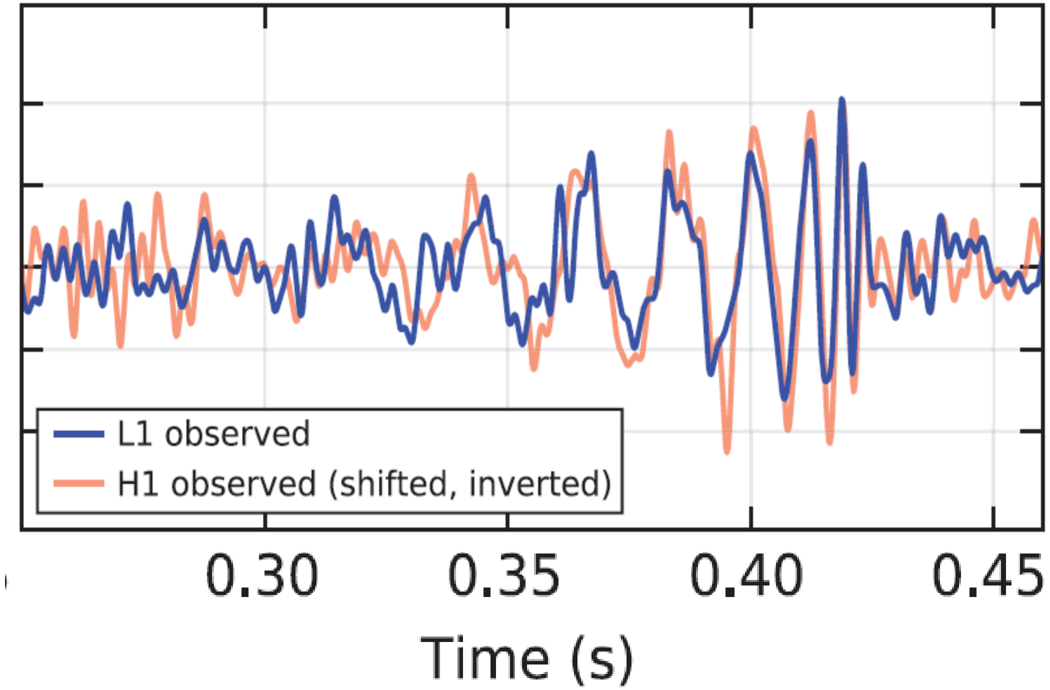
https://www.ligo.caltech.edu/page/what-is-interferometer



Laser interferometer technology is used to observe gravitational waves, because laser interferometers are very sensitive to the “length-change”.

