The Evolution of Neutrino Physics at Kamioka over the Last 40 Years

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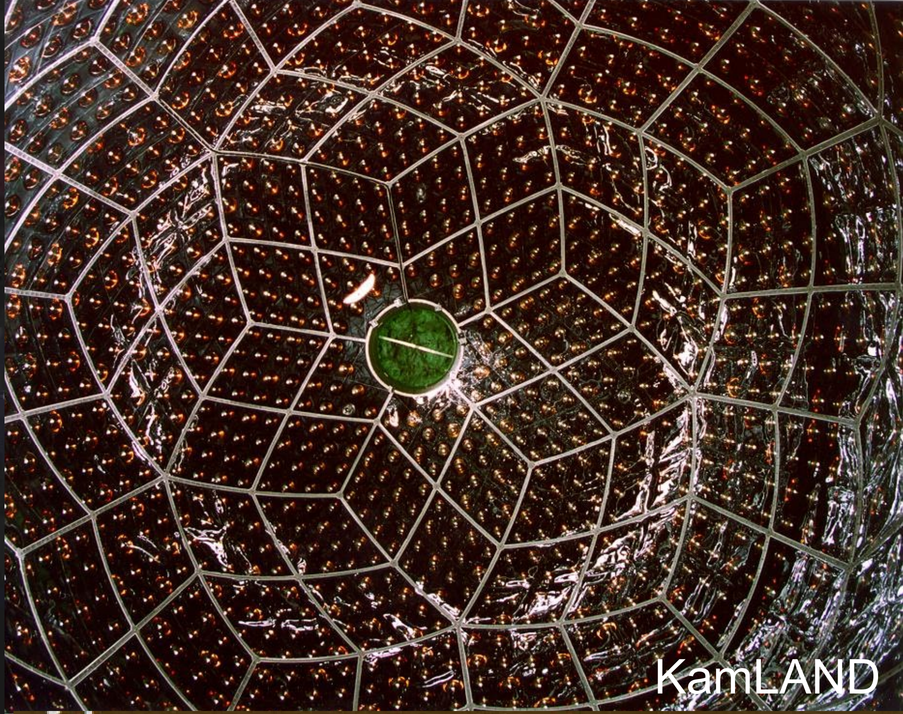
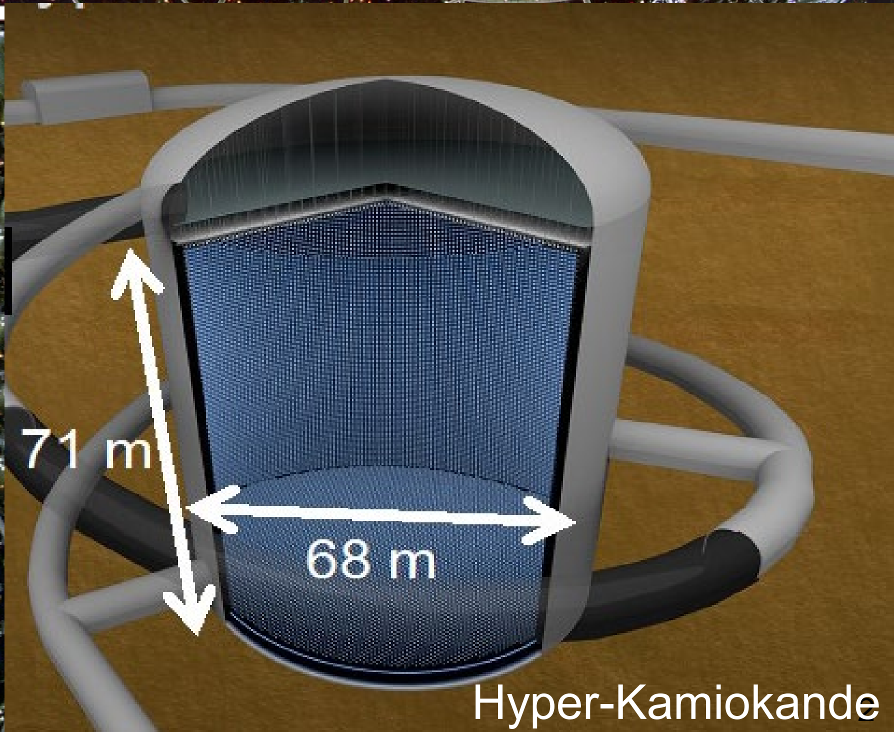
ICRR, Univ. of Tokyo

July 22, 2025

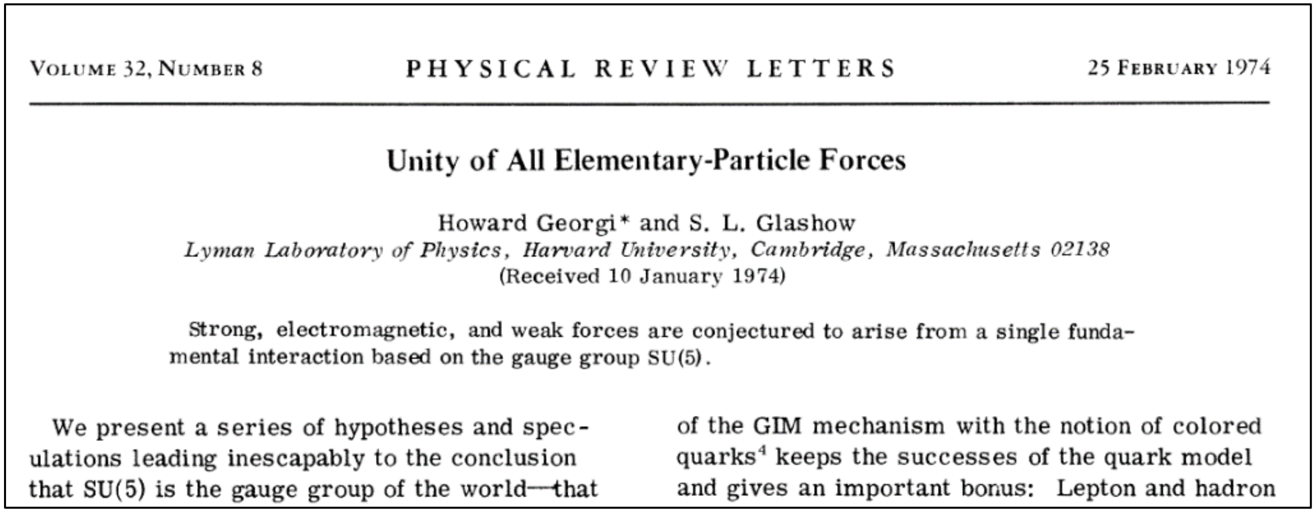

Kamiokande

KamLAND

Super-Kamiokande

71 m
68 m
Hyper-Kamiokande

Contents

- The beginning of our research at Kamioka: What were we aiming for?
- Initial struggles
- What started the evolution
- From anomaly to discovery
- More discoveries
- The Super-K accident
- Recovery from the accident
- Future prospects

Prediction of GUTs in 1970's



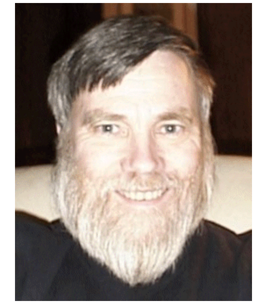
VOLUME 32, NUMBER 8 PHYSICAL REVIEW LETTERS 25 FEBRUARY 1974

Unity of All Elementary-Particle Forces

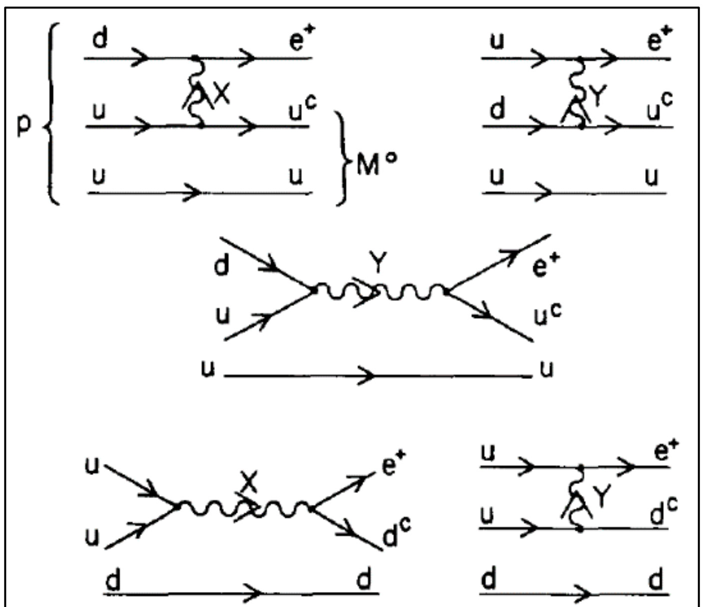
Howard Georgi* and S. L. Glashow
Lyman Laboratory of Physics, Harvard University, Cambridge, Massachusetts 02138
(Received 10 January 1974)

Strong, electromagnetic, and weak forces are conjectured to arise from a single fundamental interaction based on the gauge group SU(5).

We present a series of hypotheses and speculations leading inescapably to the conclusion that SU(5) is the gauge group of the world—that of the GIM mechanism with the notion of colored quarks[4] keeps the successes of the quark model and gives an important bonus: Lepton and hadron



Georgi and Glashow



P. Langacker, Phys. Rep. 72, No.4(1981) 185.

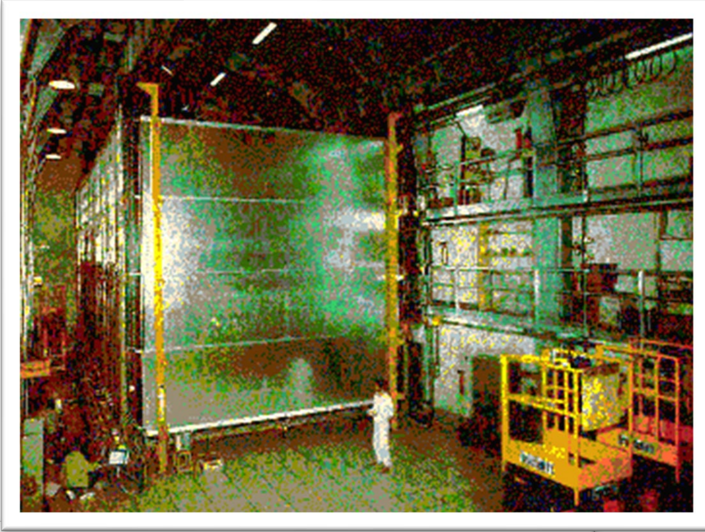
Proton decay was predicted.

Expected number of proton decay events was 30 ~ 300 events/1000ton/year for 10^{31} ~ 10^{30} years of proton lifetime.

Large proton decay detectors were constructed in 1980's

IMB (3300 ton)

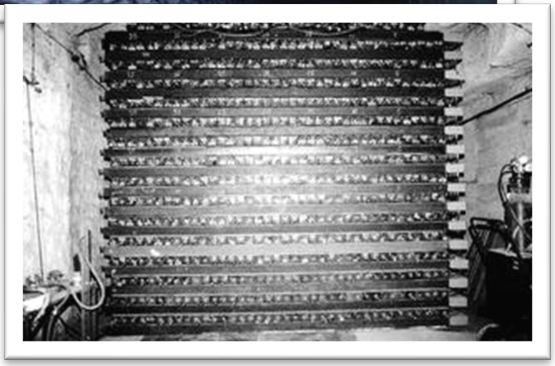
Frejus
(700 ton)



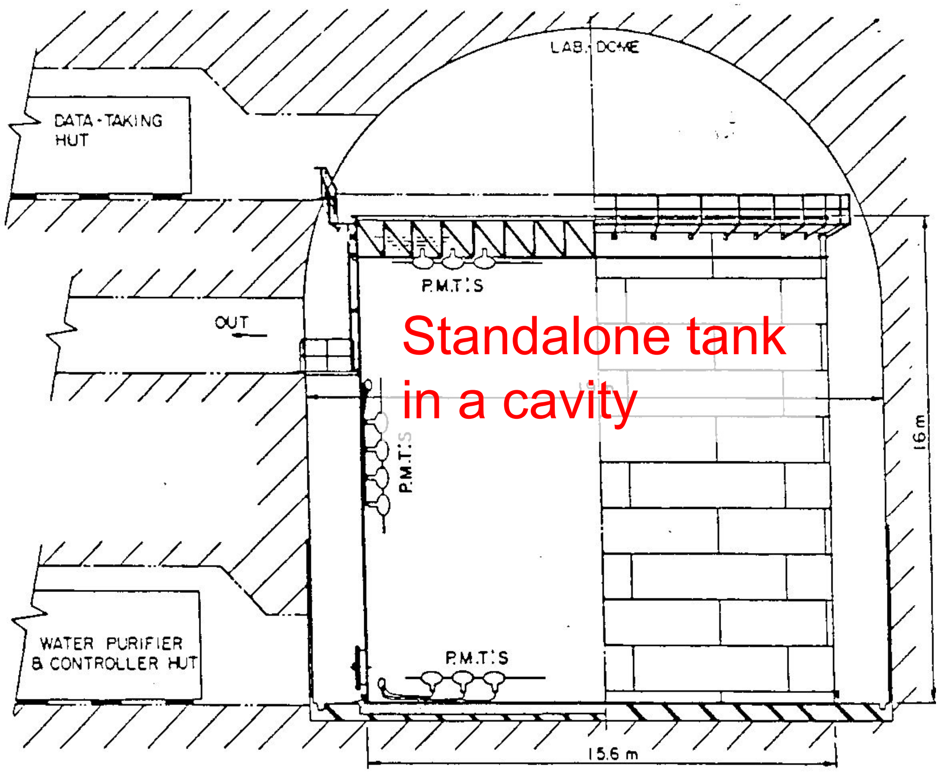
Kamiokande (1000 ton)

NUSEX
(130 ton)

KGF
(~100 ton)



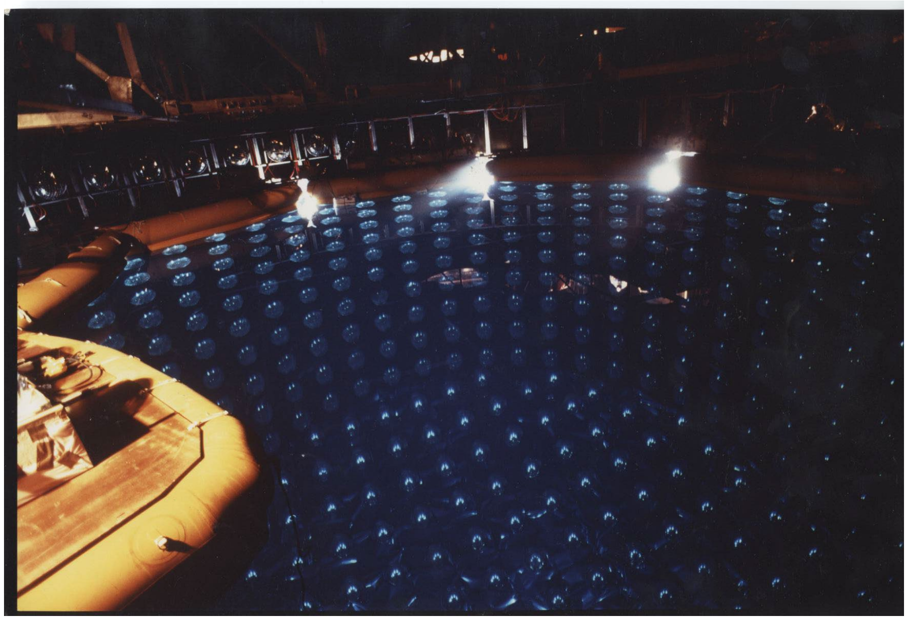
Kamiokande-I detector（1983－1984）



Original purpose:

Search for proton decay

Inner detector only, i.e. no outer detector.
Readout of charge information only (i.e. no timing information).



