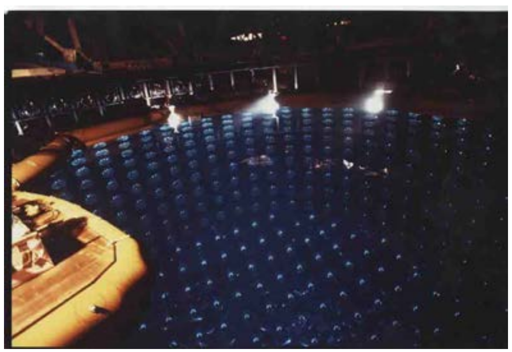
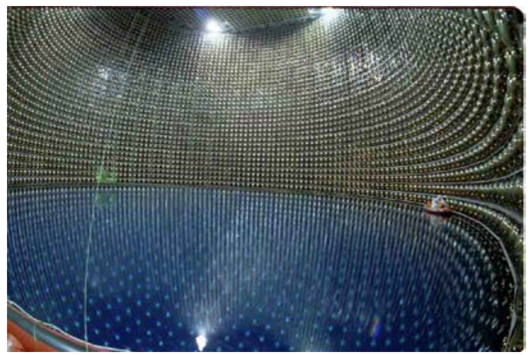
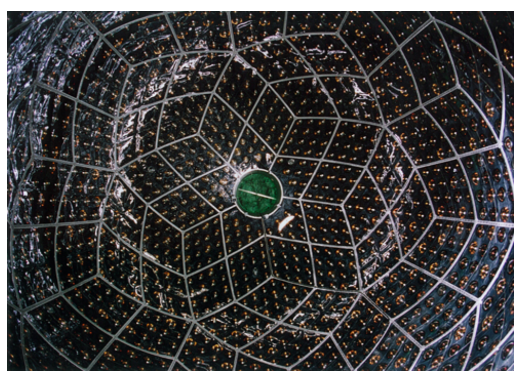
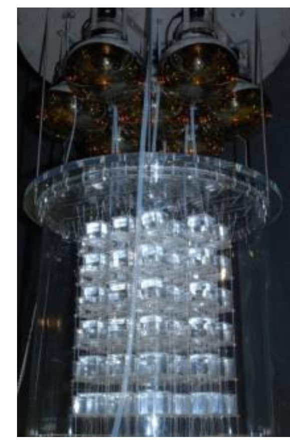
Neutrino experiments
-- 30 years at Kamioka --

M.Nakahata
Kamioka observatory
ICRR/IPMU, Univ. of Tokyo





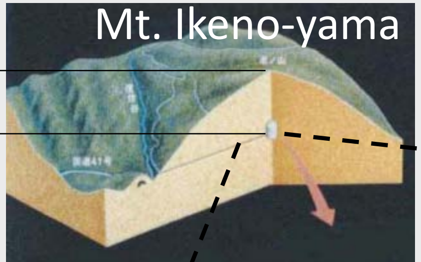




Contents

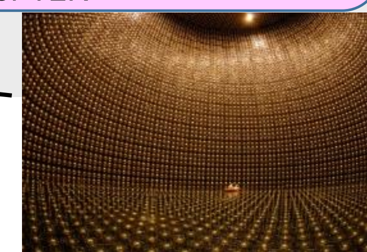
- Current experiments at Kamioka
- History of neutrino experiments at Kamioka
- Recent highlights from Super-K
- Future of Super-K, and Hyper-K project
- Future++

Kamioka underground experiments (NOW)

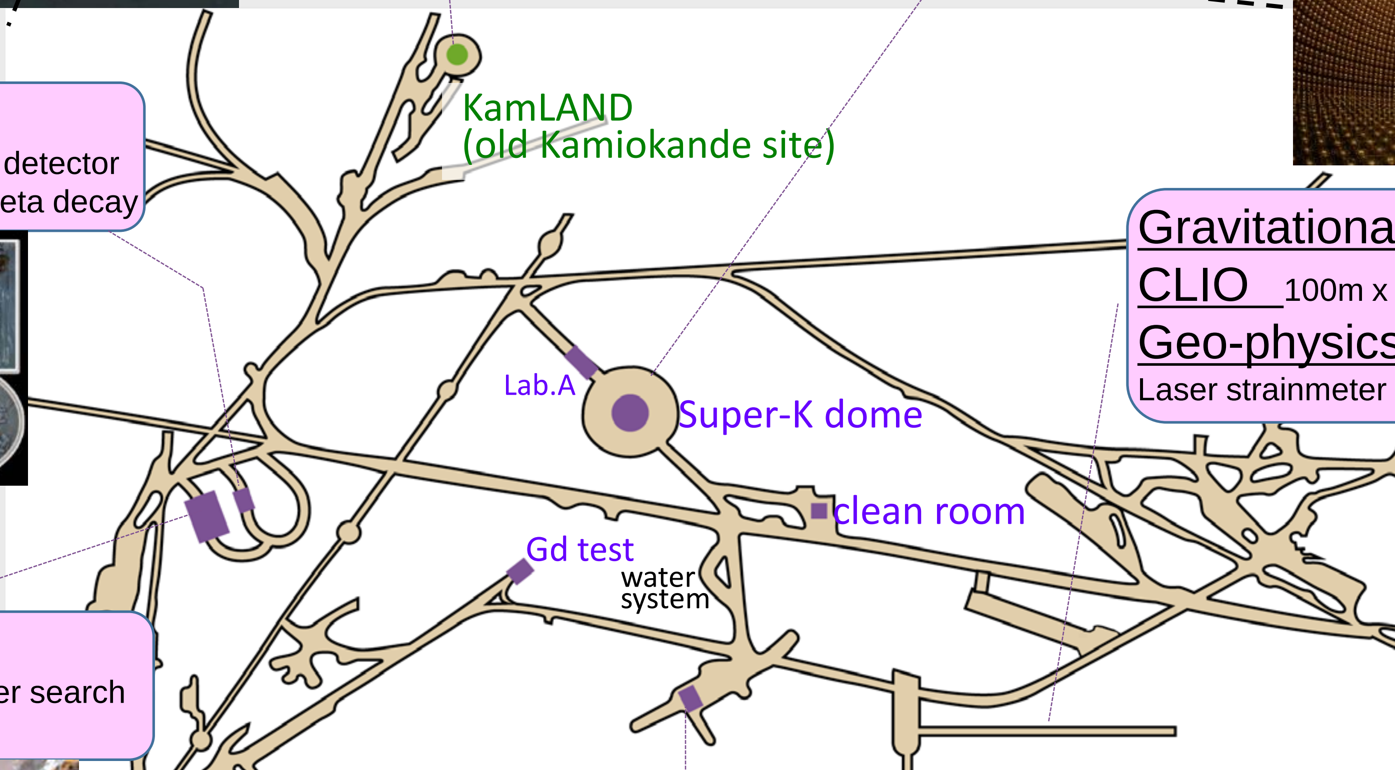


KamLAND (Tohoku Univ.)
1000ton liquid scintillator detector
Rector, geo neutrinos
^{136}Xe double beta decay

Super-Kamiokande
50,000 ton water Cherenkov detector
Atmospheric, solar, supernova neutrinos
Proton decay, indirect dark matter search
Far detector for T2K



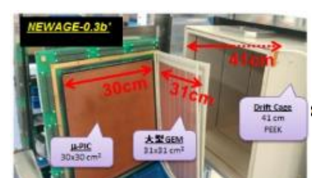
CANDLES
CaF_2 scintillation detector
for ^{48}Ca double beta decay



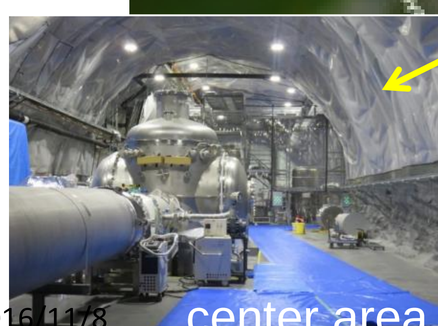
Gravitational-wave
CLIO 100m x 100m prototype
Geo-physics 100m x 100m
Laser strainmeter