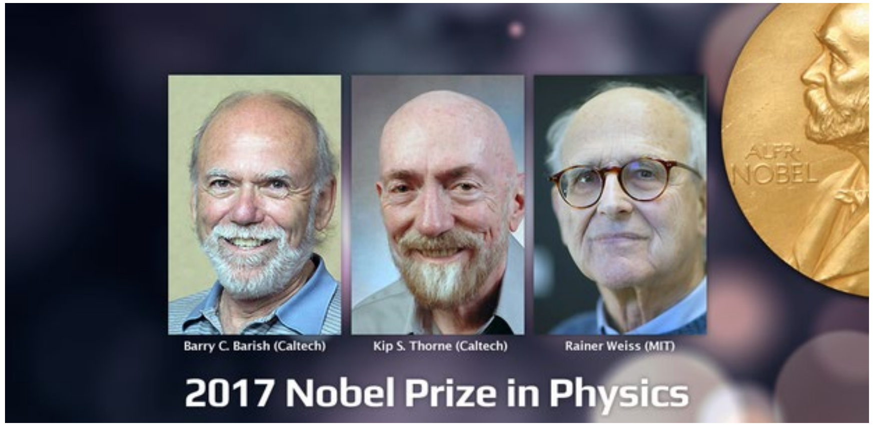
Discovery of gravitational waves

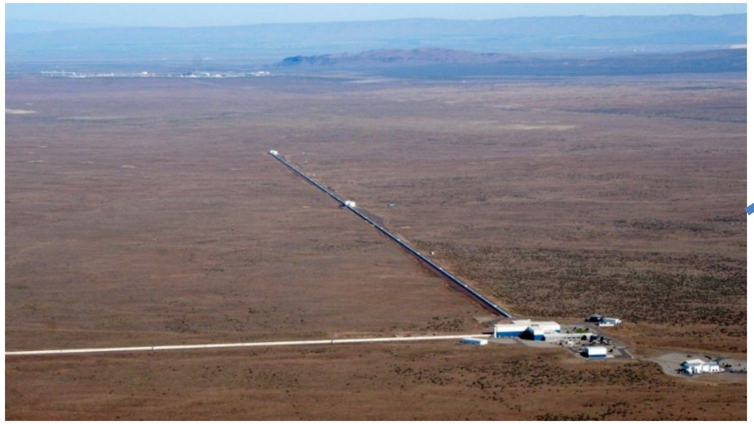
LIGO Scientific Collaboration and Virgo Collaboration, PRL, **116**, 061102 (2016)

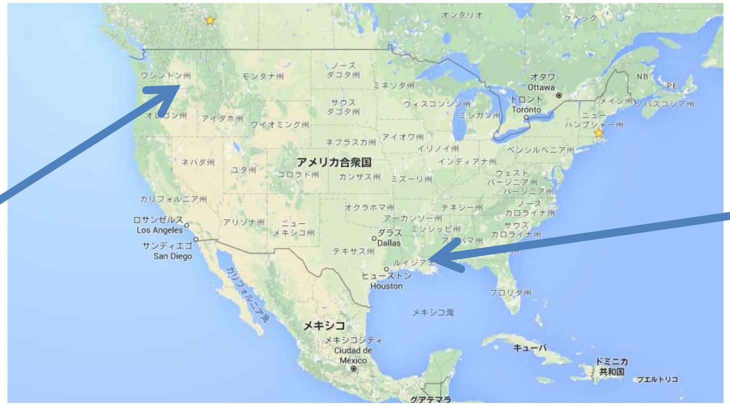


✓ On Sep. 14, 2015, LIGO observed the signal with the 2 laser interferometers. Data told us that 2 blackholes of 36 M_{Sun} and 29 M_{Sun}, respectively, merged at the distance of 1.3 Billion light-years.