Fiducial volume: 880 ton
(2m from the wall)

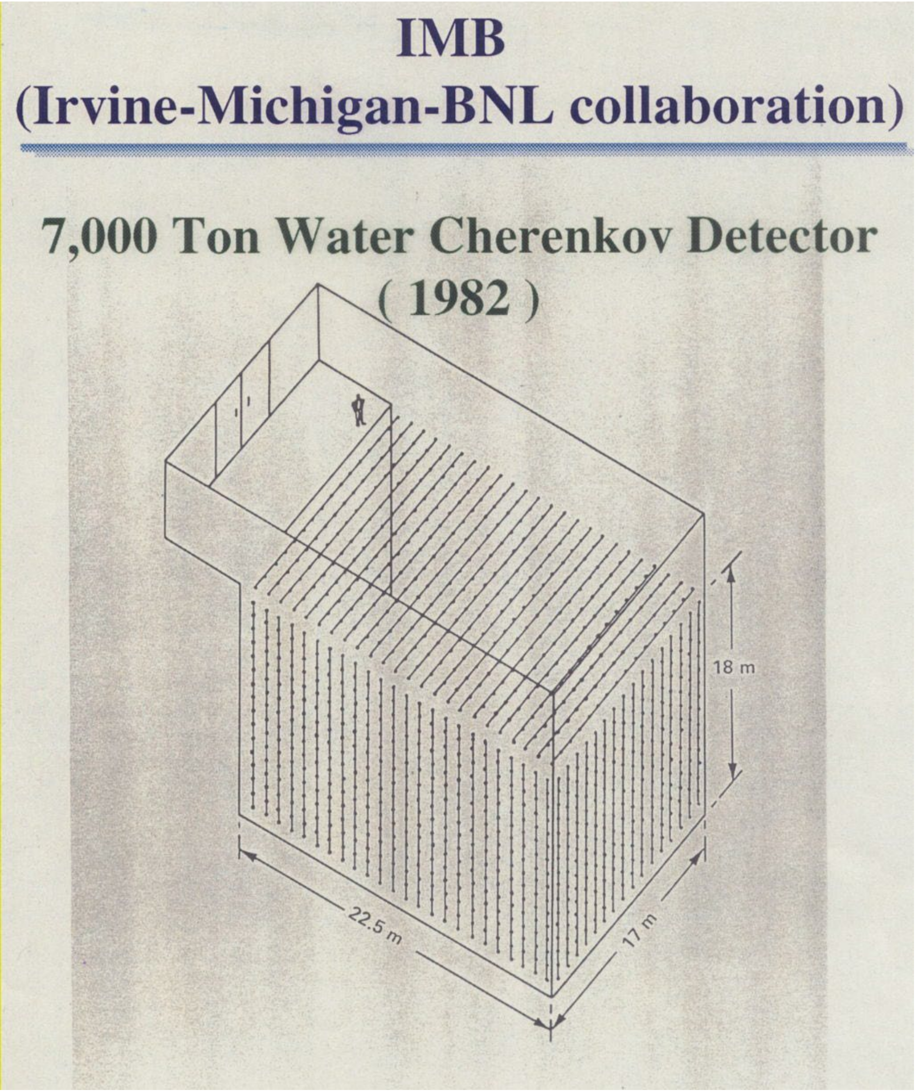
1000 20-inch PMTs were used

Photo-coverage: 20%

1983: KAMIOKANDE construction

At the entrance of the Kamioka mine

Competitor: IMB experiment



Fiducial volume: ~3400 ton
(x4 of Kamioande)

2048 5-inch PMTs

Photo-coverage: 1.3%

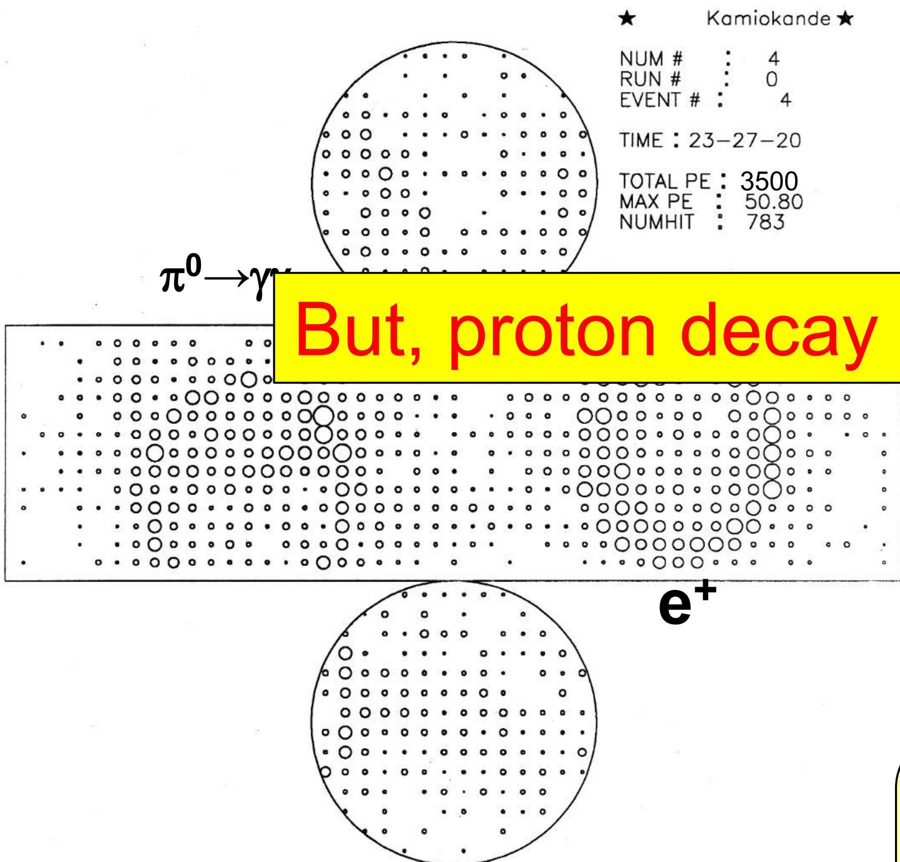
No problem for $p \rightarrow e^{+}\pi^{0}$ search

Already started in 1982

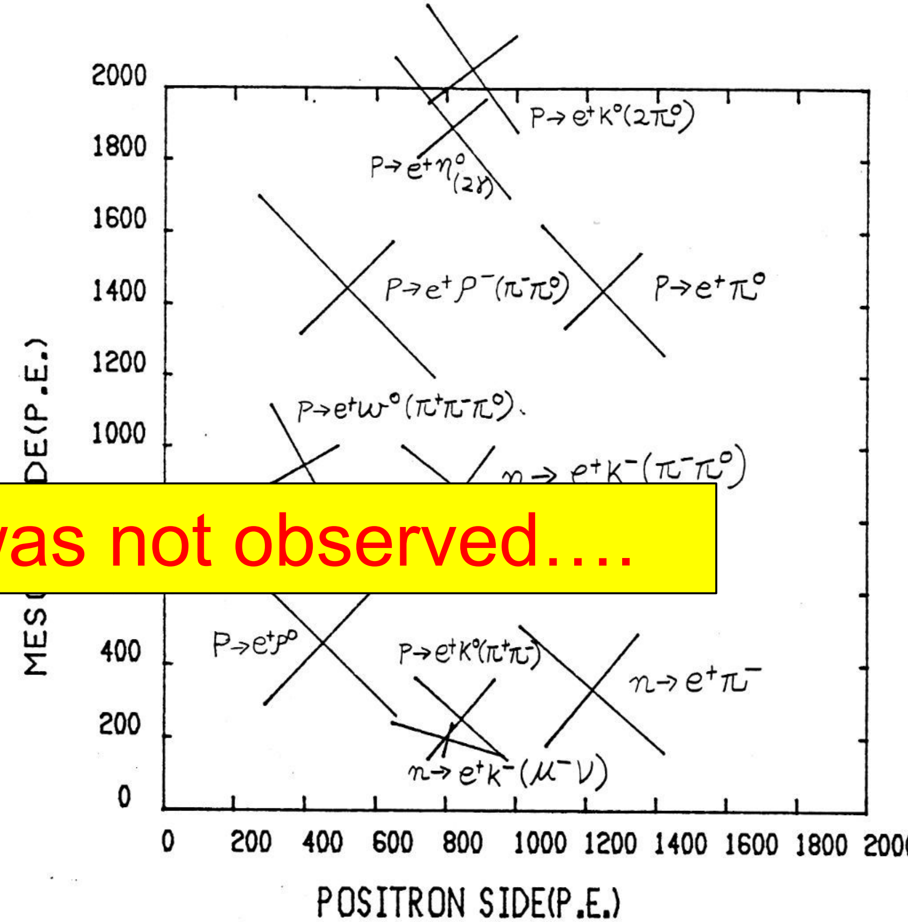
IMB is considered to be the first experiment to observe proton decay.

Purpose of Kamiokande

Aimed to measure branching ratio of proton decay



$p \rightarrow e^+\pi^0$ Monte Carlo simulation



But, proton decay was not observed….

High resolution detector for measuring the branching ratio of proton decay.

It should be useful to pin down the true GUT model.

Upgrade to Kamiokande-II (1984-1985)

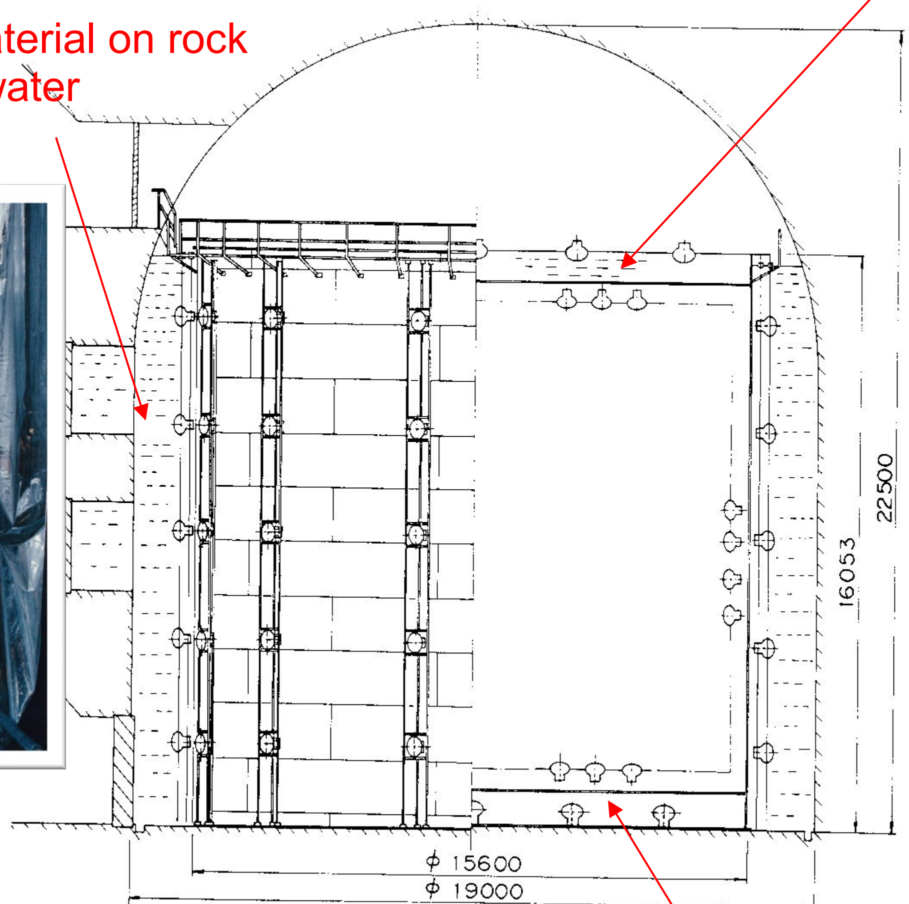
Thanks to large photo-coverage, it was found that the detector is sensitive to low energy events.
So, the detector was upgraded for solar neutrinos in 1984-1985.

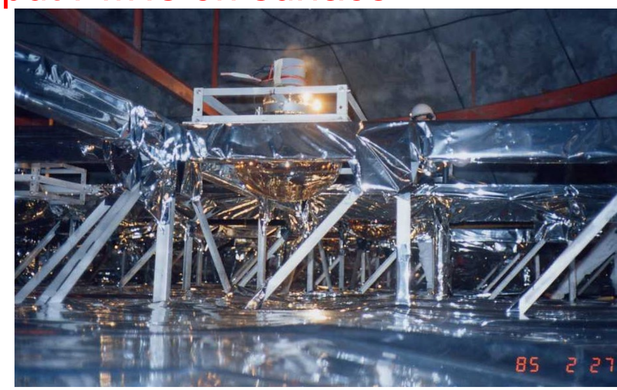
Outer Detector (OD) construction

Paint sealing material on rock surface and fill water

Raised water level by 0.7m and put PMTs on surface

OD (barrel)





OD (top)

OD (bottom)

Raised bottom structure by 1.2 m and insert OD(Bottom).

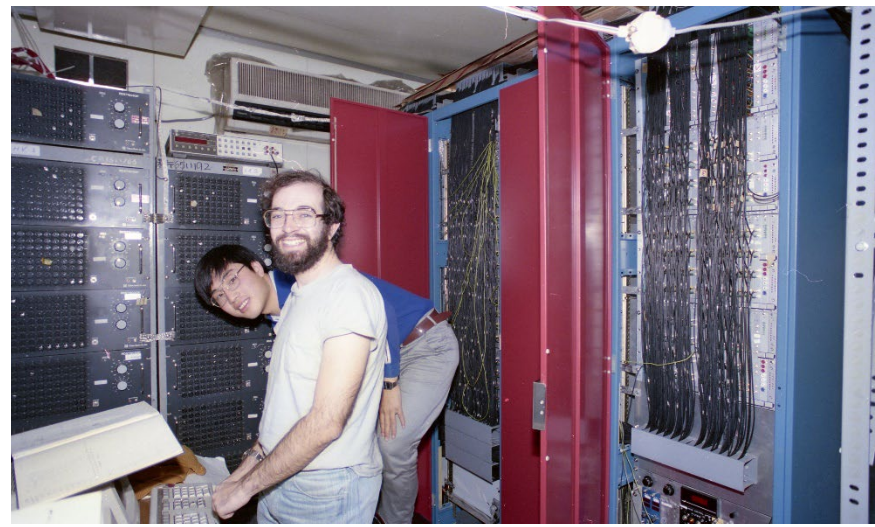
Upgrade to Kamiokande-II (1984-1985)

Upgrade electronics for readout of timing information.
It improved vertex reconstruction.

Univ. of Pennsylvania people joined.

R.Van Berg E.W.Beier

B.G.Cortez A.K.Mann



UPENN electronics was installed in 1985 autumn.

Battle against Radon(1985 →)

$^{238}U \rightarrow \ldots$ $^{222}Rn \rightarrow {}^{218}Po \rightarrow {}^{214}Pb \rightarrow {}^{214}Bi \rightarrow \beta$ (3.26MeV)

$\tau_{1/2} = 3.8 days$

mimic solar neutrino signal

$(\nu + e^- \rightarrow \nu + e^-)$

"Radon, the Flying Monster" is a kaiju film produced by Toho, released on December 26, 1956.

From Wikipedia

Battle against Radon(1985 →)

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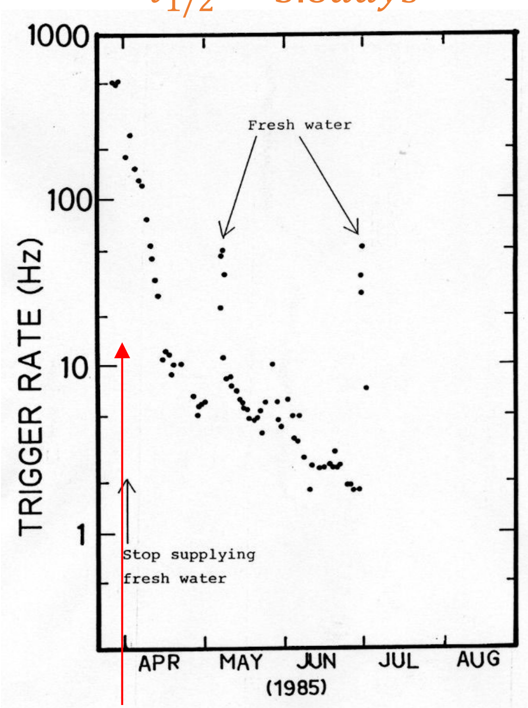
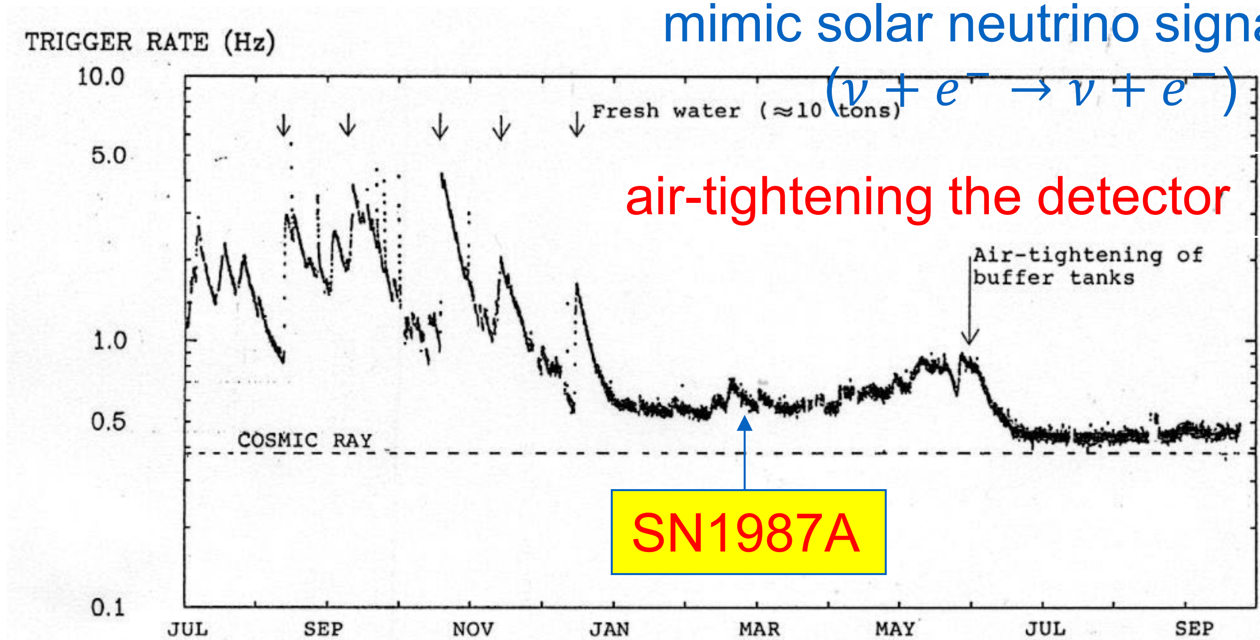




air-tightening the detector

SN1987A

1986 1987

Fresh water supply mode →recirculation mode (1985 April)

The expected number of solar neutrino events was approximately one event every two days.