XNASS
Direct dark matter search
experiment

NEWAGE
Direction dark matter
experiment

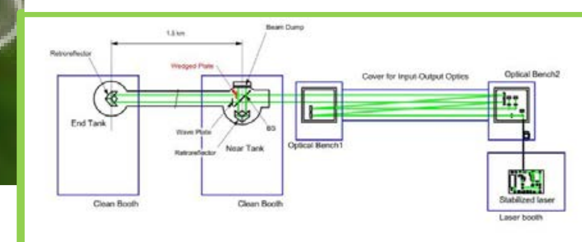


Kamioka underground experiments (NOW)



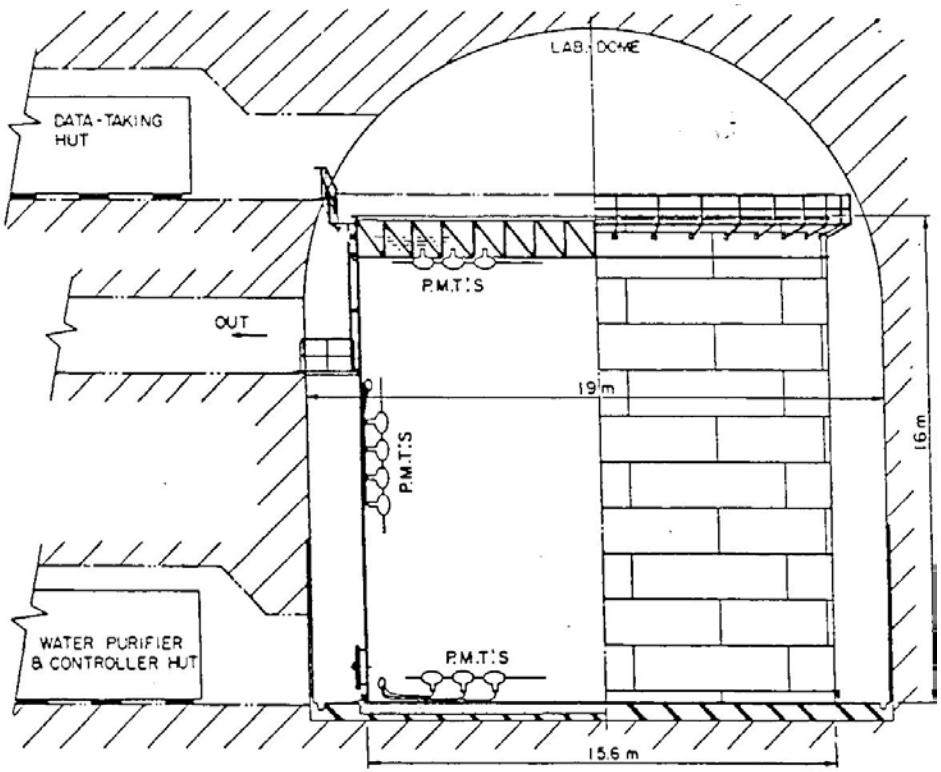
KAGRA
Gravitational-wave
Telescope

Laser strainmeter



1.5km Geophysics interferometer

Kamiokande-I detector（1983－1984）



Original purpose:

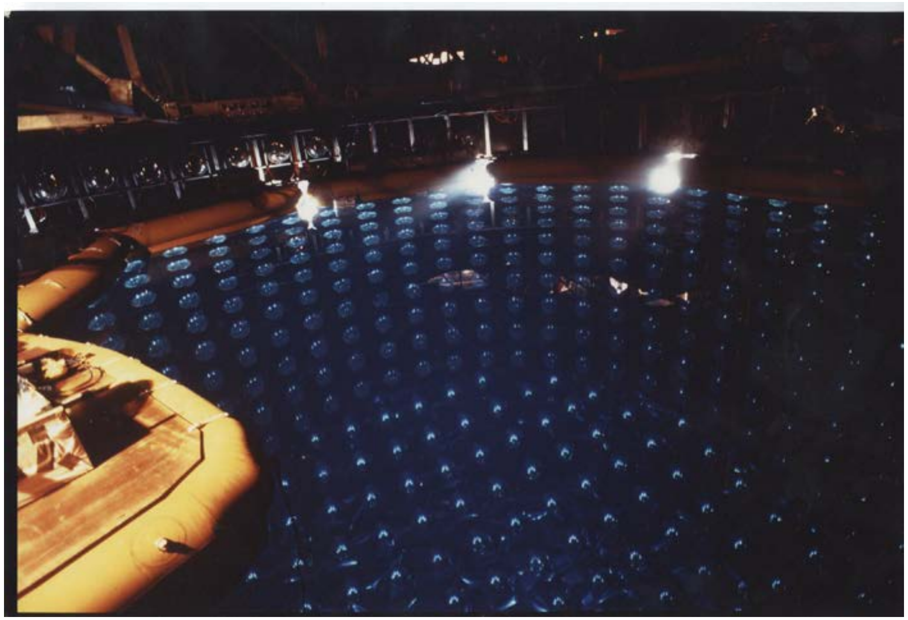
Search for proton decay

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

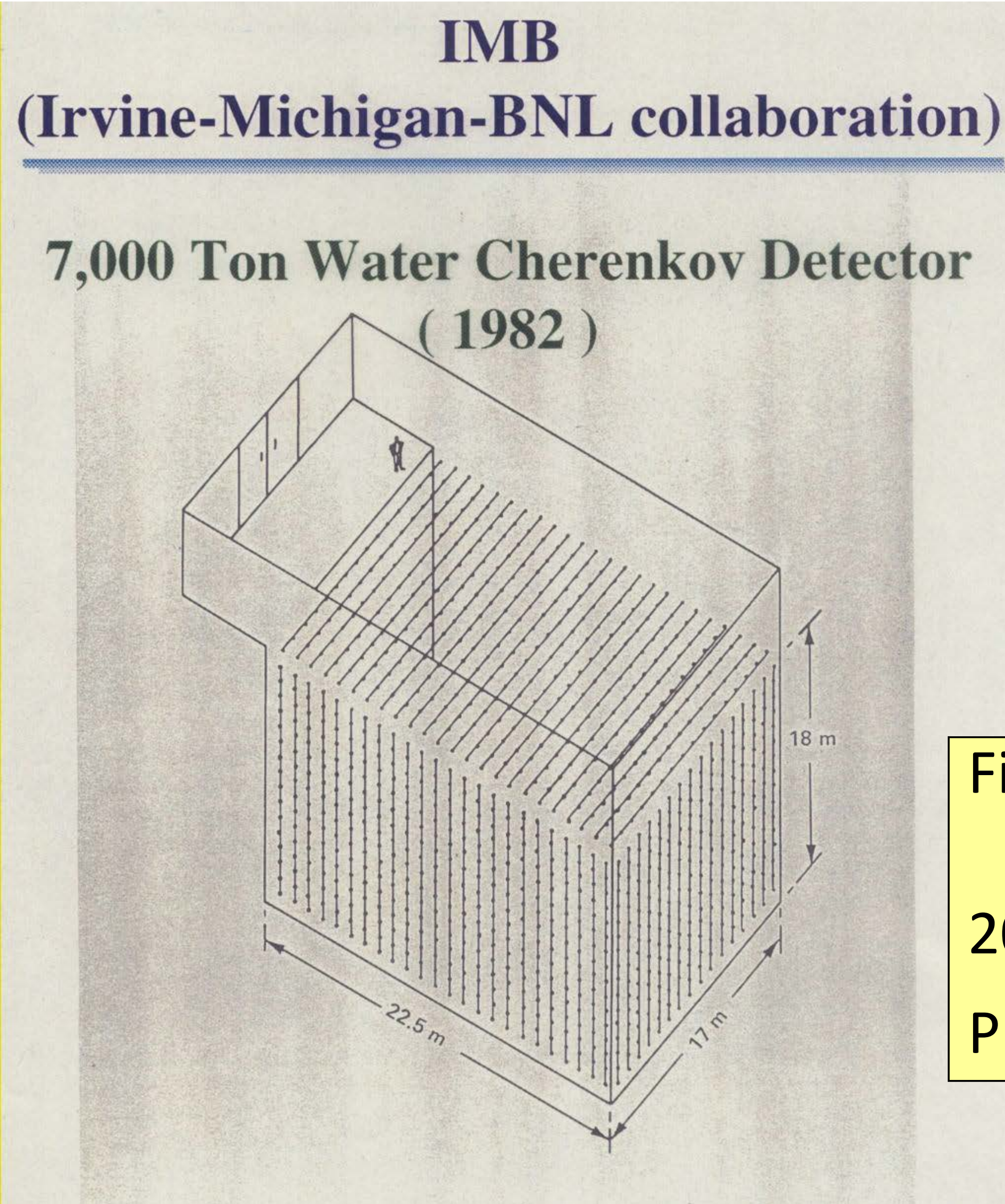
Fiducial volume: 880 ton
(2m from the wall)