✓ *Great discovery!*

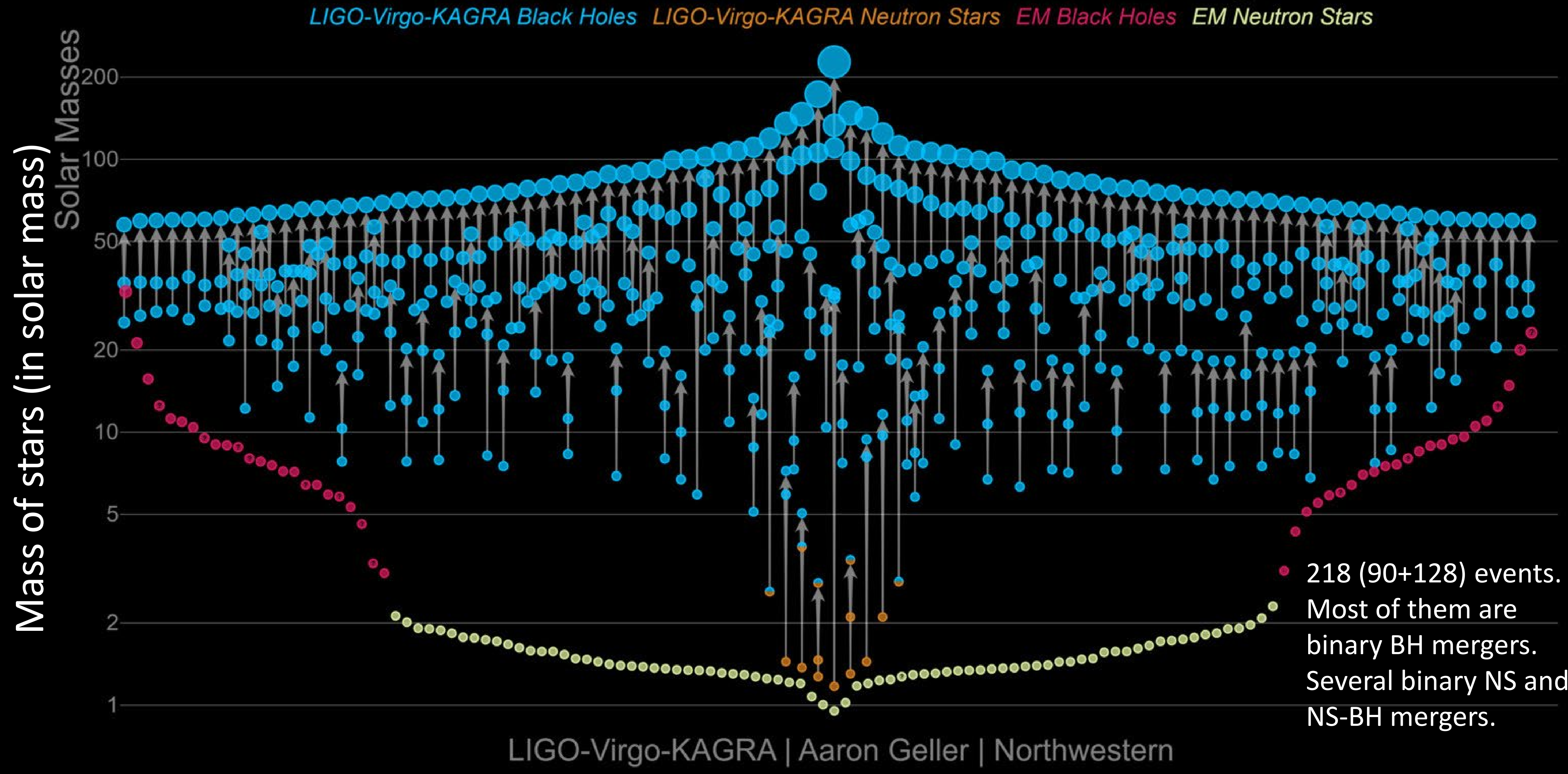






LIGO-Virgo observation summary (until Jan. 16, 2024)

https://www.ligo.caltech.edu/news/ligo20250826



218 (90+128) events. Most of them are binary BH mergers. Several binary NS and NS-BH mergers.