Air-tightening the tank

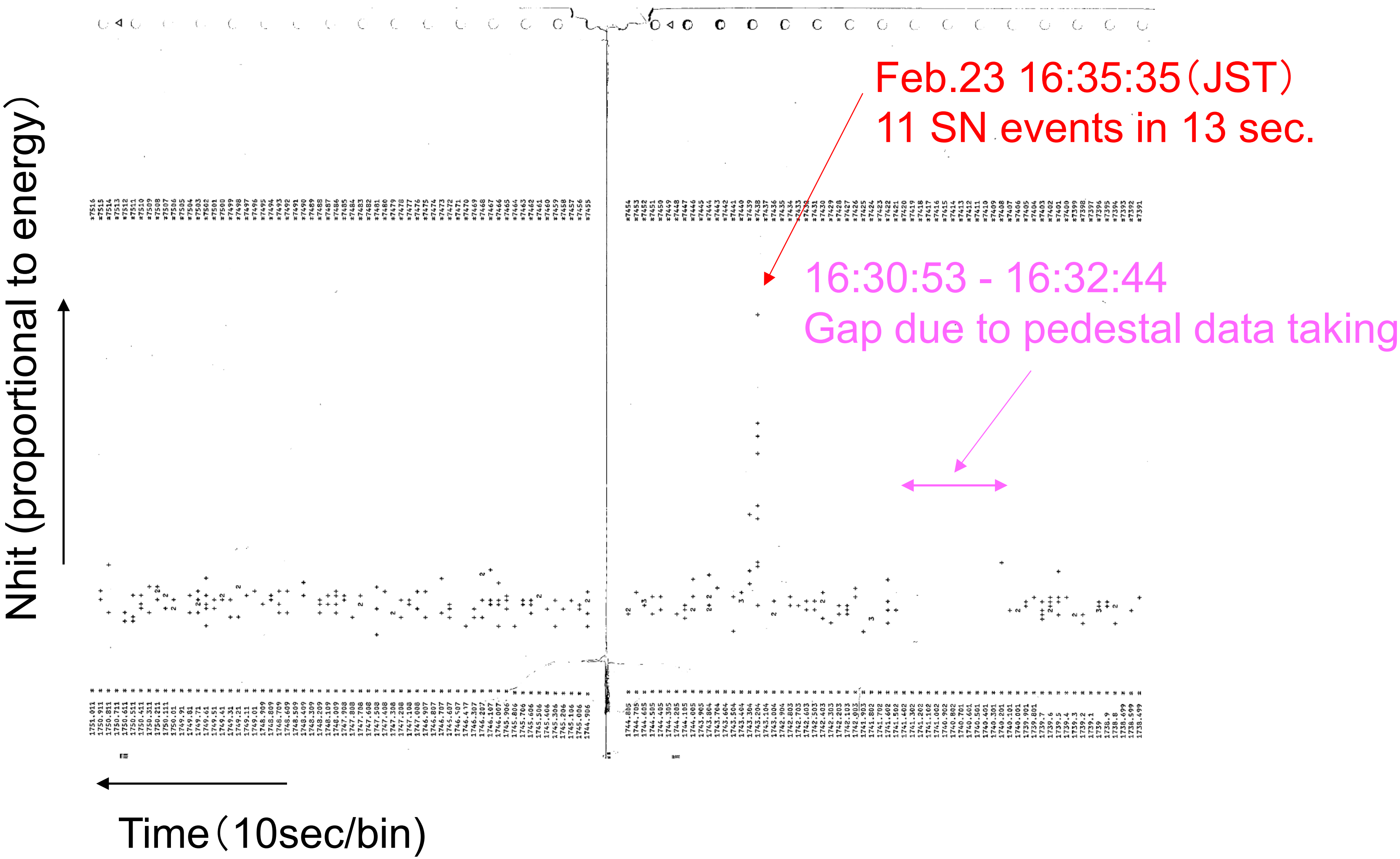
SN1987A Supernova in Large Magellanic Cloud (LMC)

The first printout of the SN1987A signal

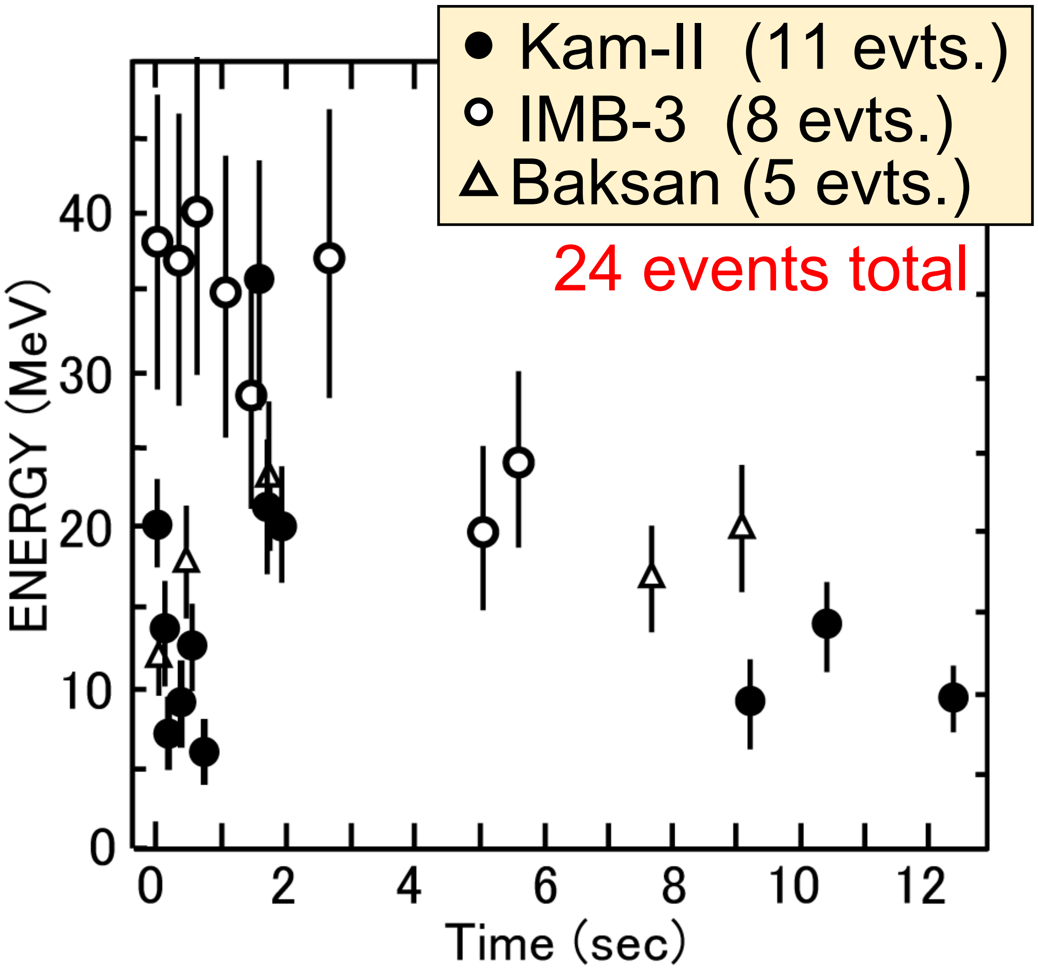
2-dimentinal HBOOK plot:

Horizontal axis：Time（10sec/bin），

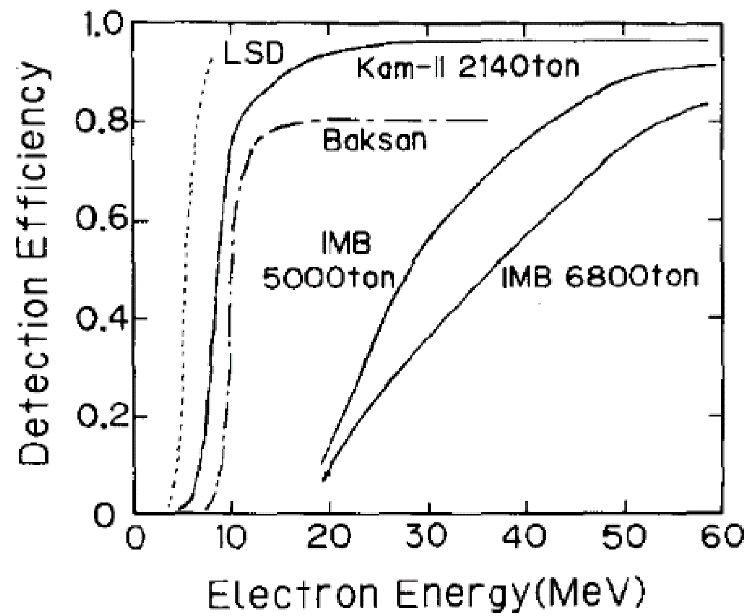
Vertical axis: Nhit (number of hit PMTs) of each event



Adjusting the 1st events from Kamiokande, IMB and Baksan



Detection efficiency



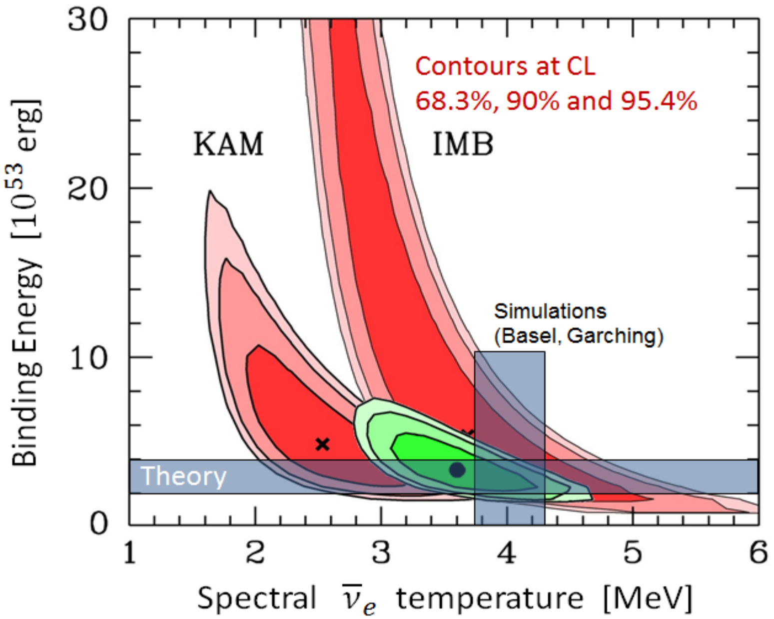
Energy threshold (at 50% eff.)

~8.5 MeV @ Kamiokande

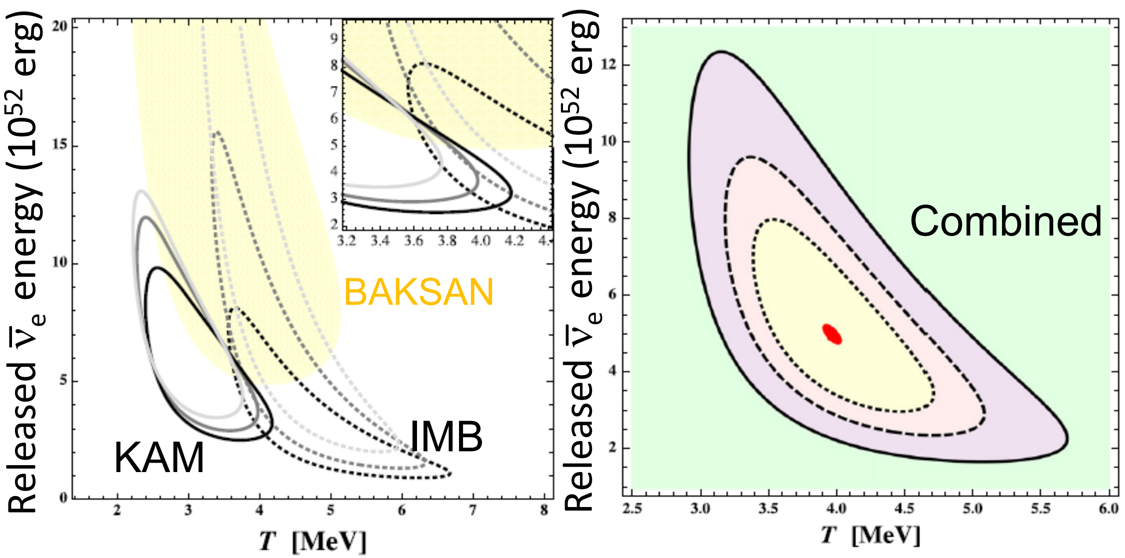
~28 MeV @ IMB

~10 MeV @ Baksan

What we have learned from SN1987A



Jegerlehner, Neubig & Raffelt, PRD 54 (1996) 1194



Vissani, J. Phys. G: Nucl. Part. Phys. 42 (2015) 013001

- Total energy released by $\overline{\nu}_e$ was measured to be ~5x10^{52} erg.
- Assuming equipartition, binding energy was estimated to be ~3x10^{53} erg.
- The observed released energy and explosion time scale were consistent with predictions from the supernova theory.

However, no detailed information of burst process was observed because of low statistics.

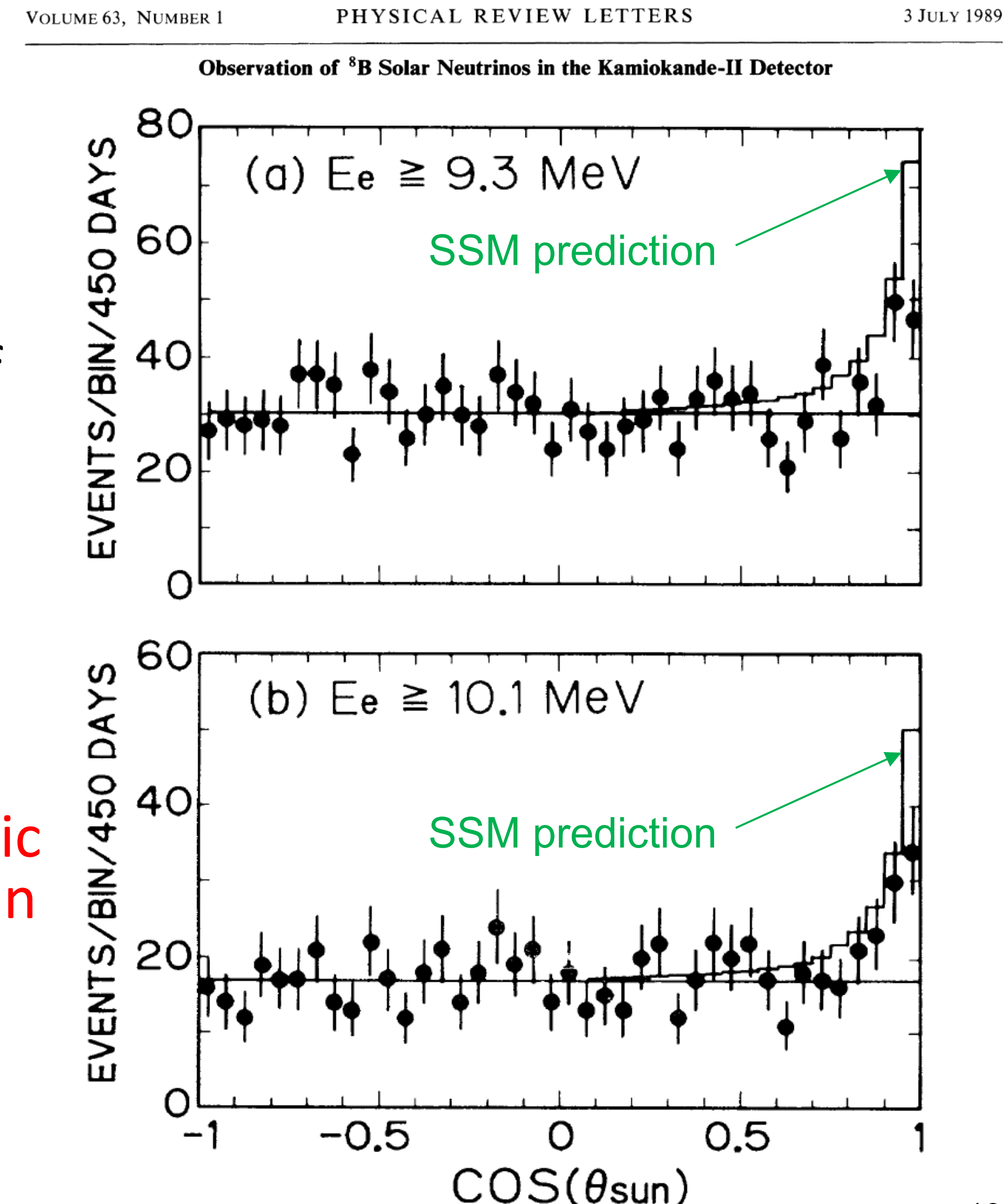
1988: First observation of solar neutrinos

Based on 450 days of data collected between Jan. 1987 and May 1988, Kamiokande successfully observed solar neutrino signals.

The observed flux was almost half of the expectation from the Standard Solar Model (SSM) and confirmed the "solar neutrino problem".