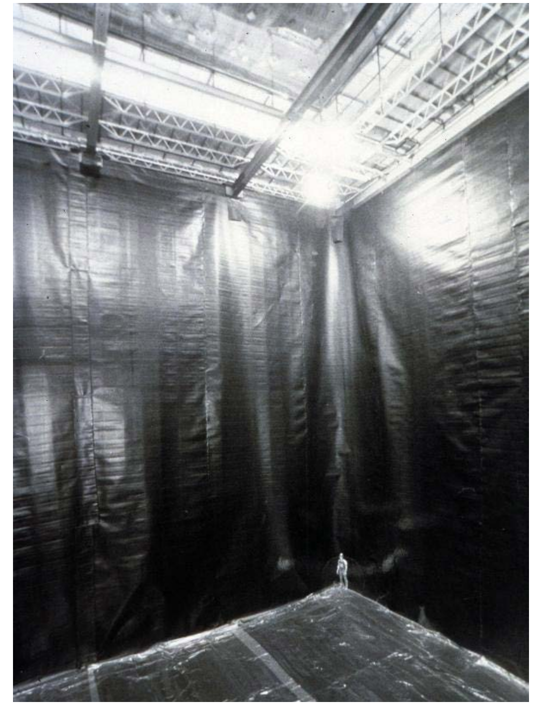
1000 20-inch PMTs were used

Photo-coverage: 20%



Competitor: IMB experiment





Fiducial volume: ~3400 ton
(x4 of Kamioande)