KAGRA

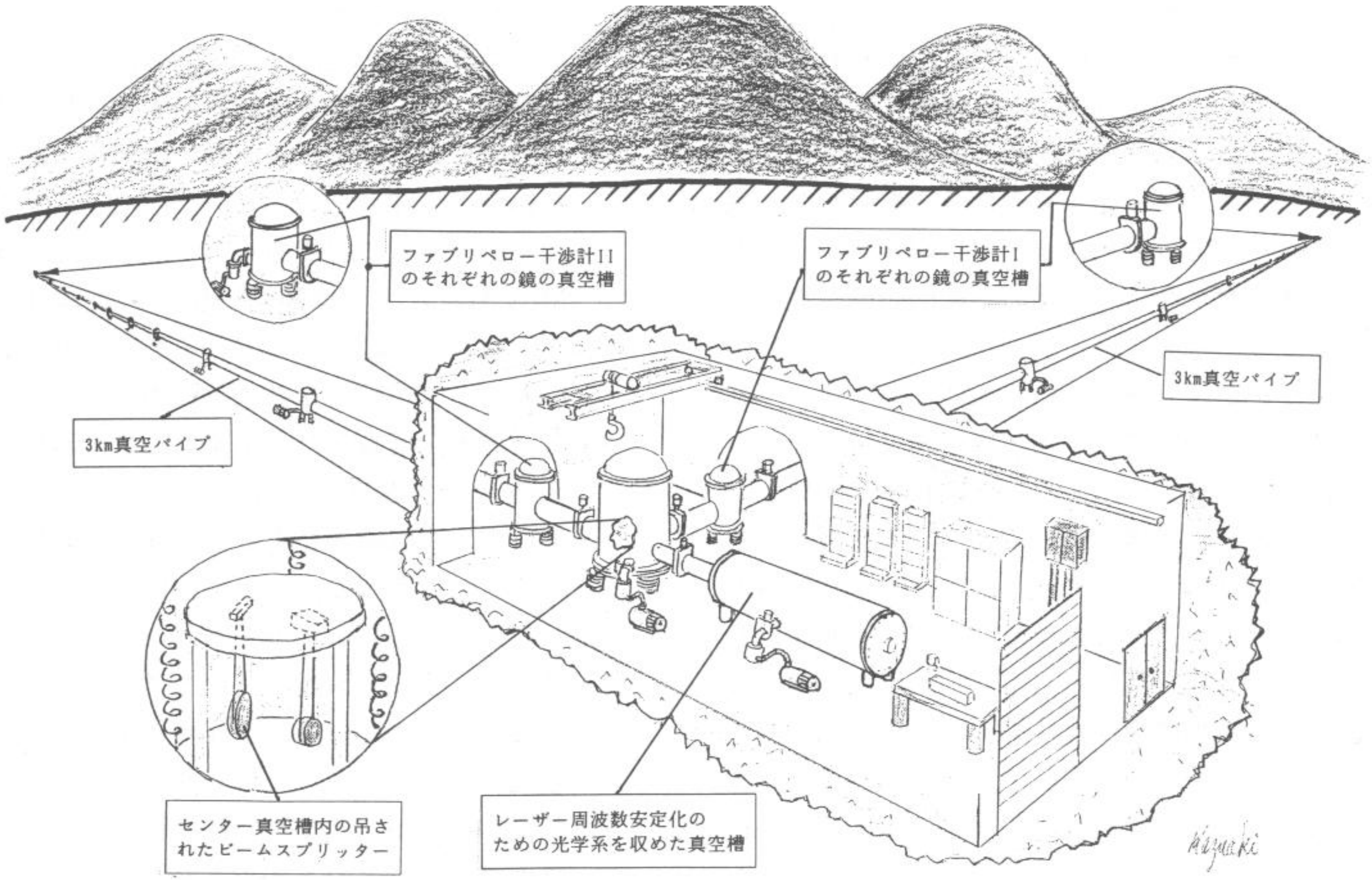
KAGRA collaboration

9 countries/regions, ~150 authors

(and ~450 collaborators)

Report: 2nd ICRR Future Project Planning Committee (1993)

- ✓ After the approval of the construction of the Super-kamiokane detector in 1991, ICRR leadership thought that it was the time to begin thinking about the next major projects in ICRR.
- ✓ 2nd ICRR future project planning committee was formed.
- ✓ The committee issued the report in 1993. They recommended two projects; one was on the projects on highest energy cosmic rays, and the other was the gravitational wave project.



レーザー干渉計型重力波検出装置

Image of a gravitational wave laser interferometer with the arm lengths of 3km X 3km in the 1993 report.