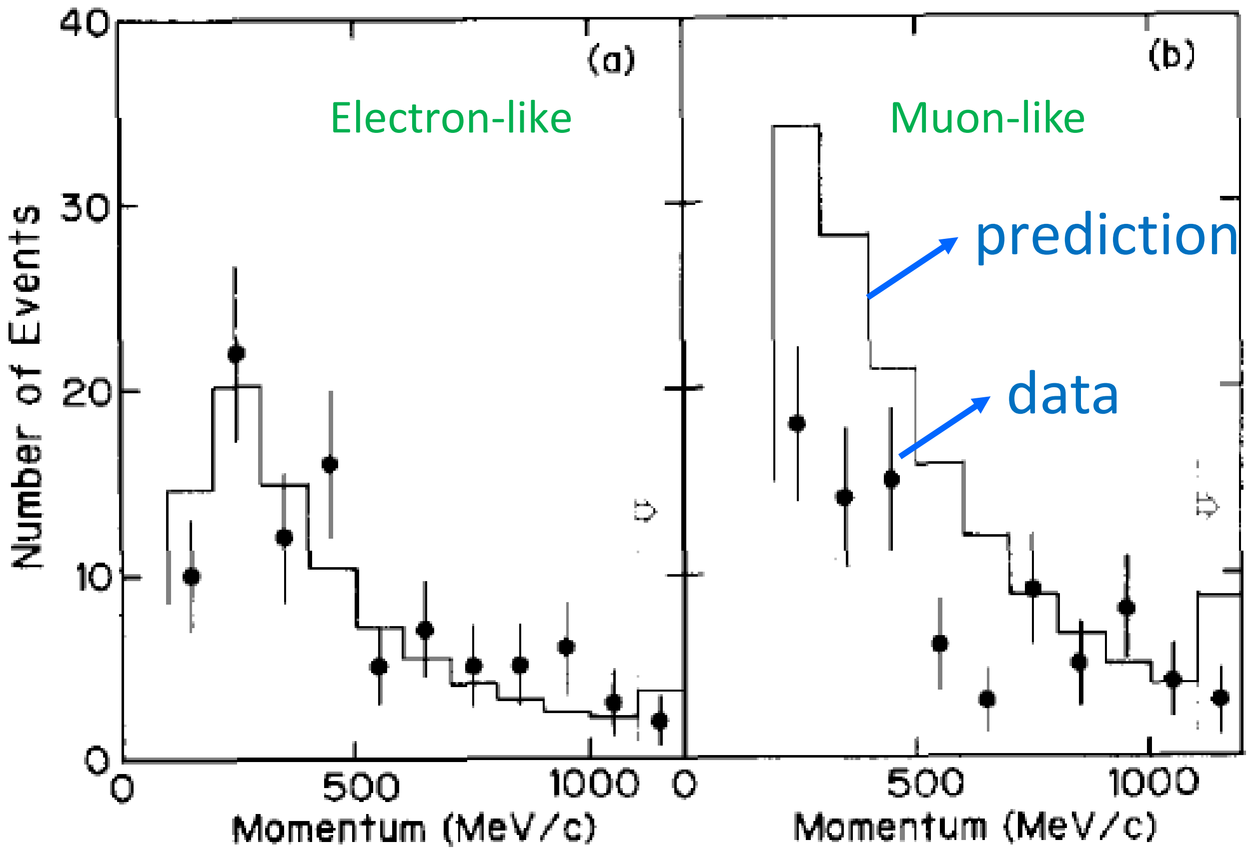
However, we could not conclude that this was due to neutrino oscillations because the systematic uncertainty in the flux prediction in SSM was still large.

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



1988: Atmospheric neutrino anomaly at Kamiokande

Data in 1988 paper
(Phys. Lett. B205 (1988)416.)



Electron-like data is consistent with prediction.
However, muon-like data is 59±7% of prediction.
Neutrino oscillation was a possible explanation for this anomaly, but we were unable to convince the scientific community.

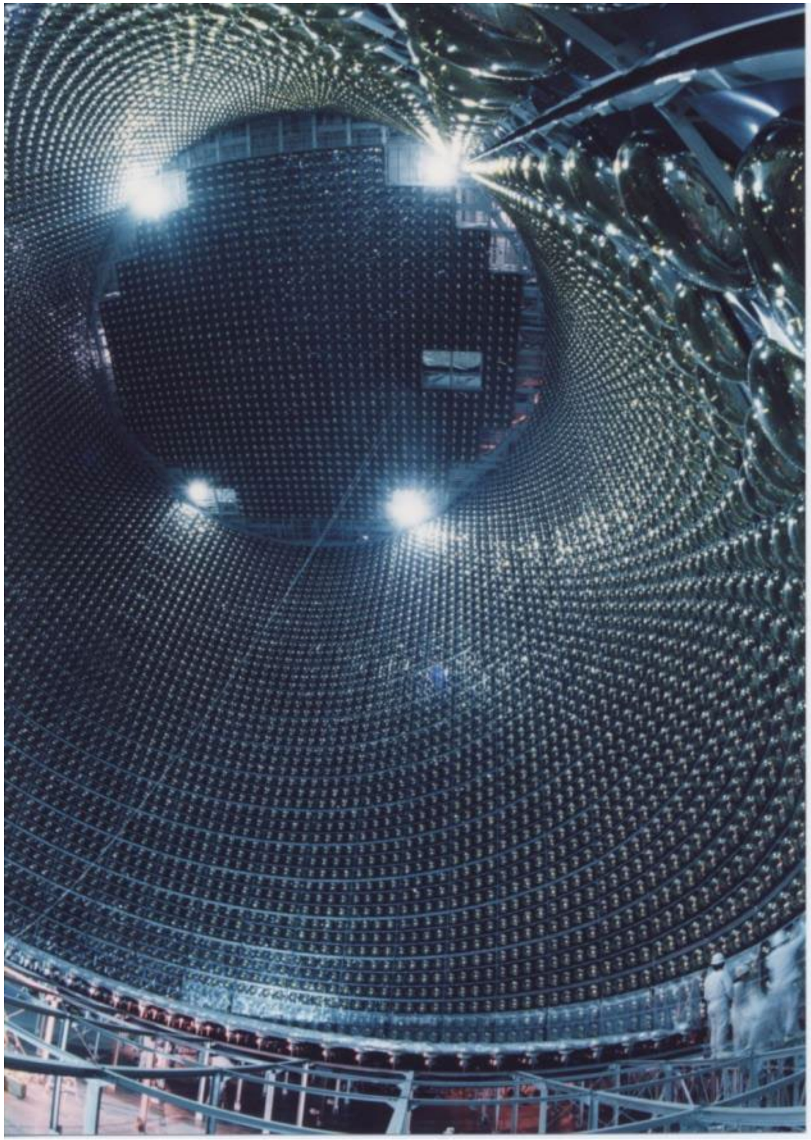
In order to solve solar and atmospheric anomalies, and as a "big neutrino telescope"(from Koshiba's proposal in 1983),

Super-Kamiokande construction（1991—）

50,000 ton detector

With 11,146 50cm-diameter PMTs

Started data taking from 1996



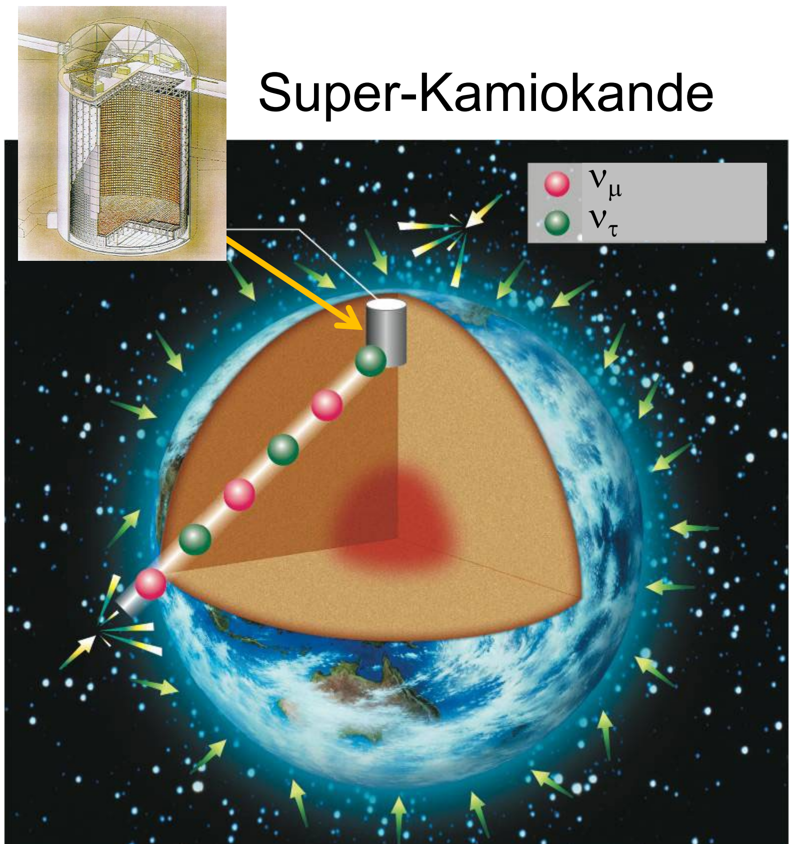
1998: Evidence for atmospheric neutrino oscillation

Cosmic rays produce neutrinos.

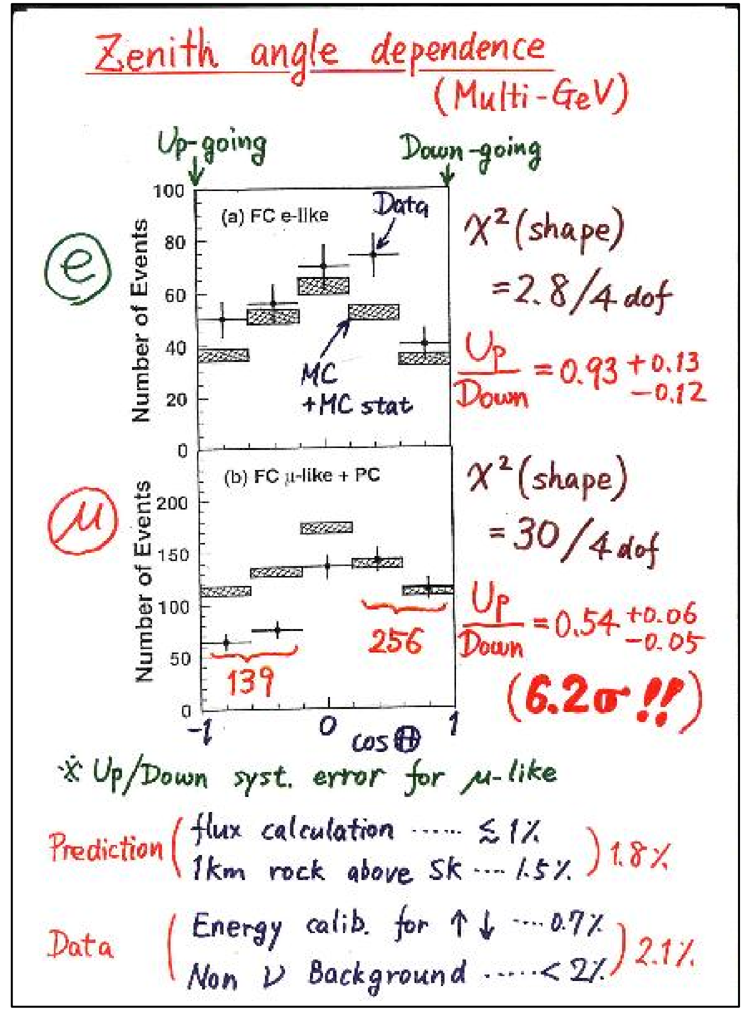
$$P + A \rightarrow N + \pi^{\pm} + X$$

$$\hookrightarrow \mu^{\pm} + \overset{(-)}{\nu}_{\mu}$$

$$\hookrightarrow e^{\pm} + \overset{(-)}{\nu}_{e} + \overset{(-)}{\nu}_{\mu}$$



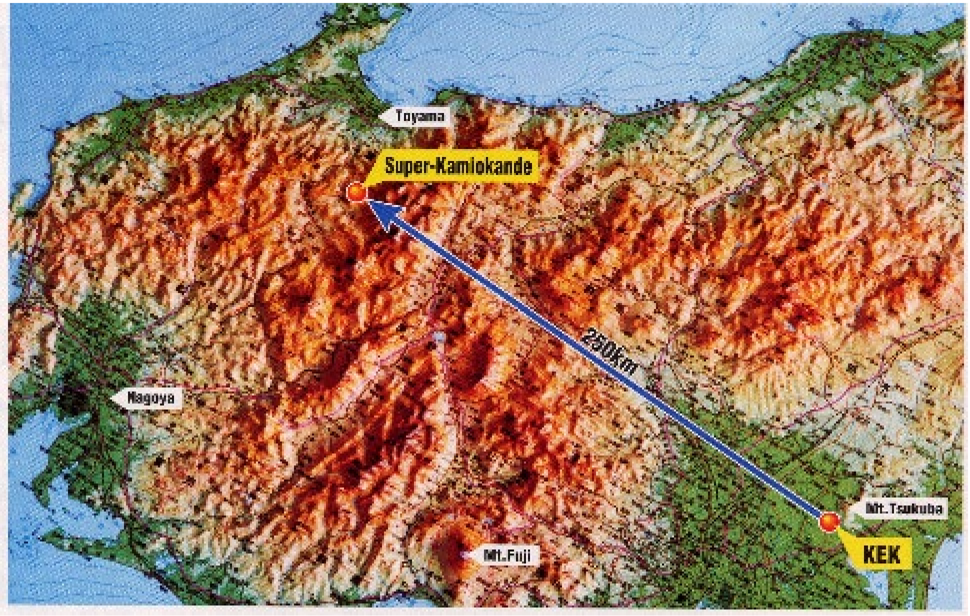
Super-Kamiokande

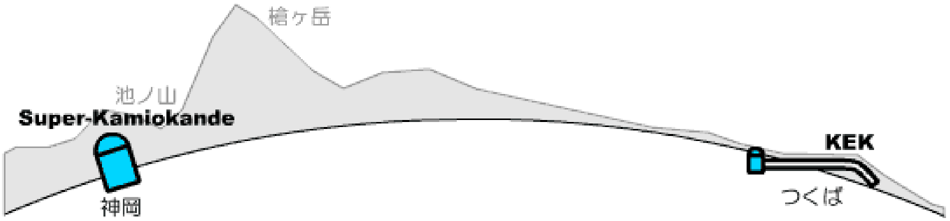


Kajita's presentation in Neutrino 1998 conference.

ν_μ disappearance

1999:K2K (KEK to Kamioka) started

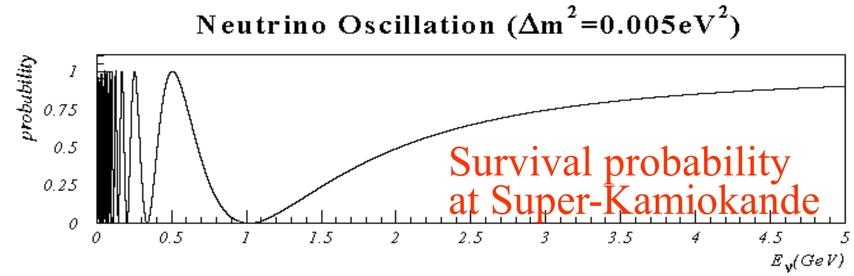


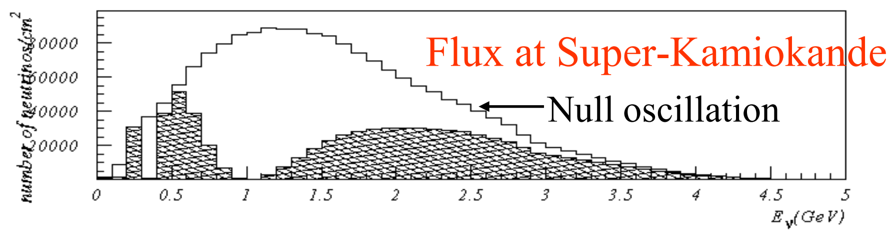


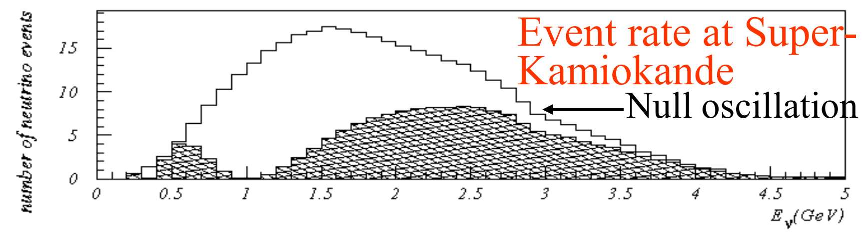
The first artificial neutrino beam experiment in the world.