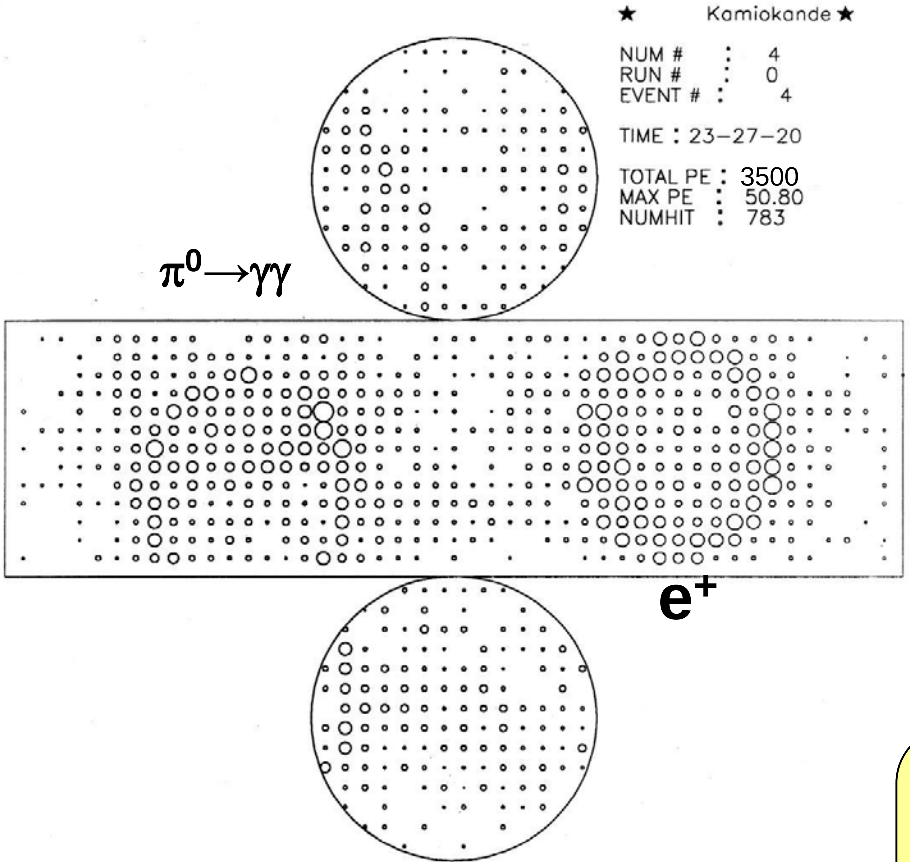
2048 5-inch PMTs

Photo-coverage: 1.3%

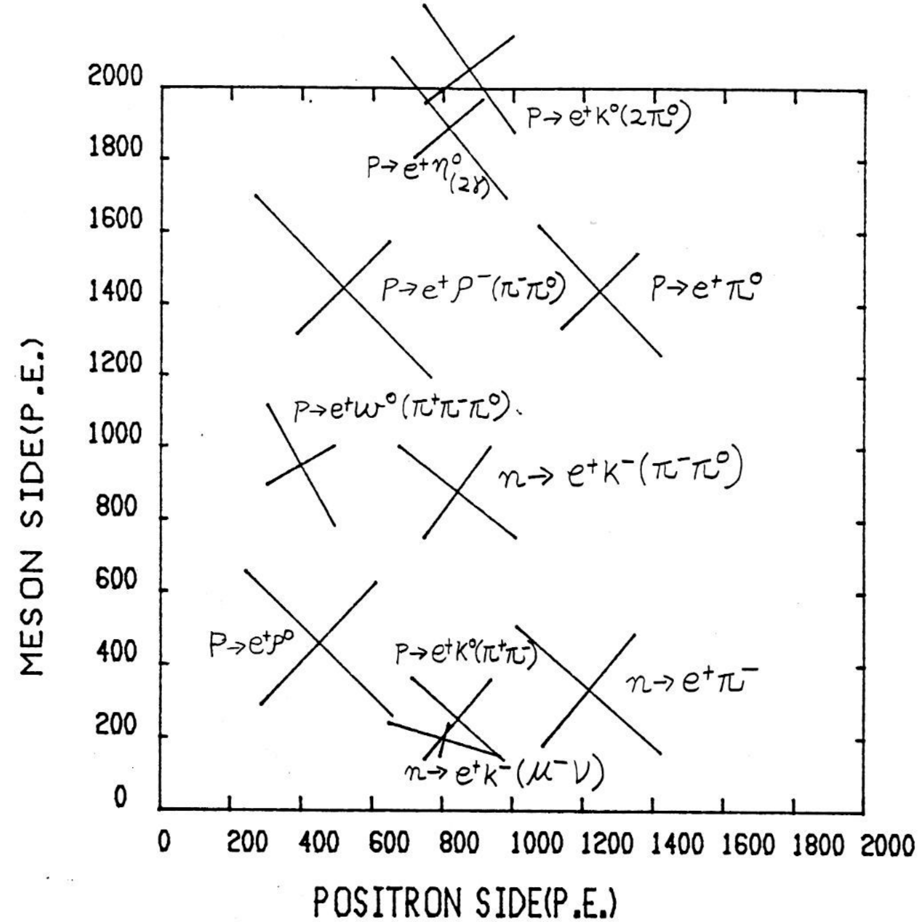
Already started from 1982

Purpose of Kamiokande

Aimed to measure branching ratio of proton decay



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

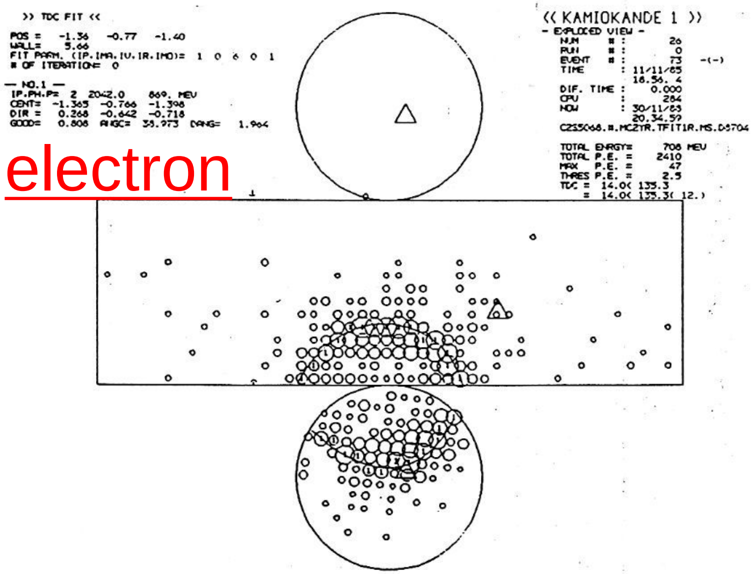


High resolution detector for measuring the branching ratio of proton decay.

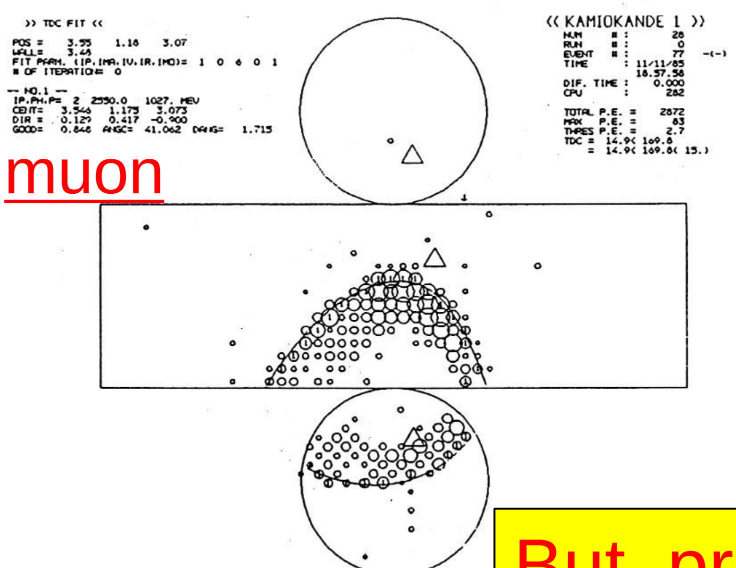
It should be useful to pin down the true GUT model.

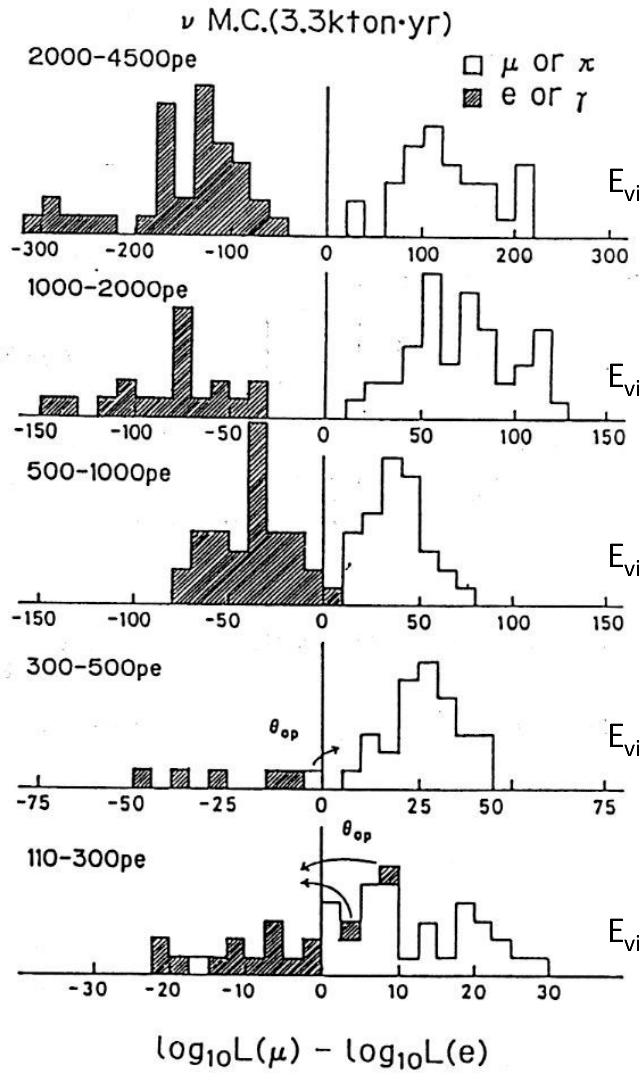
Particle identification(PID) of e/μ for proton decay

electron



muon





E_{vis}=540 - 1200 MeV

E_{vis}=270 - 540 MeV

E_{vis}=130 - 270 MeV

E_{vis}=80 - 130 MeV

E_{vis}=30 - 80 MeV

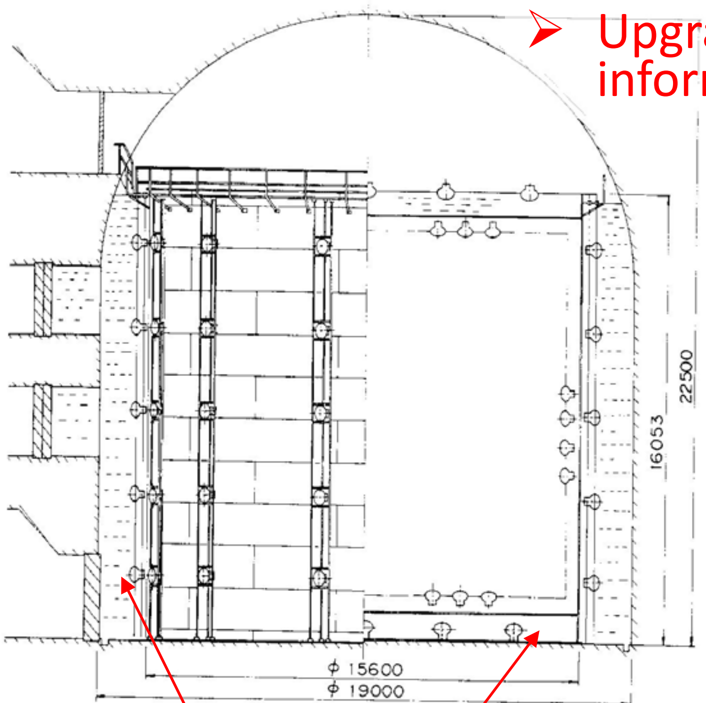
Mis-identification is less than 1%.

But, proton decay was not observed….

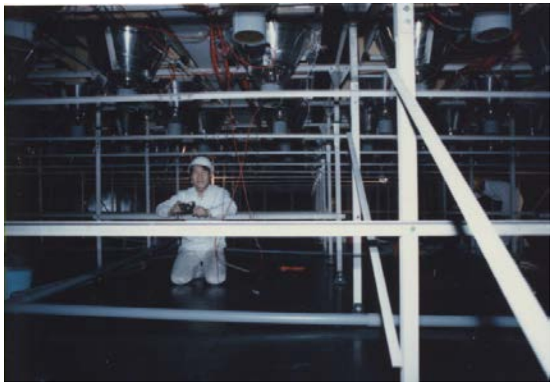
Upgrade to Kamiokande-II (1984-1985)

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.