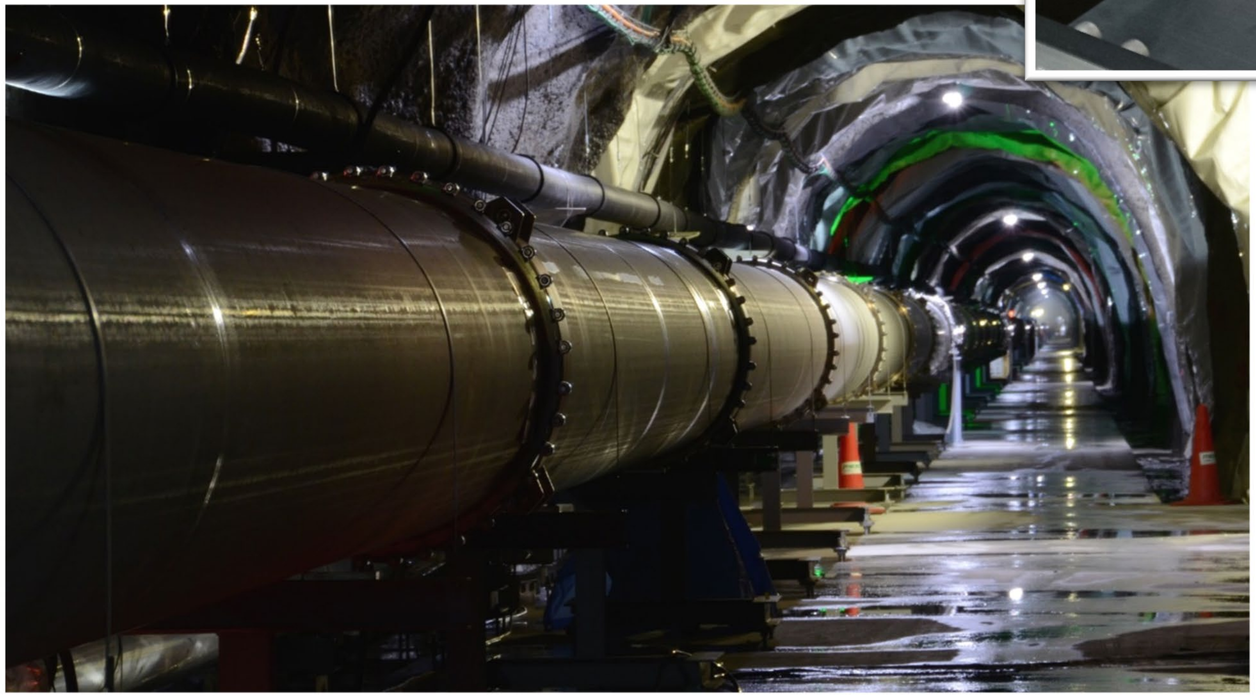
Location of KAGRA

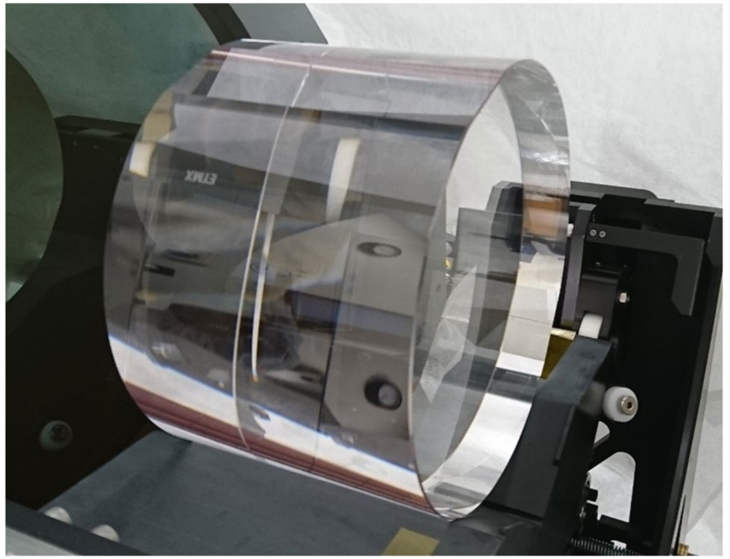
KAGRA was decided to be located in the same mountain as Super-Kamiokande (and KamLAND). This was because underground had significantly smaller seismic noises and we had already established good relations with the local people and the mine company through Kamiokande and Super-K.

KAGRA construction

For about 10 years, we worked hard to construct the KAGRA detector in underground.

3km vacuum tube (2015)





23kg sapphire mirror

Installing a mirror

Working together

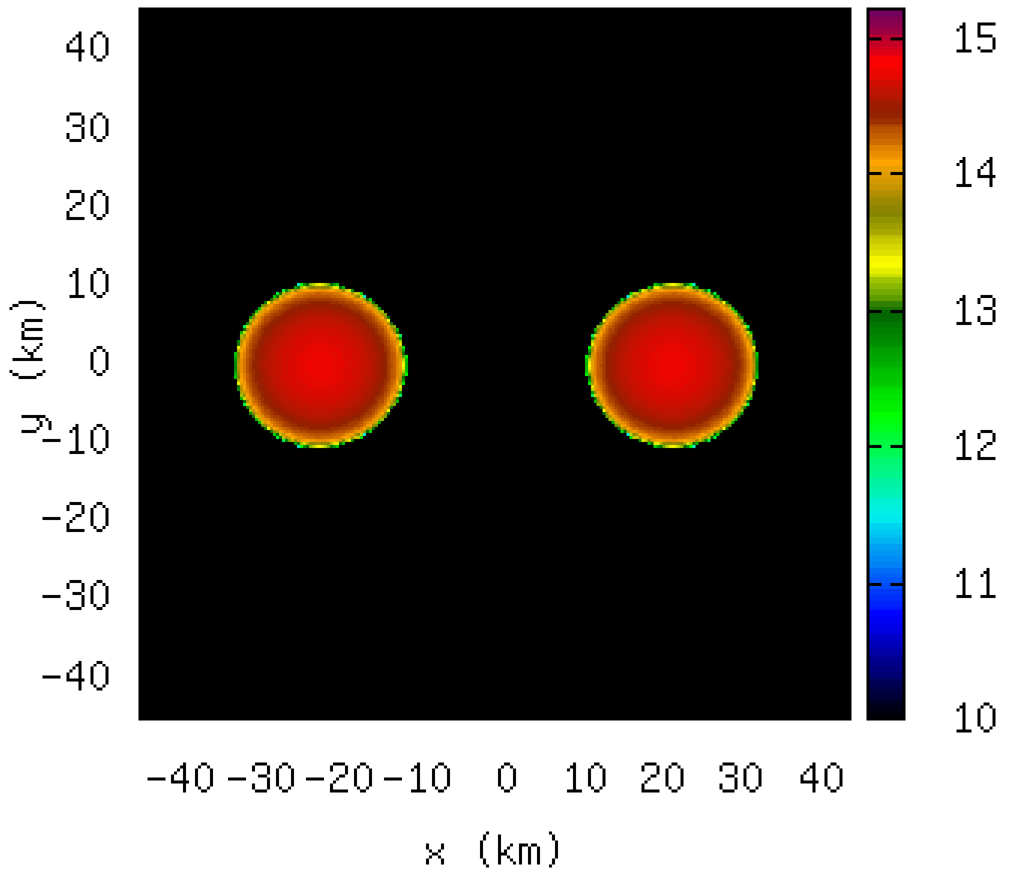
- To determine the location (direction) of the source, we need at least 3 detectors which are located far apart from each other.
- The GW detectors (LIGO, Virgo, and KAGRA) work together, namely we are observing GWs simultaneously, sharing the data, and analyzing the data as a team.
- KAGRA (re)joined the observation on June 11, 2025, recovering from a strong earthquake on Jan. 1, 2024. (We still have to improve the sensitivity further.)