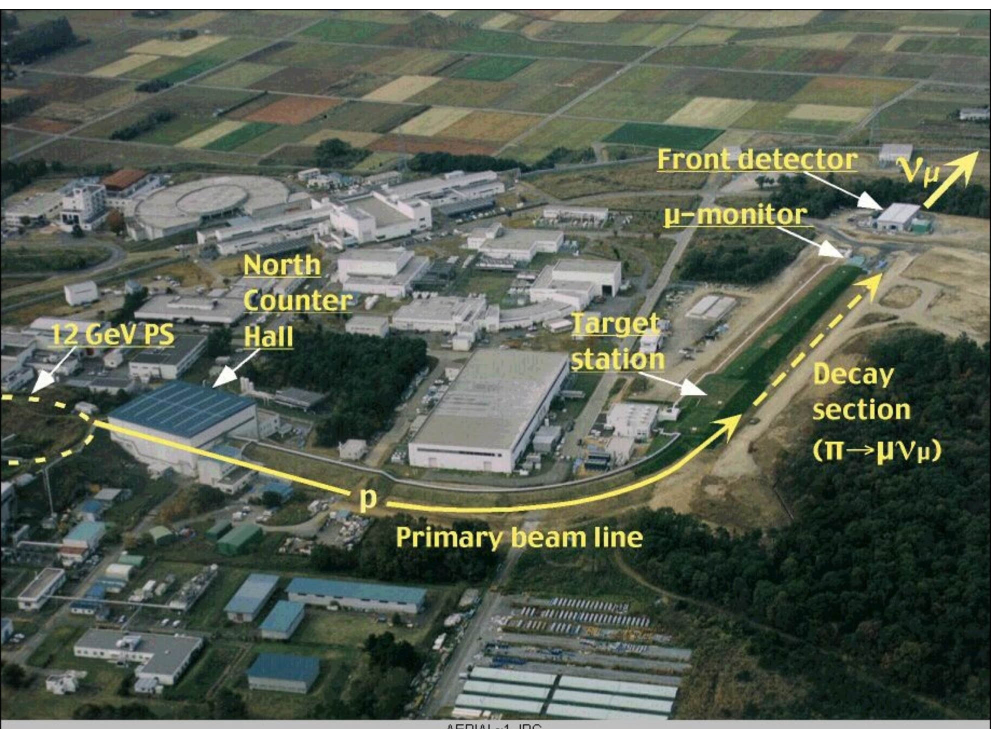
K2K Experiment

- Accelerator: 12 GeV proton synchrotron
  beam intensity: 6×10^{12} protons/pulse
  repetition: 1 pulse / 2.2 sec
  pulse width: 1 μsec
- Average neutrino energy: 1.4GeV
- Front (near) detector: 300m from the target
- Far detector (Super-Kamiokande): 250 km from the target
- Goal: 10^{20} protons on target

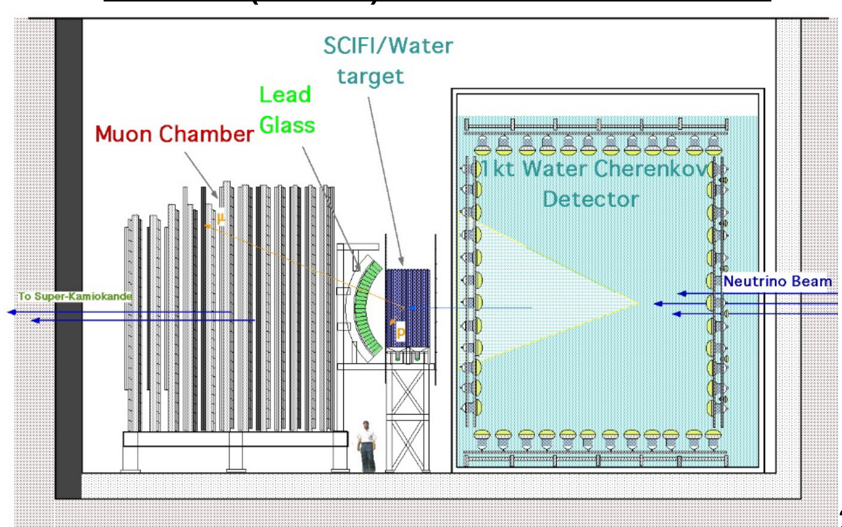








Front (near) detector at KEK



2001: Evidence of solar neutrino oscillations

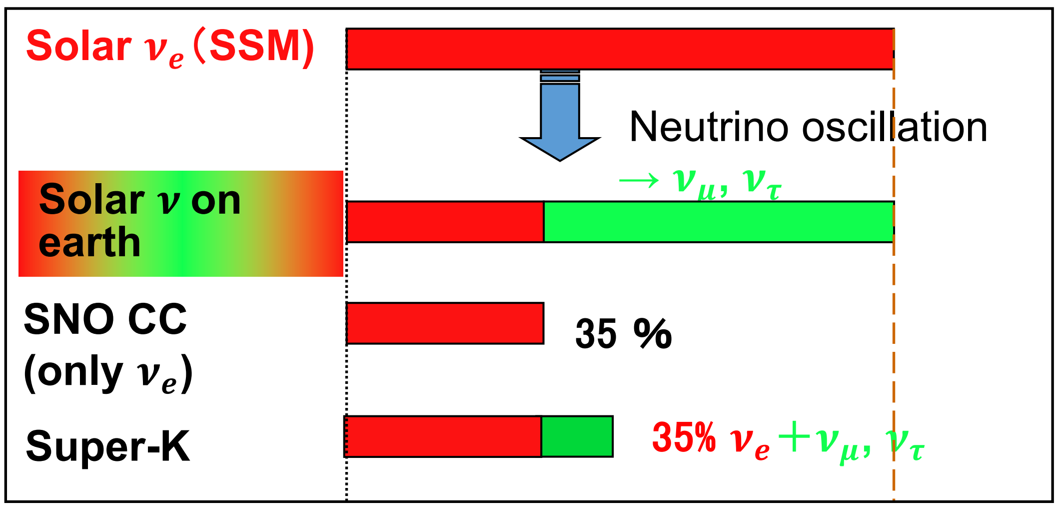
SNO announced CC flux on June 18, 2001

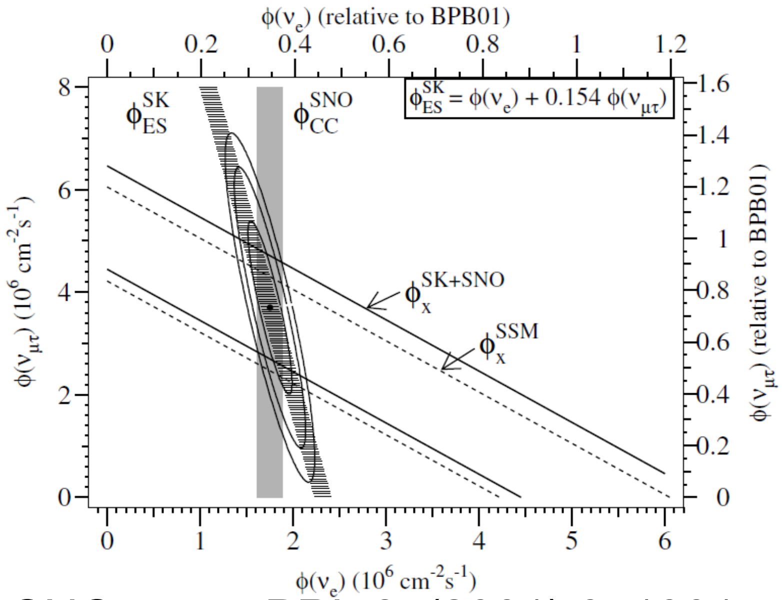
SNO(CC): $1.75 \pm 0.07\ ^{+0.12}_{-0.11}$ [x 10^6 /cm^2/sec]

SK submitted results of 1298 days' data on March 19, 2001 (published on June 18)

SK(ES): $2.32 \pm 0.03\ ^{+0.08}_{-0.07}$ [x 10^6 /cm^2/sec]

ES: Electron Scattering($\nu + e^- \rightarrow \nu + e^-$)





SNO paper,PRL 87(2001) 071301

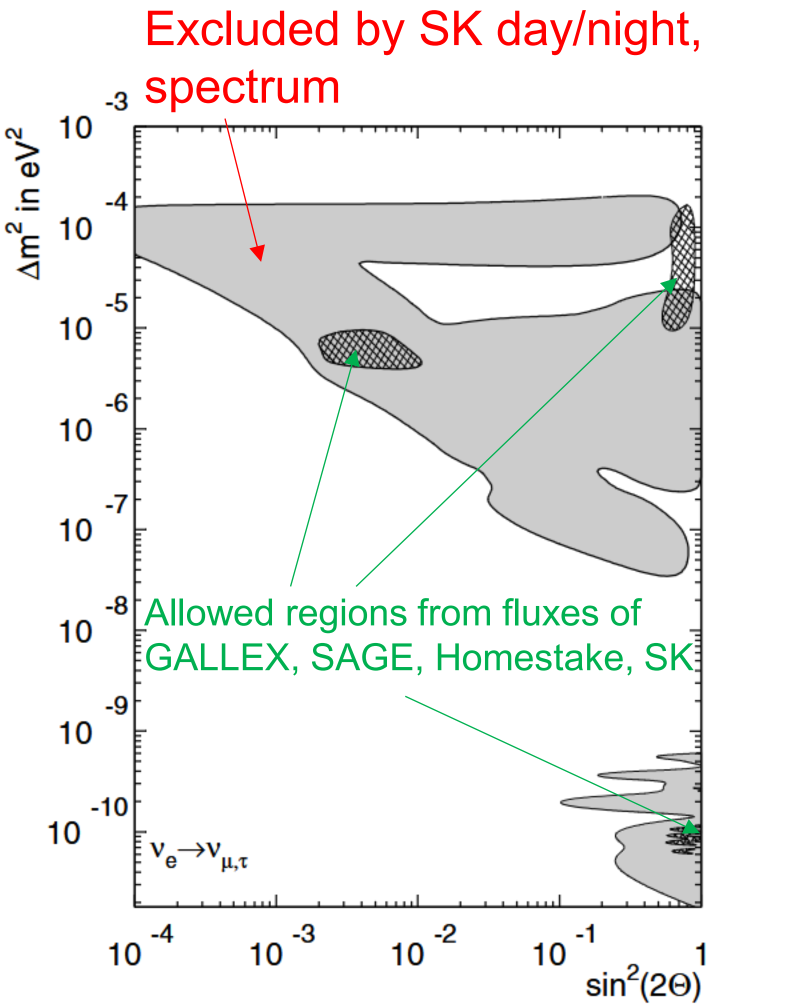
Solar model independent evidence by comparing SK and SNO（CC）.

ν_e disappearance

What is the solution of Solar neutrino oscillation?

Super-K paper in 2001

Submitted on March 19, 2001

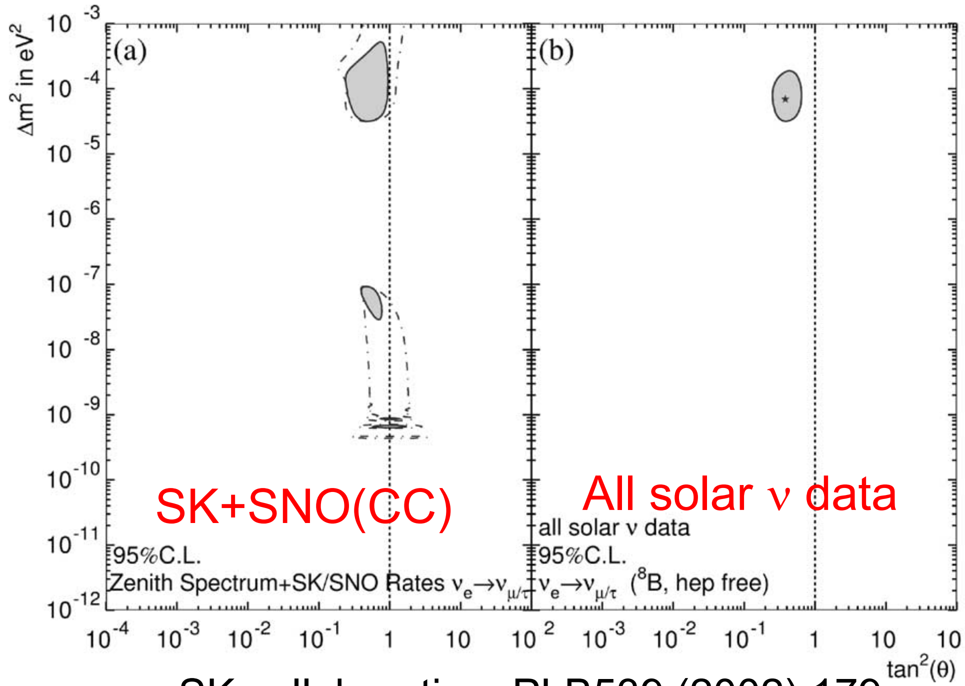


SK collaboration, PRL86 (2001) 5656

Assuming the SSM predicted flux

Super-K paper in 2002

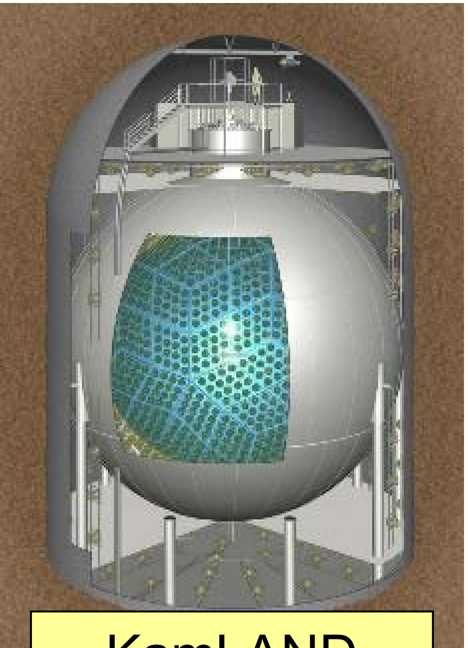
Submitted on May 23, 2002



SK collaboration, PLB539 (2002) 179

As of May 2002, the solar global analysis selected the LMA solution with 95% CL.

2002: Reactor neutrino oscillation by KamLAND

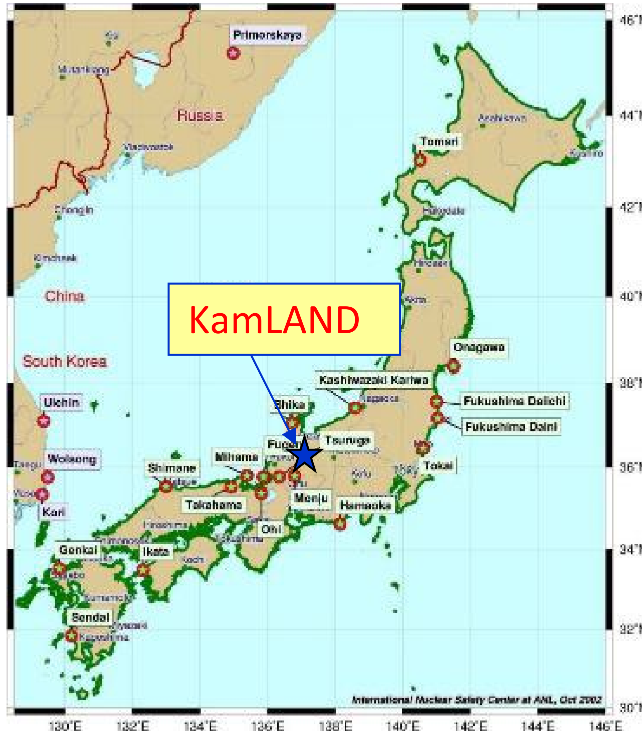


KamLAND

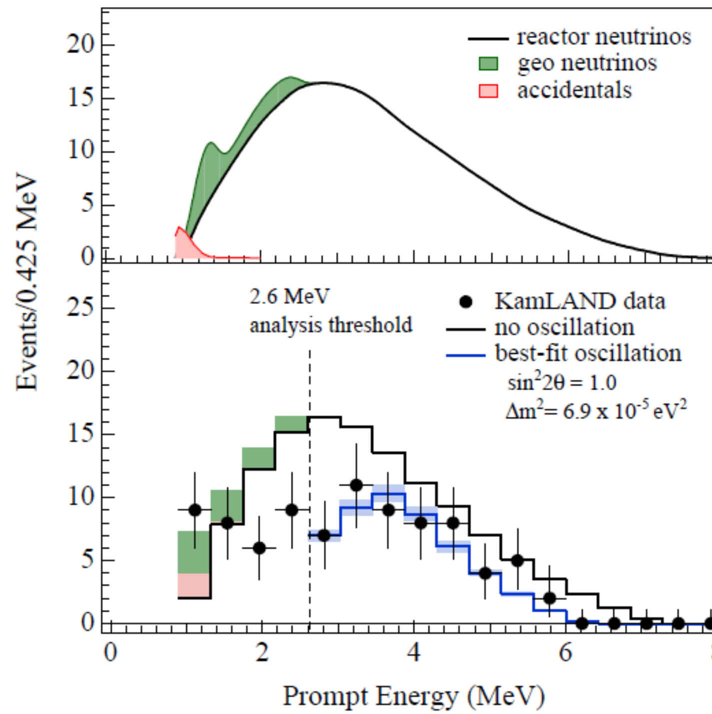
Built at old Kamiokande site

1000 ton liquid scintillator.

Run by Tohoku University.



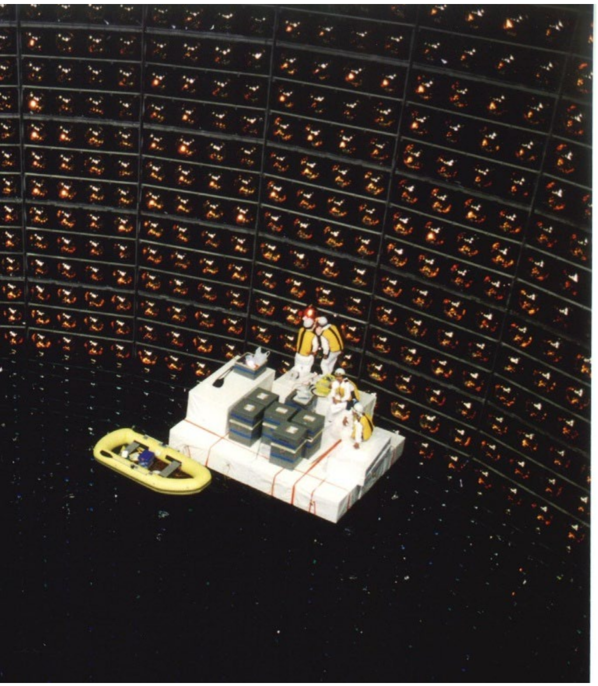
70GWatt power(7% of world total) was generated by reactors in 140 - 210 km from Kamioka.