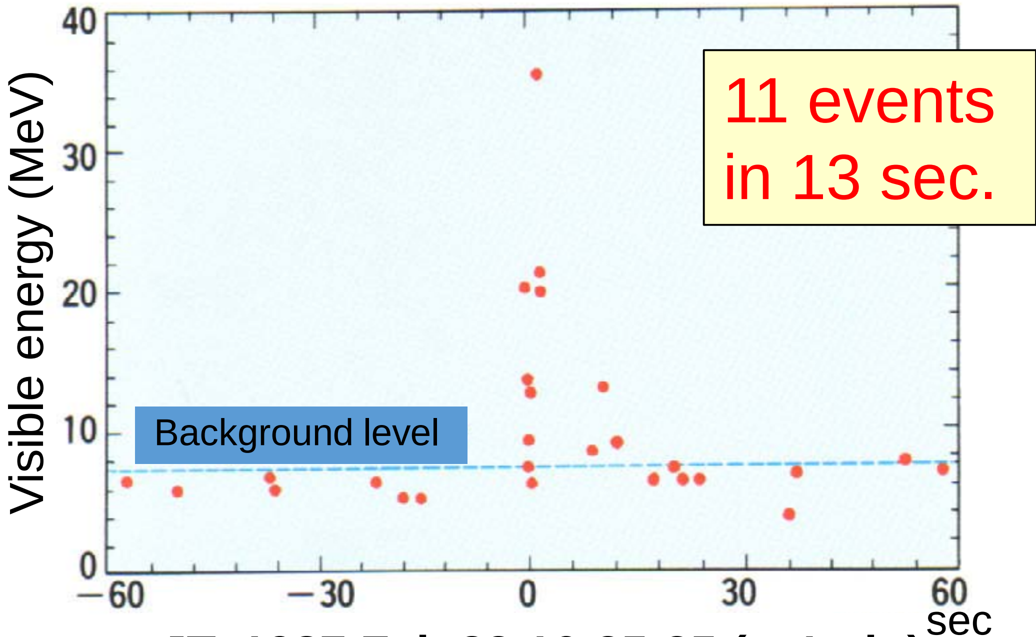
- Upgrade electronics for readout of timing information. It improved vertex reconstruction.
- Made outer detector to shield external gamma rays



SN1987A: a supernova at LMC (Feb.23rd, 1987)

It happened when the Kamiokande detector was almost ready for solar neutrino measurement.

After Before



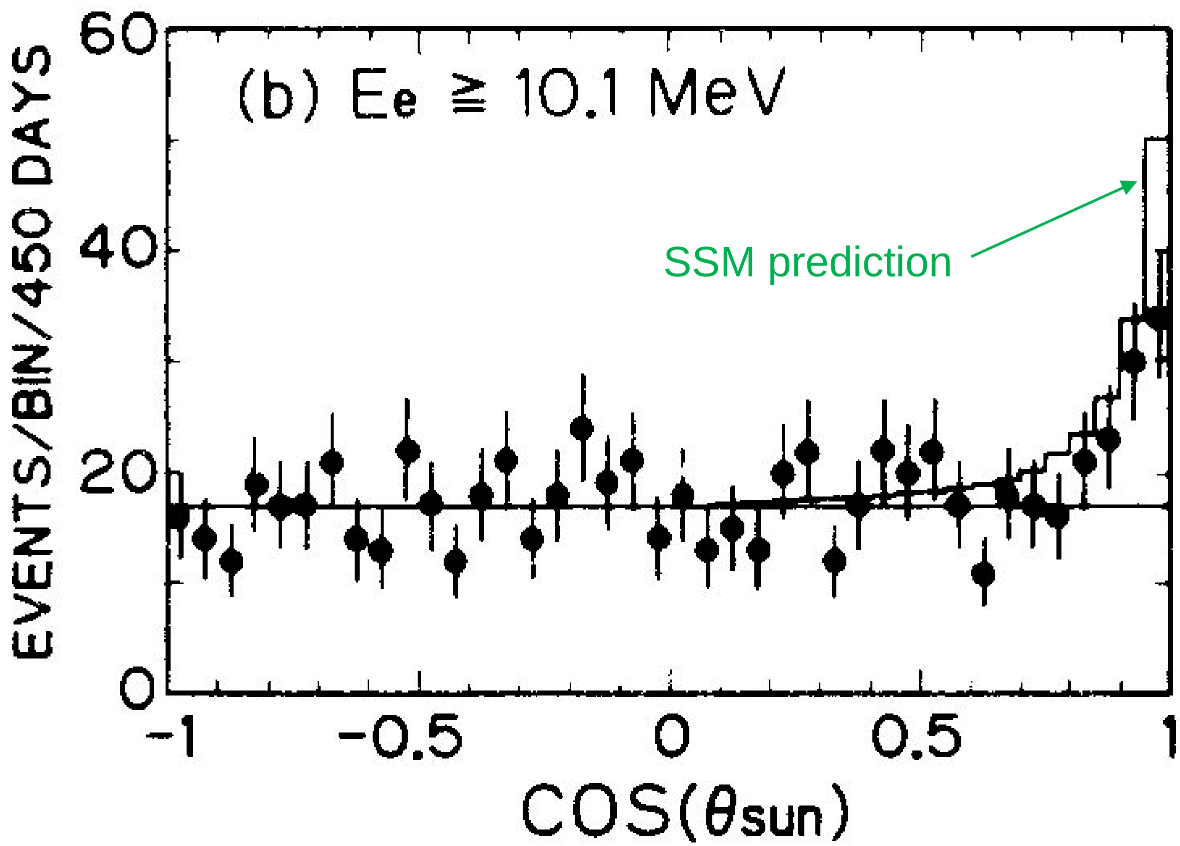
JT: 1987 Feb 23 16:35:35 (±1min)
UT: 7:35:35

Total energy released by $\bar{\nu}_e$ was measured to be ~5x10^{52} erg.

It was consistent with core-collapse scenario of supernova.

1988: First observation of solar neutrinos

Based on 450 days' Kamiokande data taken from Jan.1987 to May 1988



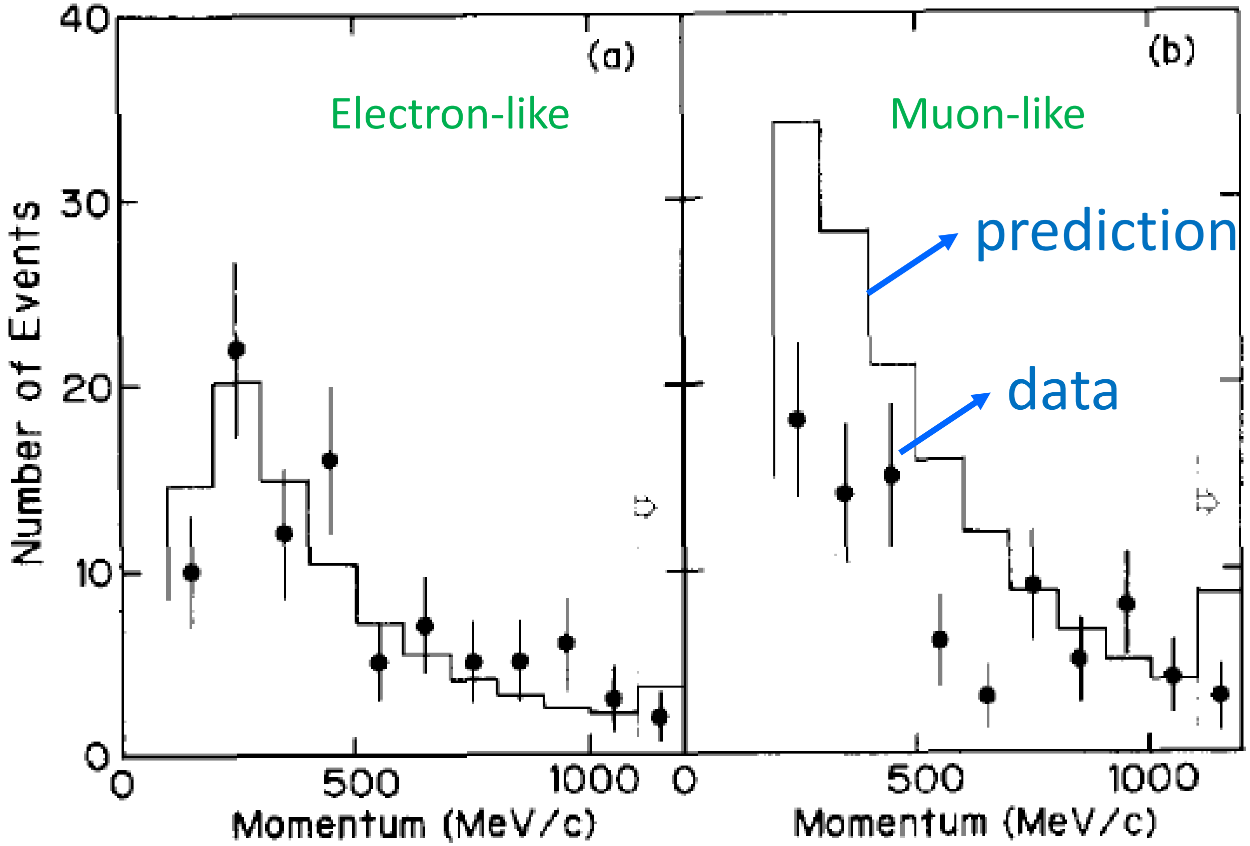
Observed number of solar neutrinos was about 50.