KAGRA in the 2030's

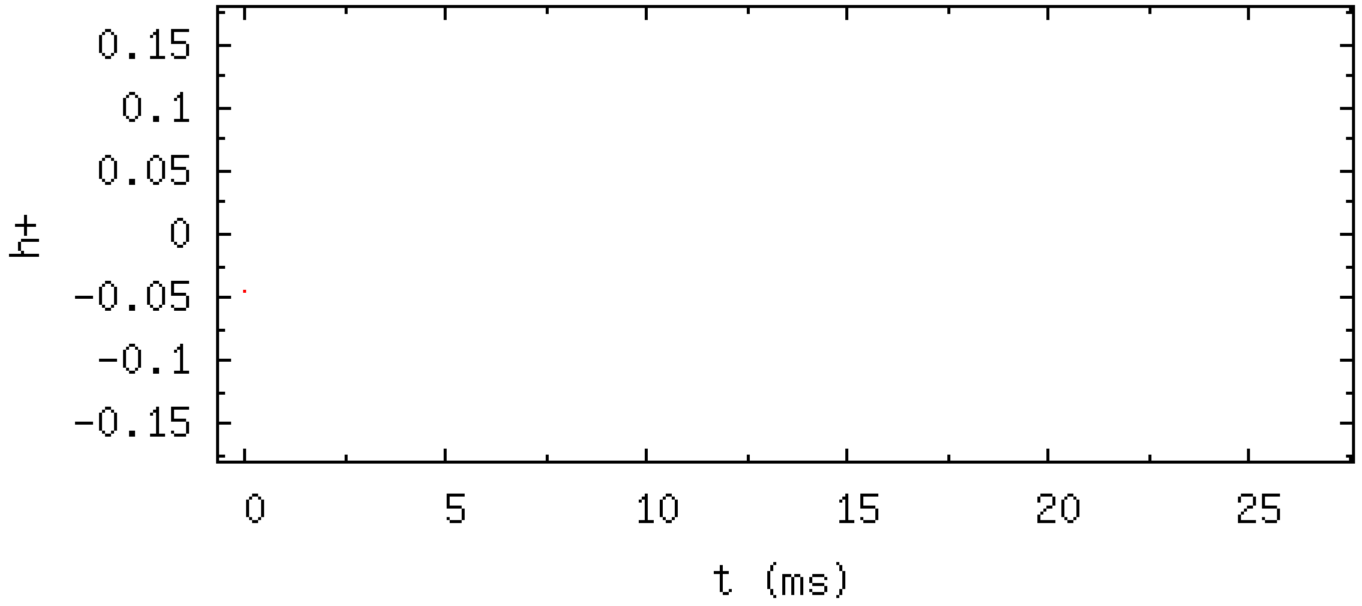
arXiv:2508.03392v1 [gr-qc]

Simulated binary neutron-star merger

M. Shibata, Kyoto Univ



Gravitational wave



Based on scientific importance and the feature of the KAGRA interferometer, KAGRA decided to improve the sensitivity in the kHz range.

⇒

KAGRA would like to make a unique contribution in the International LIGO-Virgo-KAGRA network in the 2030's and beyond!

Summary

- *The story of Kamioka underground facilities started about 50 years ago.*
- *During this 50 years, the facilities have been expanded, both in the number and the size.*
- *These facilities have contributed to physics and astrophysics and will continue to do so.*