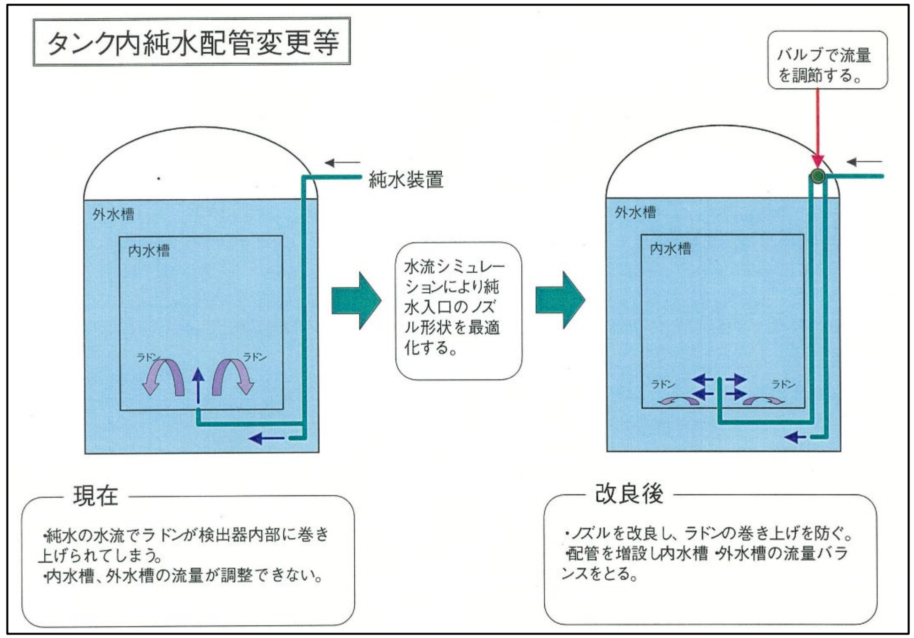


LMA solution was verified.

PMT replacement work in 2001

- Five years had passed since the experiment began in 1996, and the number of dead PMTs had increased.
- To reduce radon levels associated with the supply of pure water from the bottom of the tank, improvements to the piping were also necessary.



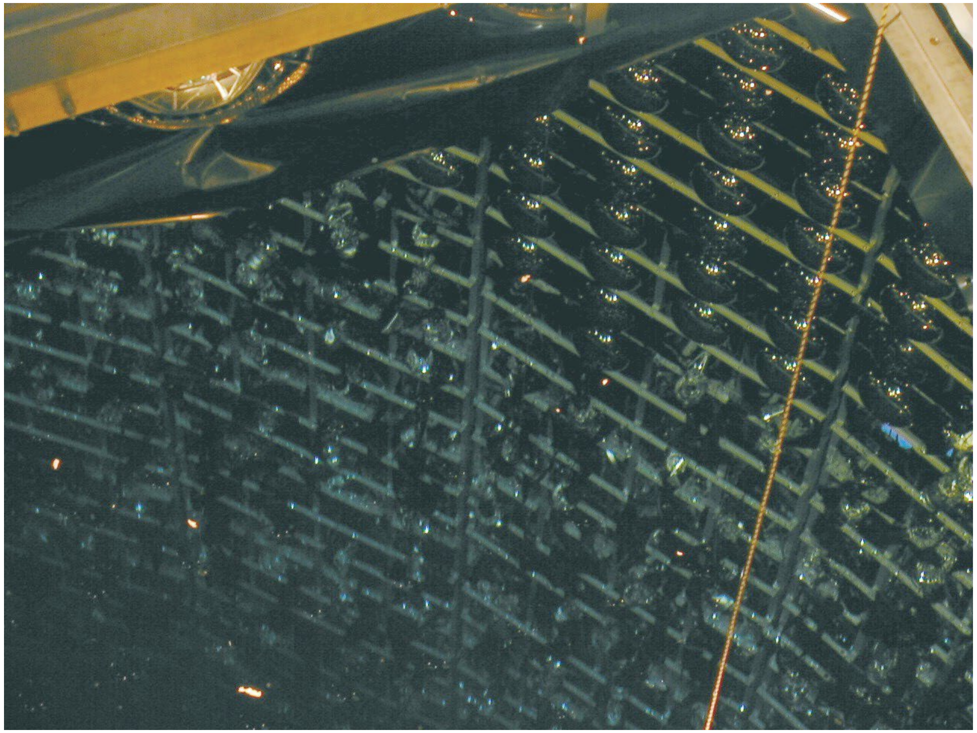


New water pipe outlet

July 18 Drain start
July 21 Start PMT replacement
Sep. 7 Replacement completed
Sep.18 Started to fill pure water

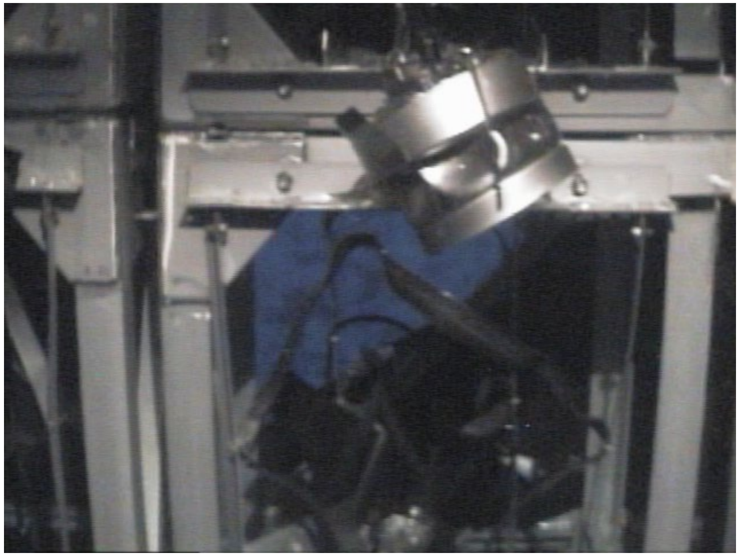
The work proceeded smoothly, and the supply of pure water began on Sep. 18.
By Nov. 12, ultrapure water had accumulated to a depth of 31.7 meters from the bottom of the tank—approximately 3/4 of the entire tank. (→ next page)

November 12, 2001 Super-K accident



Inner PMTs 6777 were destroyed
Outer PMTs 1100 were destroyed

Approximately 60% of the PMTs were destroyed. The initial trigger was the failure of a single PMT located at the bottom of the tank. This generated a shock wave, which caused a chain reaction that led to the destruction of many other PMTs.



Crashed dinode

Glass debris at the bottom of tank

e-mail from Totsuka-san on the next day(2001.11.13)

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. Details of what happened and a preliminary evaluation of the damage are described in Appendix. Please DO NOT DISTRIBUTE it to outside people, as it is very preliminary and subject to a substantial change.

The cause and how to deal with the loss in future will be discussed by newly found committees.

However, even before discussing with my colleagues of the Super-K and K2K collaborations, I have decided to express my intension 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 by 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.

J-PARC

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.To achieve our objective is formidable but we are determined to do so. But 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,

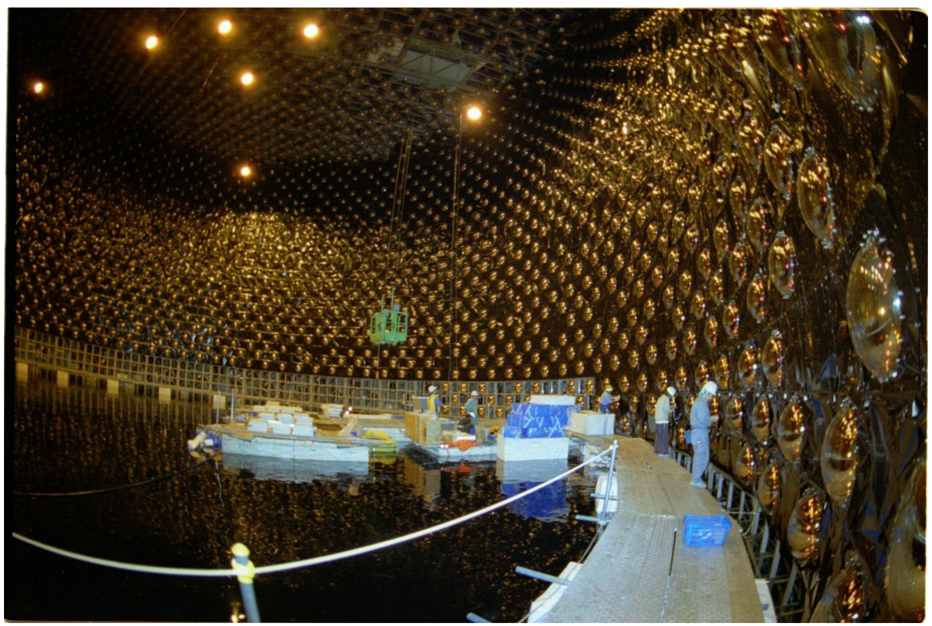
Yoji Totsuka

Reconstruction using survived PMTs

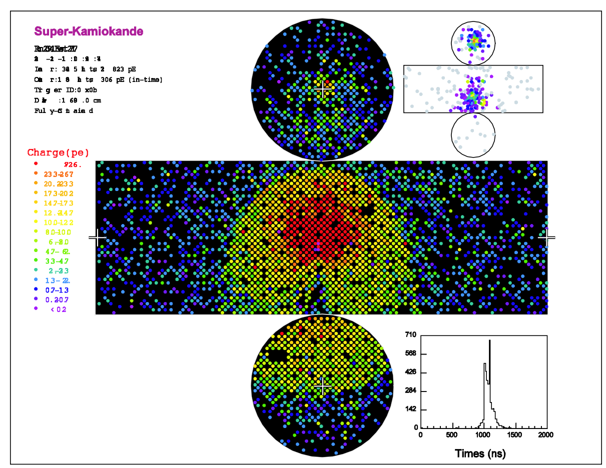
Remove debris

A case designed to prevent shock wave generation: 13 mm thick acrylic at the front and a FRP case at the rear.

The work completed in October 2002.
Oct.-Dec. fill pure water.
Data taking resumed on Dec.10, 2002.



PMT mounting with the case.

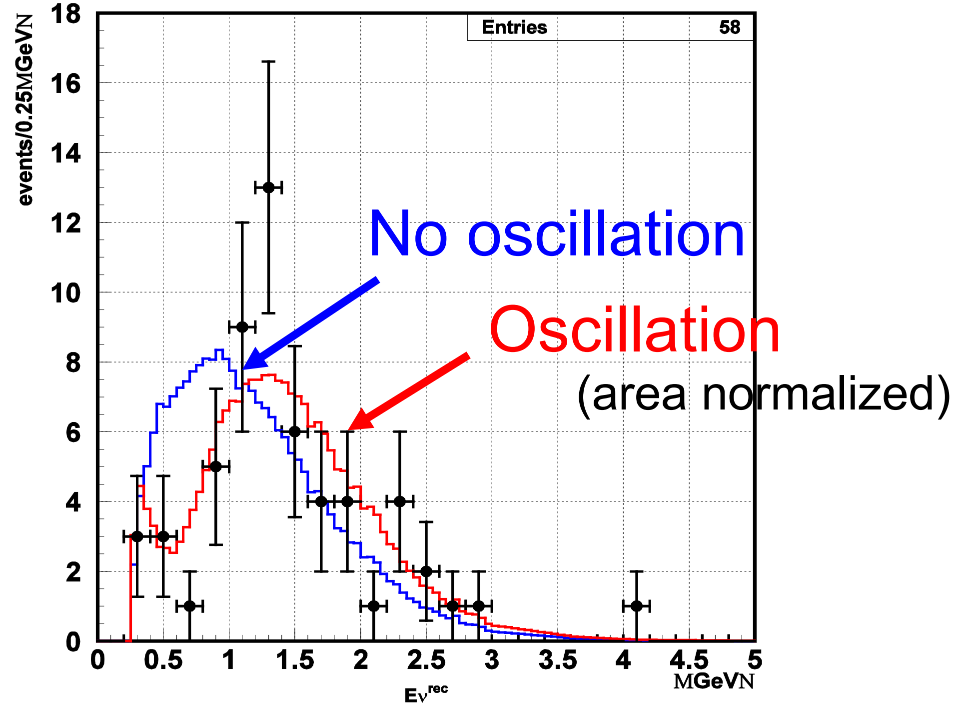


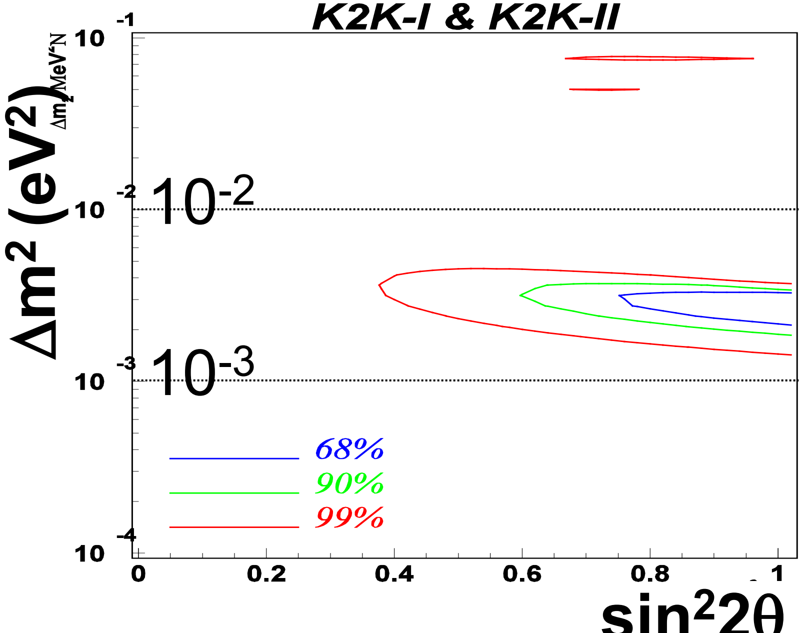
Cosmic ray muon after the recovery.

Final result of K2K experiment

K2K data was taken from June 1999 to November 2004

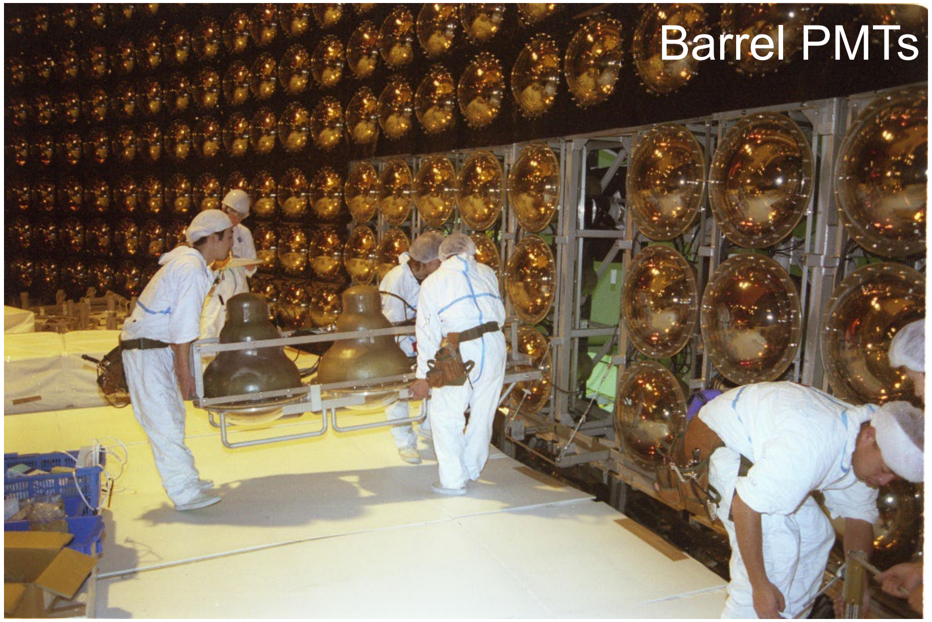
	N_{sk}^{obs}	N_{sk}^{pred}
All	**112**	**155.9**
1 ring	**67**	99.0
μ-like	58	90.8
e-like	9	8.2
multi-ring	**45**	56.8

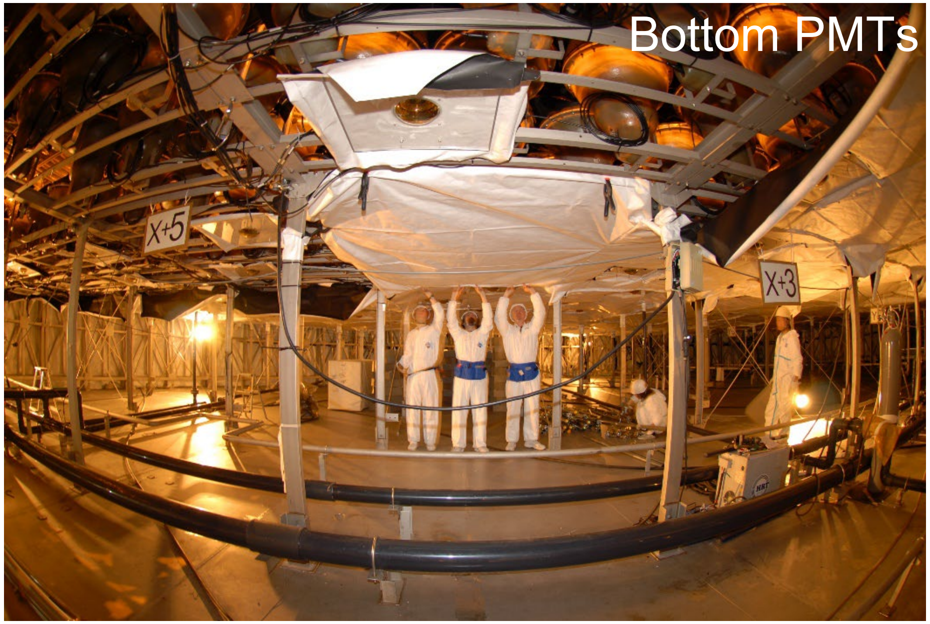




No oscillation was excluded with 4.3 σ (0.0015%) significance.
The "atmospheric oscillation" was confirmed by the artificial beam experiment.