It was almost half of the expectation from the Standard Solar Model (SSM) and confirmed the solar neutrino problem.

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

1988: Atmospheric neutrino anomaly at Kamiokande

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

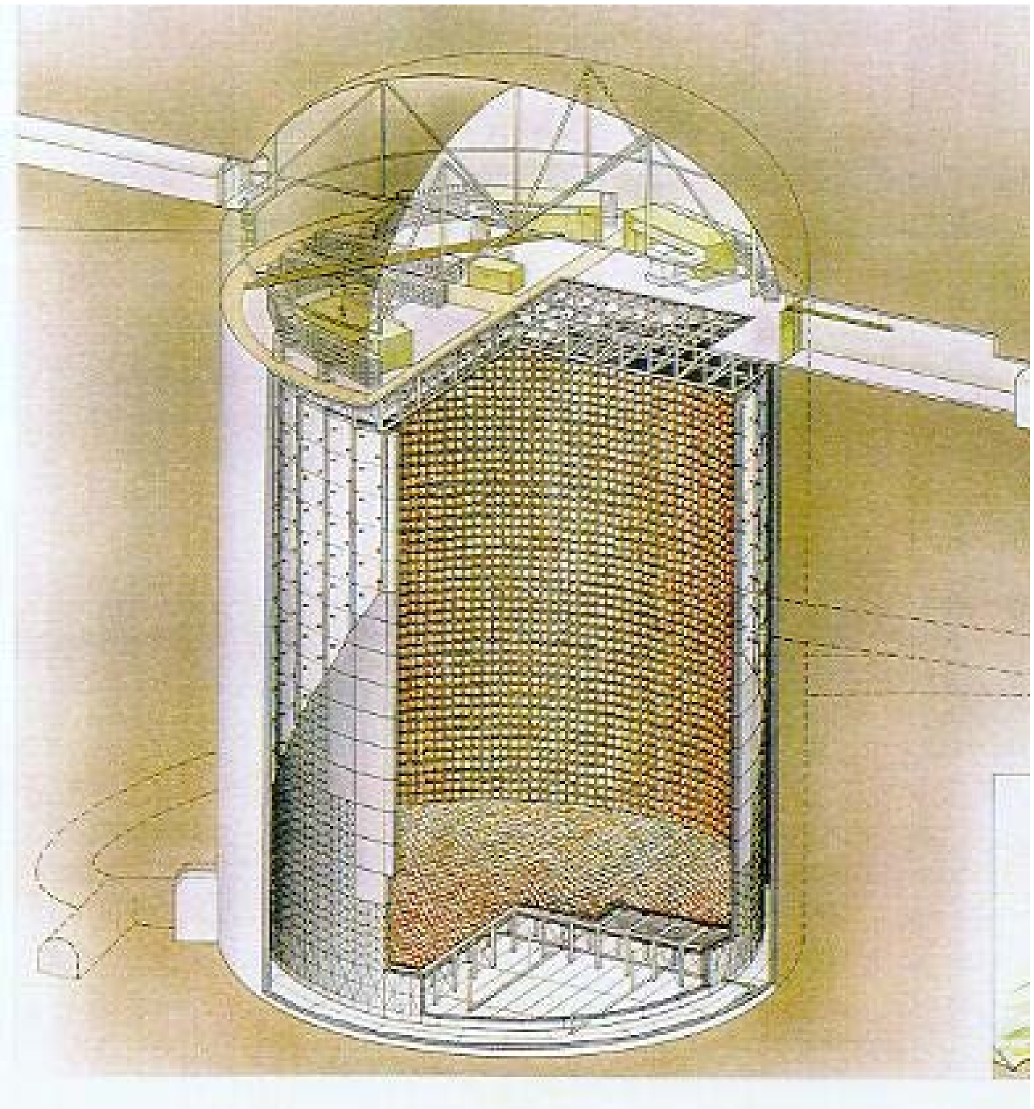


Electron-like data is consistent with prediction.
But, muon-like data is 59±7% of prediction.

The first hint of neutrino oscillations.

Super-Kamiokande detector (1996 –)

In order to solve the problems of solar and atmospheric ν and detect more supernova ν.

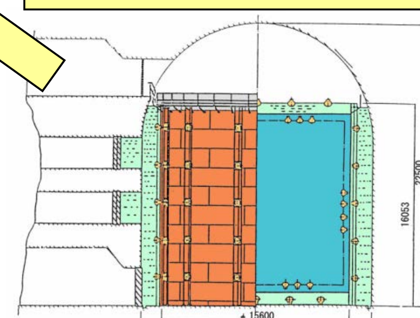


- 50,000 t water tank
  (42m high, 40m diameter)

  32,000 t photo-sensitive volume

  22,000 t fiducial volume
- 11,146 20-inch PMTs
- Photo-coverage: 40%
  (x2 of Kamiokande in order to lower energy threshold)
- 1000m underground in Kamioka mine

X 25 fiducial volume than Kamiokande



1998: Evidence for atmospheric neutrino oscillation

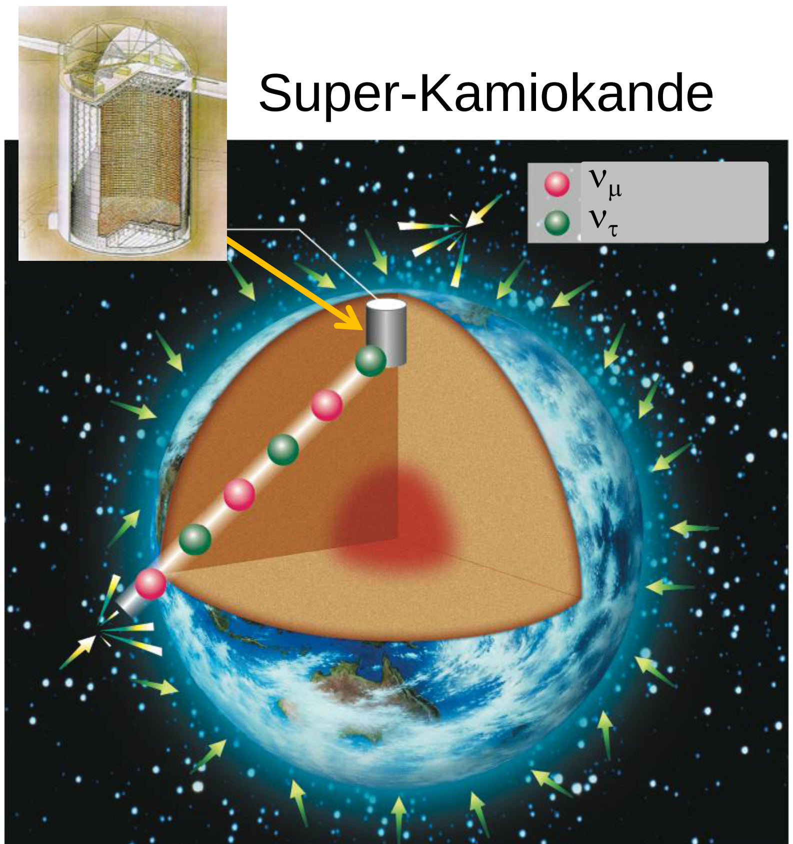
Cosmic rays produce neutrinos.

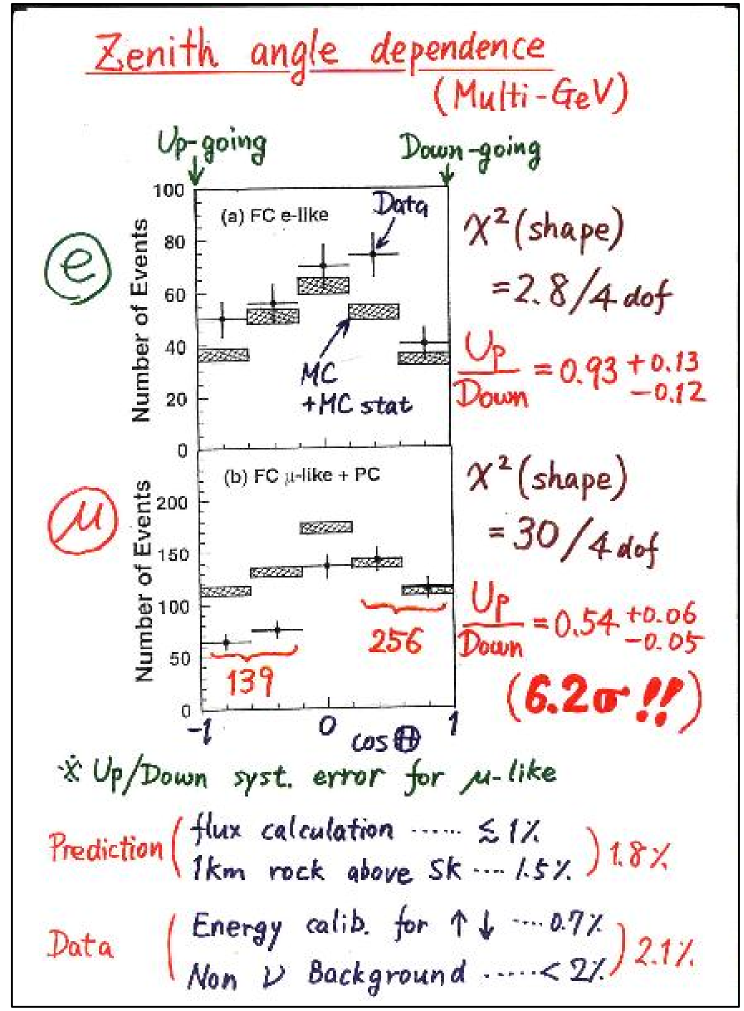
$P + A \rightarrow N + \pi^{\pm} + X$

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

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

Super-Kamiokande

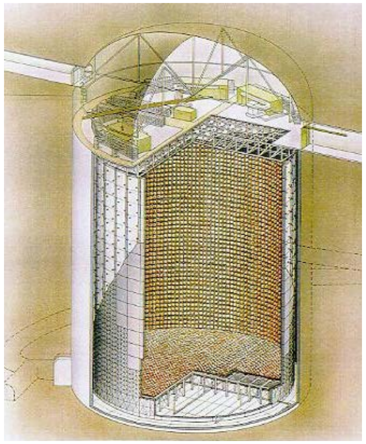


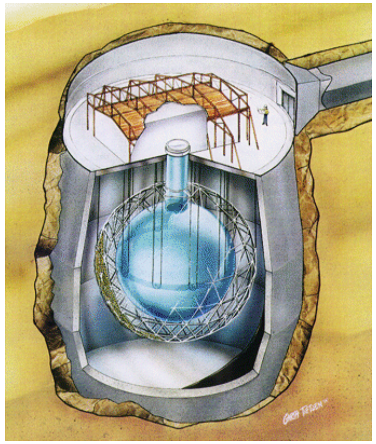


Kajita's presentation in Neutrino 1998 conference.

ν_μ disappearance

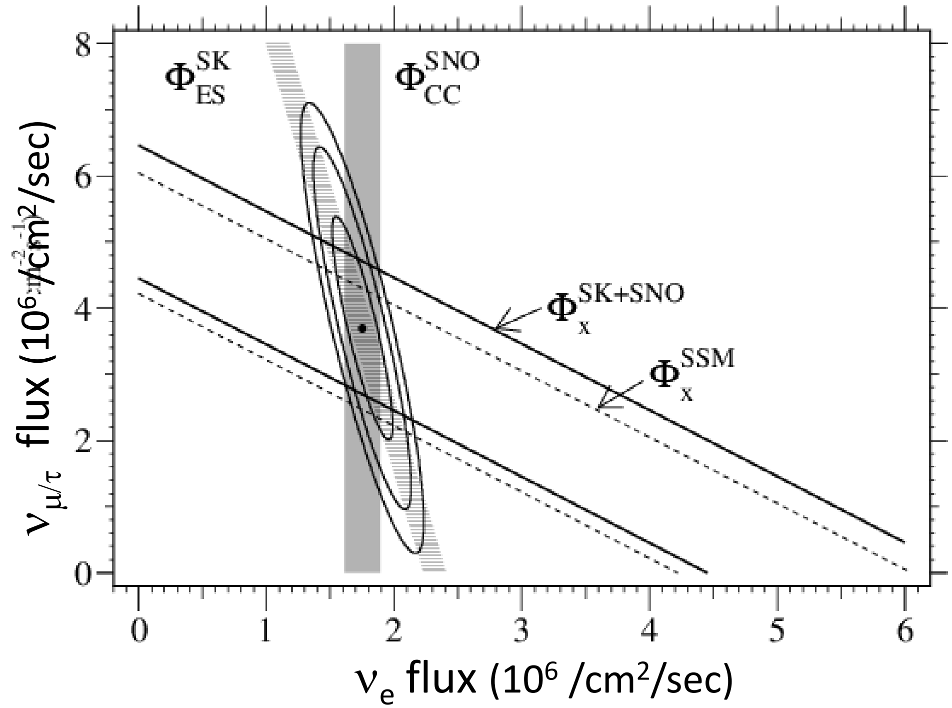
2001: Evidence for solar neutrino oscillation





SK ES vs. SNO CC

2001 SNO paper



Interactions

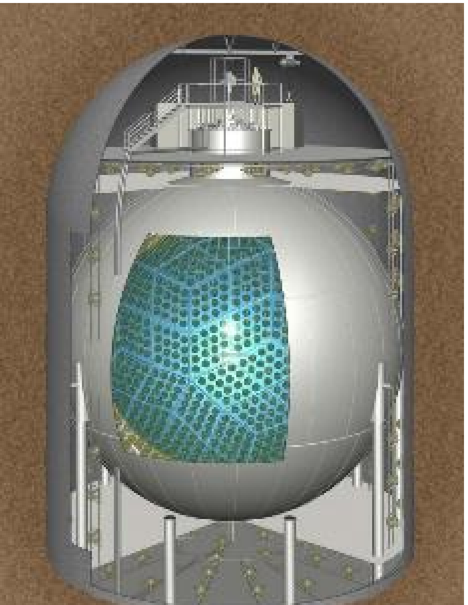
(ES) $\nu + e^- \rightarrow \nu + e^-$ (σ of $\nu_{\mu/\tau}$ is 1/7 of ν_e)