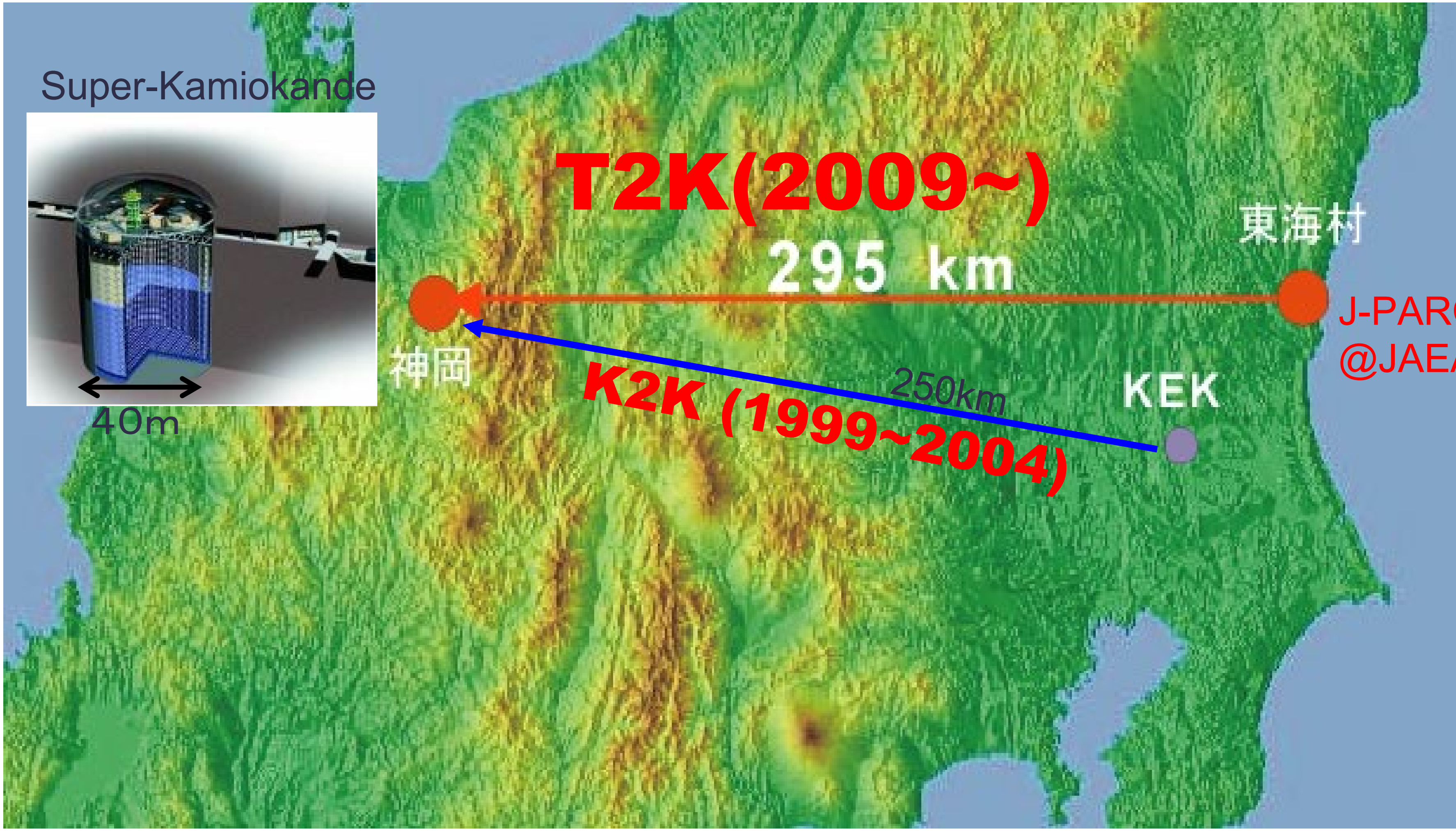
Full reconstruction (Oct. 2005 – July 2006)





Since July 2006, data taking resumed with a 40% photocoverage, using 11,129 photomultiplier tubes (PMTs). (SK-III)

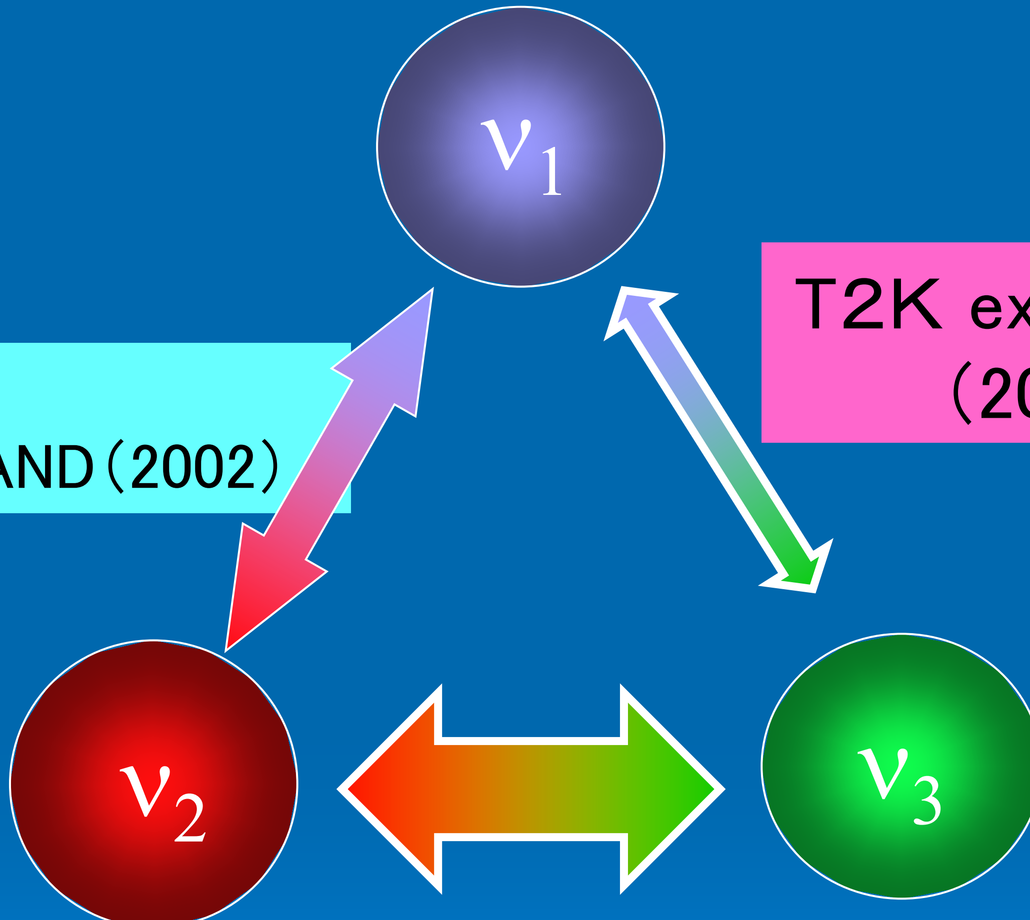
2009: T2K (Tokai to Kamioka) started



High intensity neutrino beam by J-PARC

→ Takashi Kobayashi and Thomas Leplumey's talks today

Evolution in neutrino physics



Solar ν at SK (2001)
Reactor ν at KamLAND (2002)

T2K experiment (2011)

Atmospheric ν at SK (1998)
K2K experiment (2004)

All oscillation modes have been discovered at Kamioka.

Three Generations of Water Cherenkov Detector in Kamioka

- **Kamiokande (1983 - 1996)**
  - Atmospheric and solar neutrino "anomaly"
  - Supernova 1987A

  Birth of neutrino astrophysics

- **Super-Kamiokande (1996 - ongoing)**
  - Neutrino oscillation (atm/solar/LBL)
    - All mixing angles and Δm^2s
  - Proton decay: world best-limit

  Discovery of neutrino oscillations

- **Hyper-Kamiokande (2028 -)**
  - Precision measurement of neutrino oscillation including CPV and MO
  - Extended search for proton decay
  - Neutrino astrophysics

  Explore new physics

The excavation of the large cavity will soon be completed, and tank construction will begin shortly.

The data taking is scheduled to start in 2028.

→ Menai Lamers James' talk on July 25

SK-Gd Phase since 2020

SK-Gd Phase:

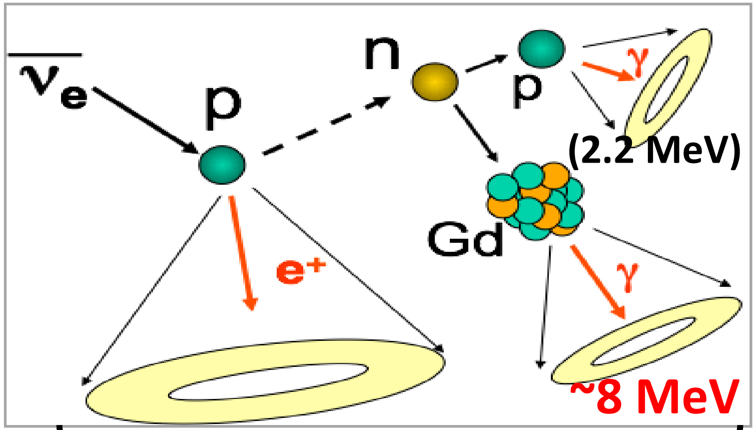
Add gadolinium (Gd) to enhance neutron tagging efficiency of the SK detector.

Physics targets:

- Detect Diffuse Supernova Neutrino Background (DSNB)
- Improve pointing accuracy for supernova
- Early warning of nearby supernova from pre-burst signal (silicon burning)
- Enhance ν or $\bar{\nu}$ discrimination in atmospheric ν & T2K analysis
- Reduce backgrounds in proton decay search

SK refurbishment was done in 2018

- Fix water leakage, clean inside the detector
- Replace dead PMTs
- Improve water piping in the SK detector



- **Reduce BG of $\bar{\nu}_e$ signal**
  - Delayed coincidence
  - ΔT ~ 60 μs (@0.03% Gd)
  - Vertices within ~ 50 cm

Gd concentration

SK-VI: 0.01% (18 Aug. 2020-)

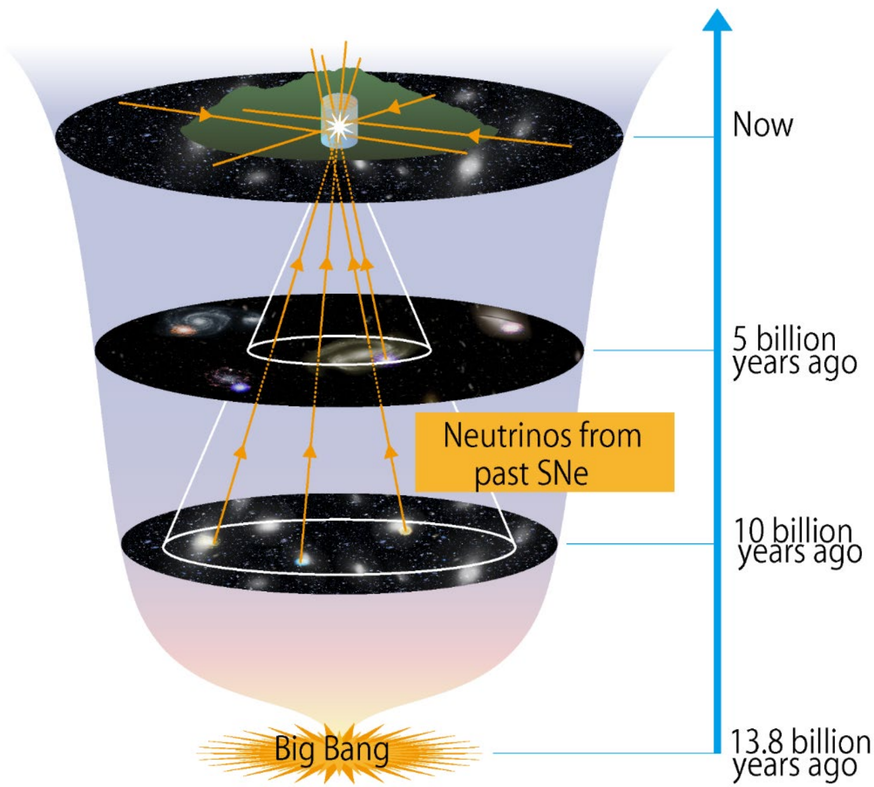
SK-VII~: 0.03% (5 Jul. 2022-)

Neutron capture eff. in water

- 0.01% Gd : ~50% on Gd
- 0.03% Gd : ~75% on Gd

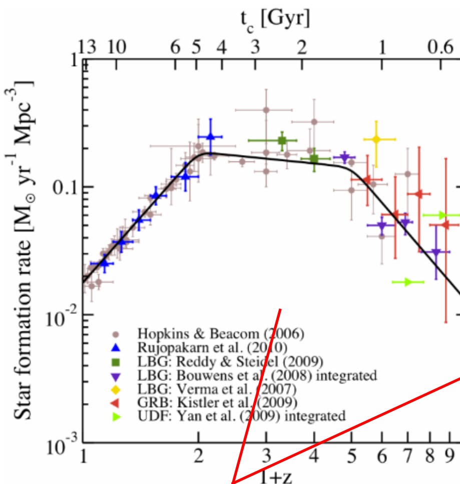
Diffuse Supernova Neutrino Background (DSNB)

$10^{22\text{-}23}$ stars in the universe（～10^{11} galaxies, ~$10^{11\text{-}12}$ stars/galaxy）
At present, we are getting neutrinos from 10^8 supernovae every year.

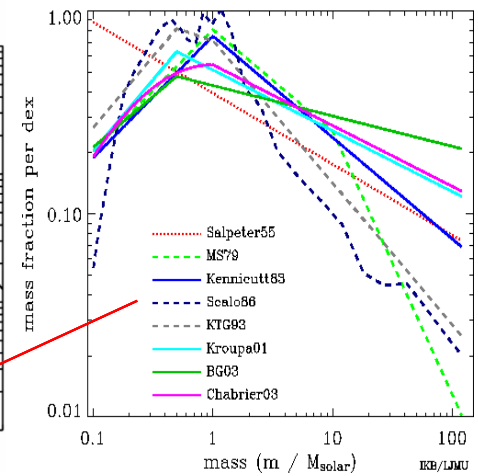


Horiuchi,Beacom(2010)

Star Formation Rate

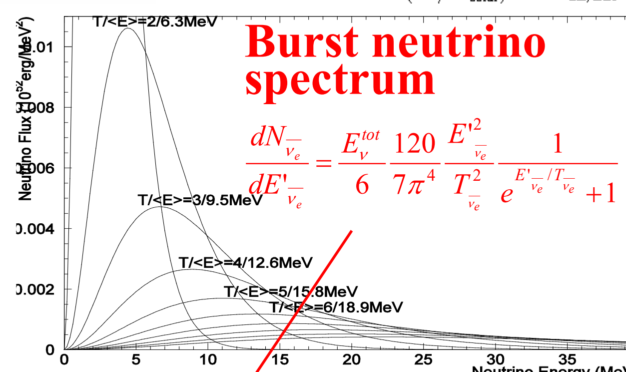


Initial Mass Function



Burst neutrino spectrum

$$\frac{dN_{\bar{\nu}_e}}{dE'_{\bar{\nu}_e}} = \frac{E_\nu^{tot}}{6}\frac{120}{7\pi^4}\frac{E'^2_{\bar{\nu}_e}}{T^2_{\bar{\nu}_e}}\frac{1}{e^{E'_{\bar{\nu}_e}/T_{\bar{\nu}_e}}+1}$$



$$\frac{dF_\nu}{dE_\nu} = c\int_0^{z_{\max}} R_{\rm SN}(z)\frac{dN_\nu(E'_\nu)}{dE'_\nu}(1+z)\frac{dt}{dz}dz$$

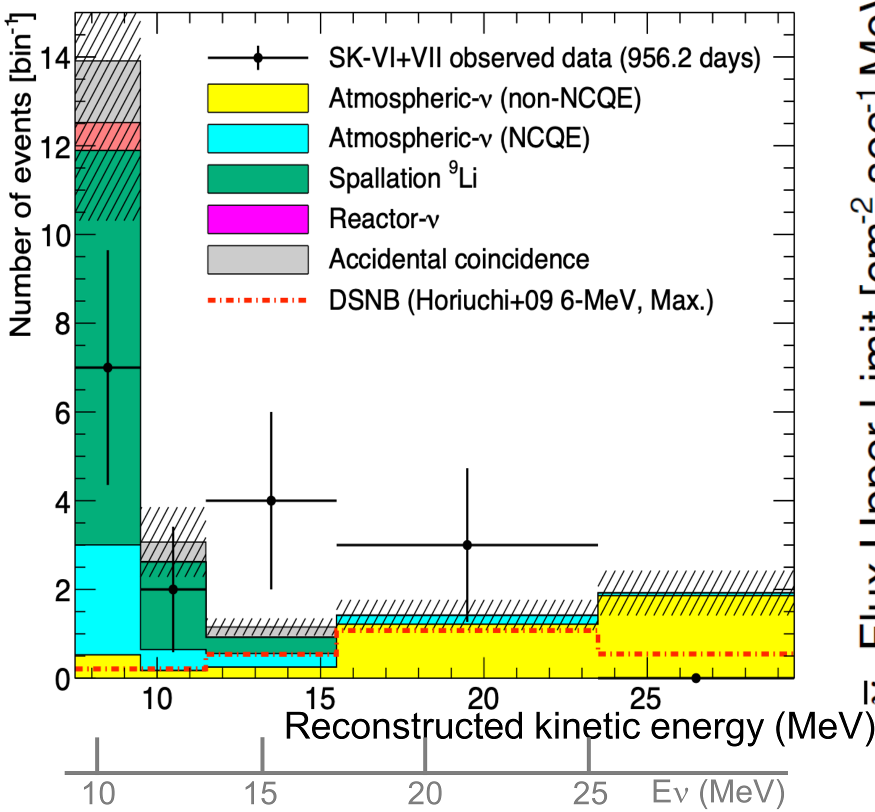
We can study
star formation history and
averaged neutrino spectrum.

Preliminary DSNB search results (with SK-Gd)

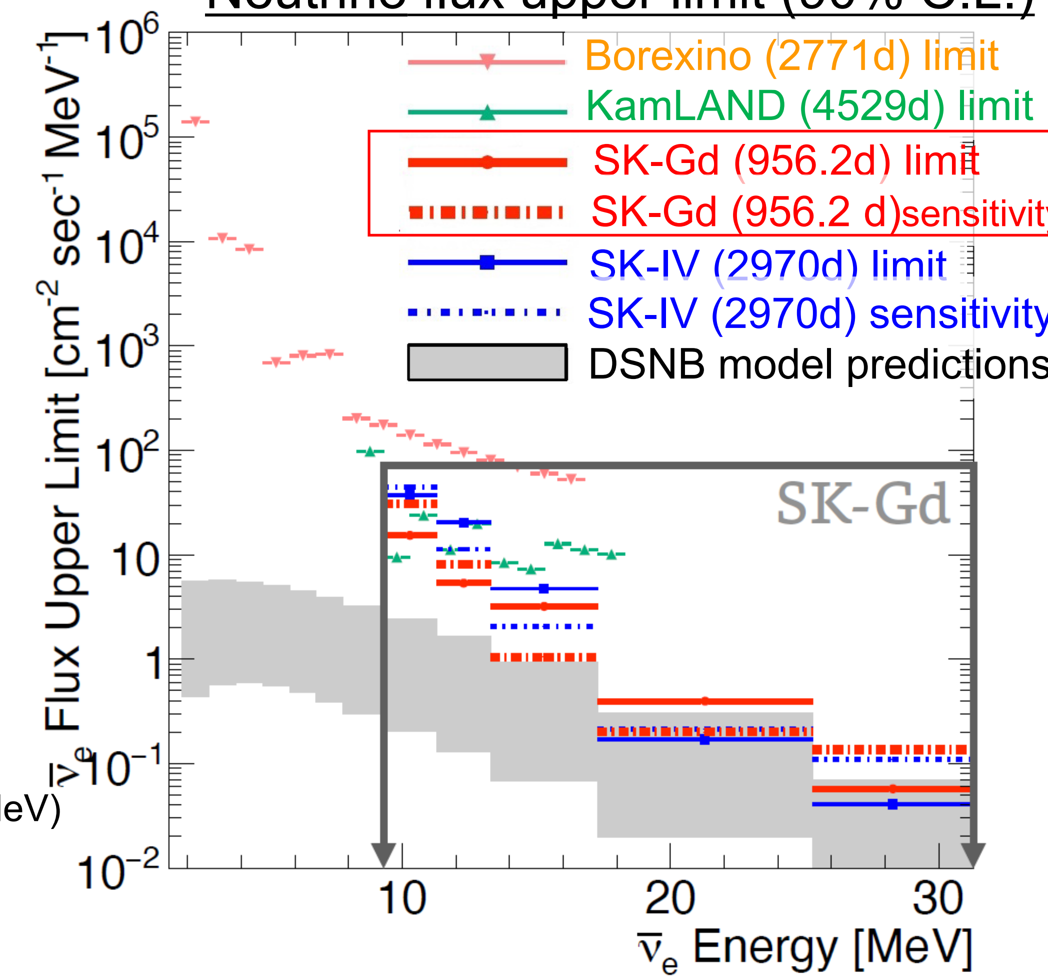
SK-Gd data 956.2 days

(SK-VI (0.01%Gd): 552.2 days, SK-VII(0.03%Gd): 404.0days)

Energy spectrum



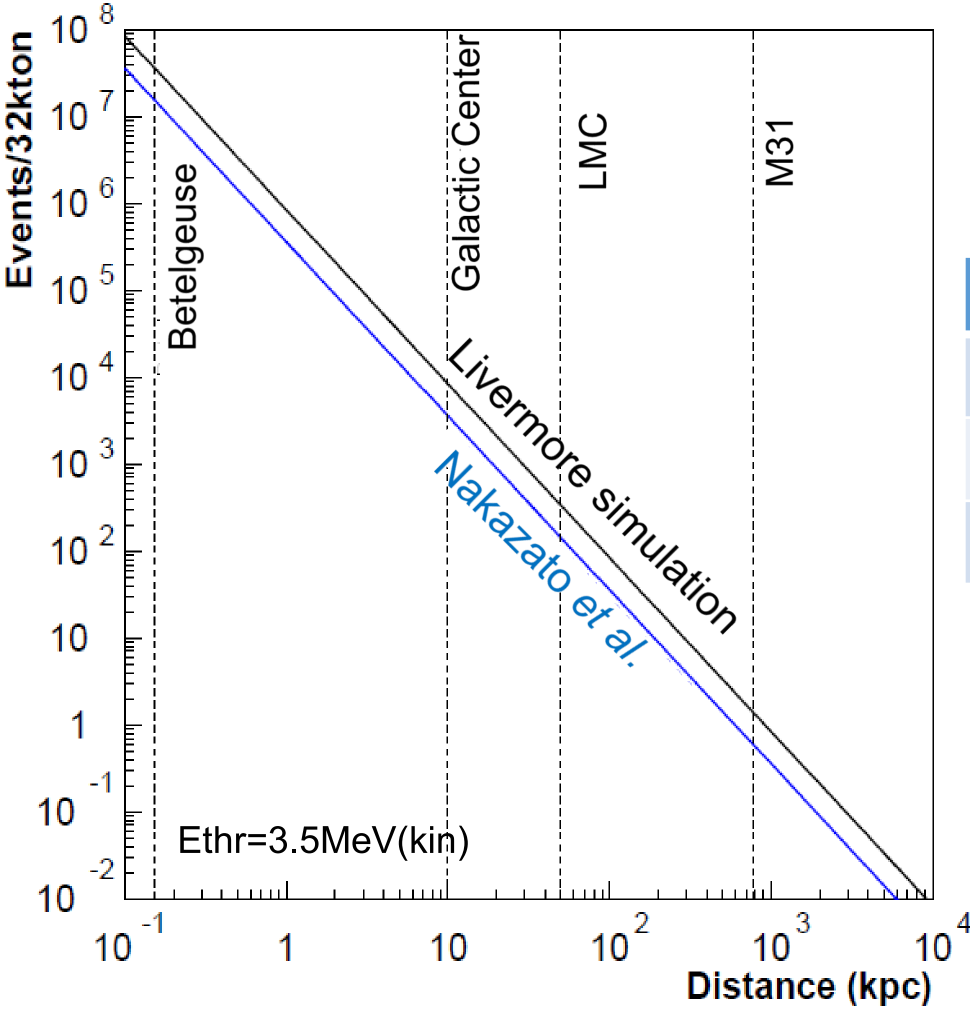
Neutrino flux upper limit (90% C.L.)



SK sensitivity get into the model prediction region for Eν > 17 MeV.
SK-Gd gives world best flux limit for Eν > 12 MeV.
Interesting to see future progress in 14 – 25 MeV energy range.

Galactic Supernova Search at Super-K

Number of events vs. distance



For each interaction

	Livermore	Nakazato
$\bar{\nu}_e p \rightarrow e^+ n$	7300	3100
$\nu + e^- \rightarrow \nu + e^-$	320	170
^{16}O CC	110	57

Directional info.

Supernova at 10 kpc
32kton SK volume
4.5MeV(kin) threshold
No oscillation case.

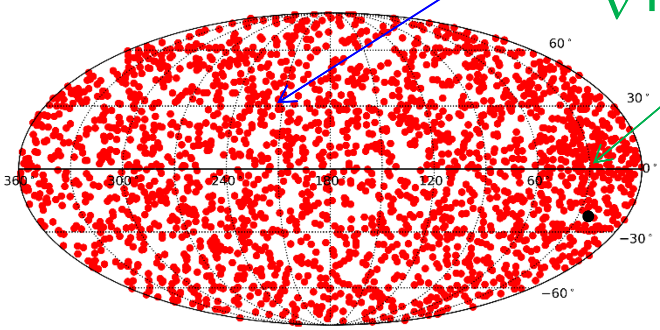
Livermore simulation T.Totani, K.Sato, H.E.Dalhed and J.R.Wilson, ApJ.496,216(1998)

Nakazato et al. K.Nakazato, K.Sumiyoshi, H.Suzuki, T.Totani, H.Umeda, and S.Yamada, ApJ.Suppl. 205 (2013) 2, ($20M_{sun}$, trev=200msec, z=0.02 case)

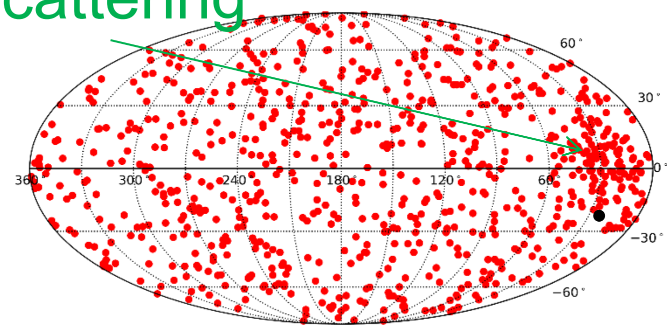
In case of Galactic supernova pointing accuracy has been improved with Gd

Simulation of skymap of observed events (10 kpc SN)

All events — $\bar{\nu}_e p \rightarrow e^+ n$ — $\nu + e$ scattering — Tagged $\bar{\nu}_e$ are removed

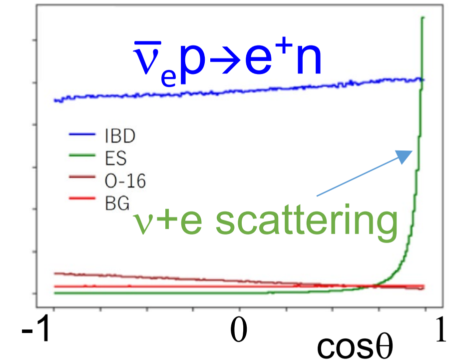


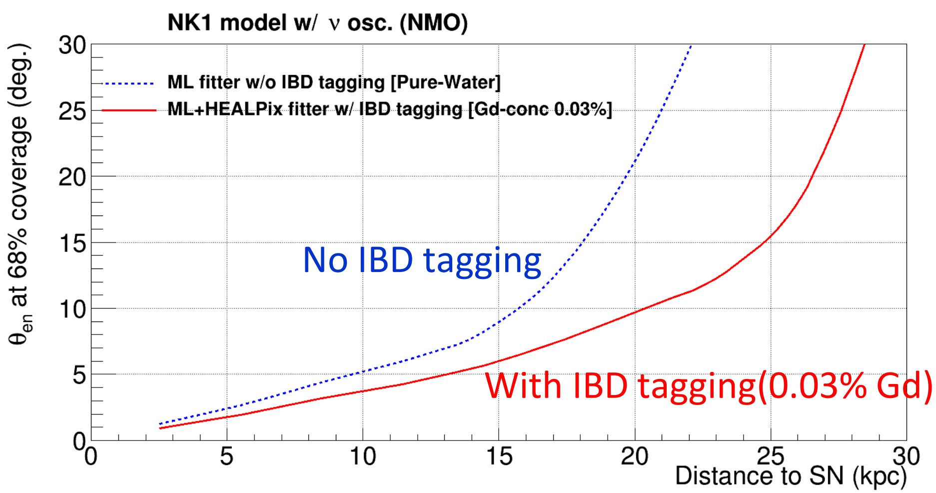
SN burst events w/o IBD tagging
(10kpc simulation)



SN burst events w/ 72% IBD events tagged/removed
(10kpc simulation)
(Expected with 0.1% Gd)

Angular distribution of each interaction

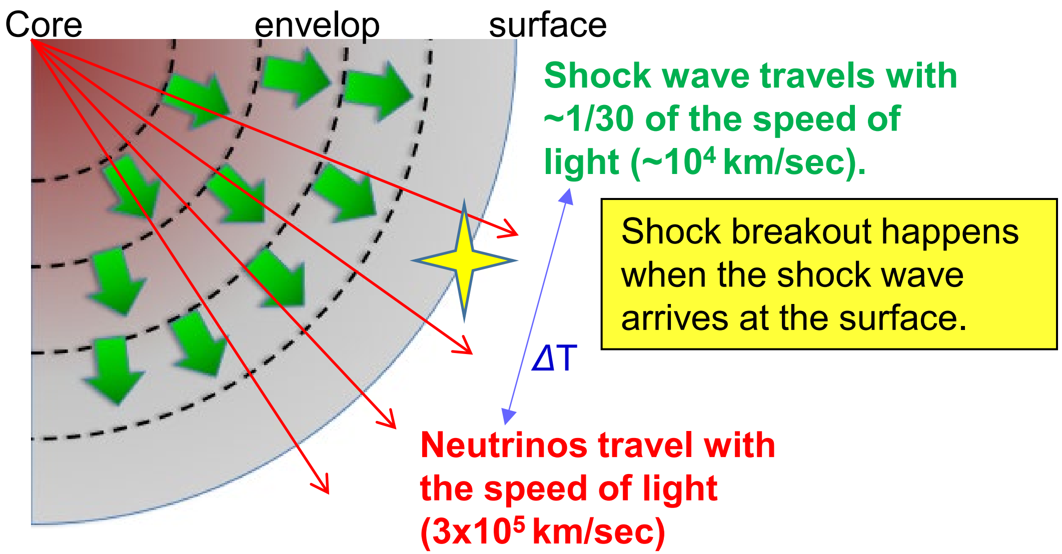


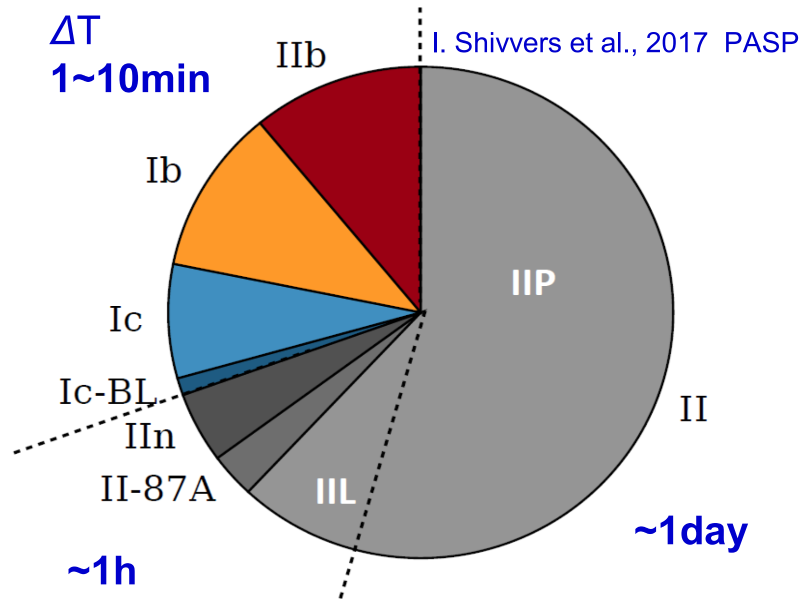


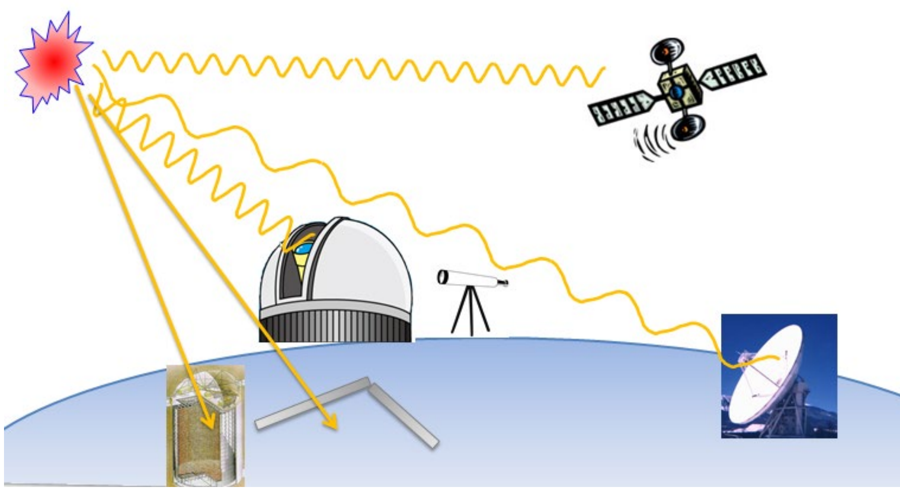
Current status

With 0.03% Gd (46% IBD tagging efficiency), the supernova direction pointing accuracy is ~3.7 degrees at 10 kpc.

Role of SK in Multi-messenger astronomy







For ~70% of SNe, the time difference is several hours to tens of hours. For remaining ~30%, that is several minutes.

SK will send a GCN Notice alert when a supernova burst is detected within ~1.5 minutes (at present).

Using elastic scattering, the Super-K detector is the world's best detector for determining direction of the supernova.

Summary

- Without the strong motivation to search for proton decay, the neutrinos from SN1987A might not have been detected at Kamiokande.
- Fortunately, the observed anomalies turned out to be hints of groundbreaking discoveries of neutrino oscillations at Kamioka.
- Neutrinos are mysterious particles, and uncovering their secrets has been a fascinating journey.
- I hope neutrino research will continue to advance both at Kamioka and around the world.