(CC) $\nu_e + d \rightarrow p + p + e^-$

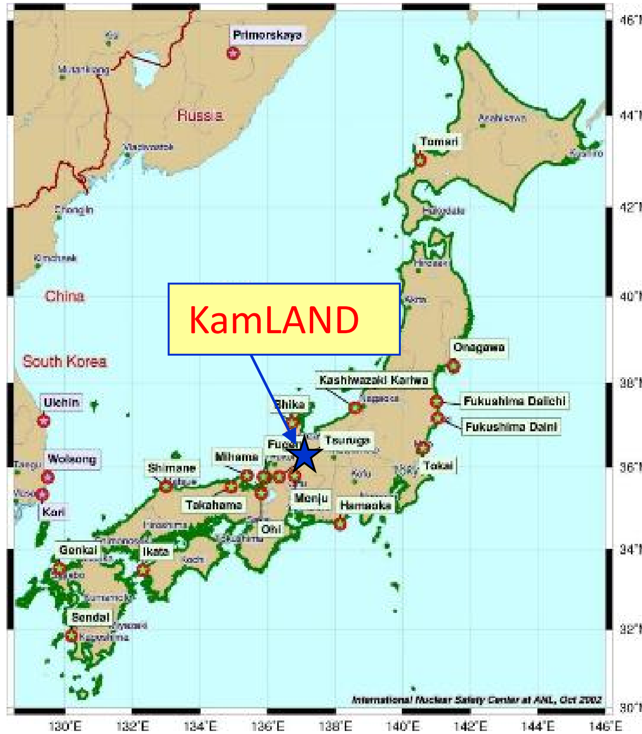
(NC) $\nu_x + d \rightarrow \nu_x + p + n$ (X=e,μ,τ)

ν_e to $\nu_{\mu/\tau}$ conversion

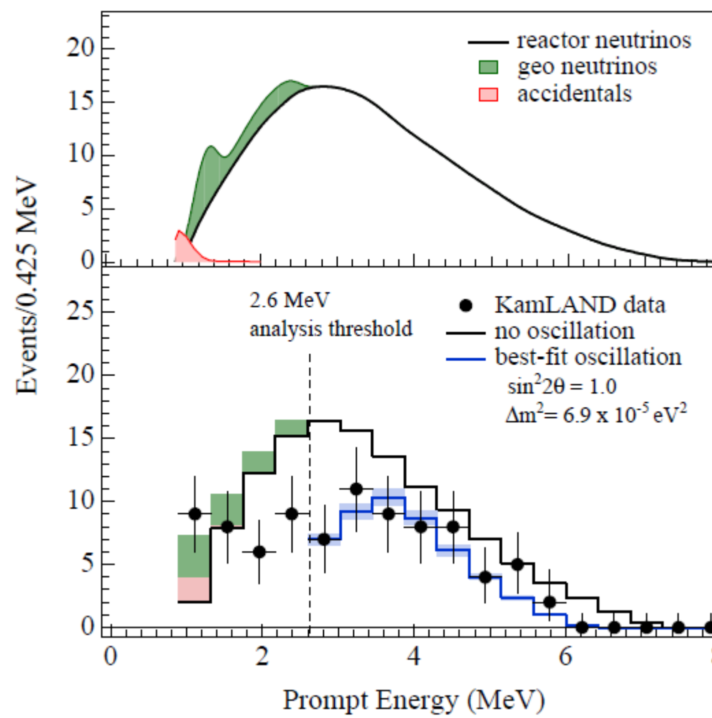
2002: Reactor neutrino oscillation by KamLAND



KamLAND



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



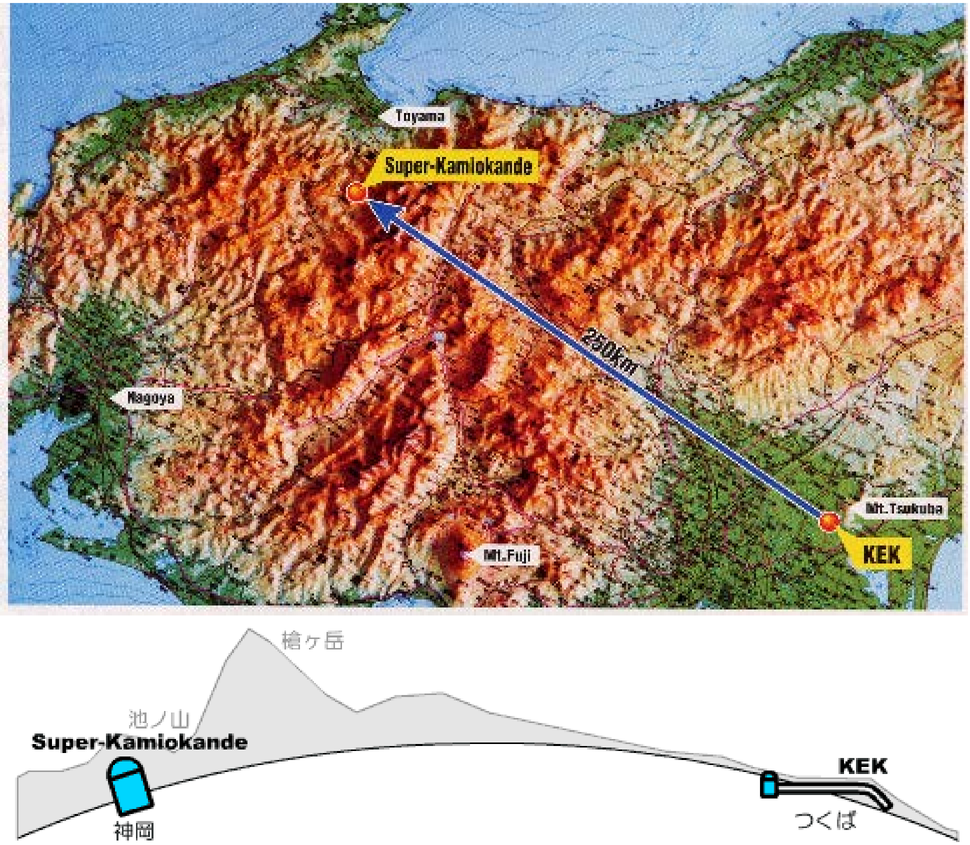
Built at old Kamiokande site

1000 ton liquid scintillator.

Run by Tohoku University.

$\bar{\nu}_e$ disappearance

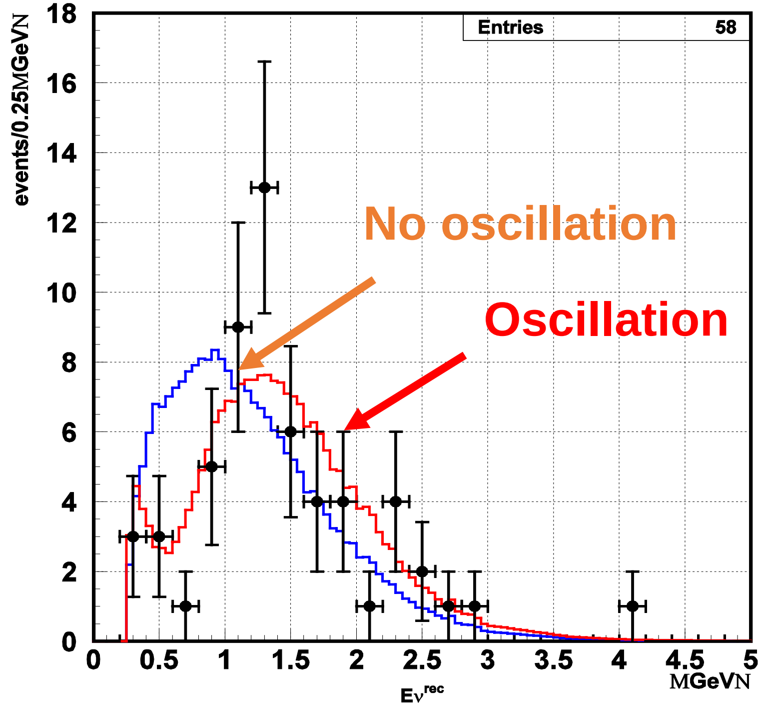
1999-2004: K2K (KEK to Kamioka)

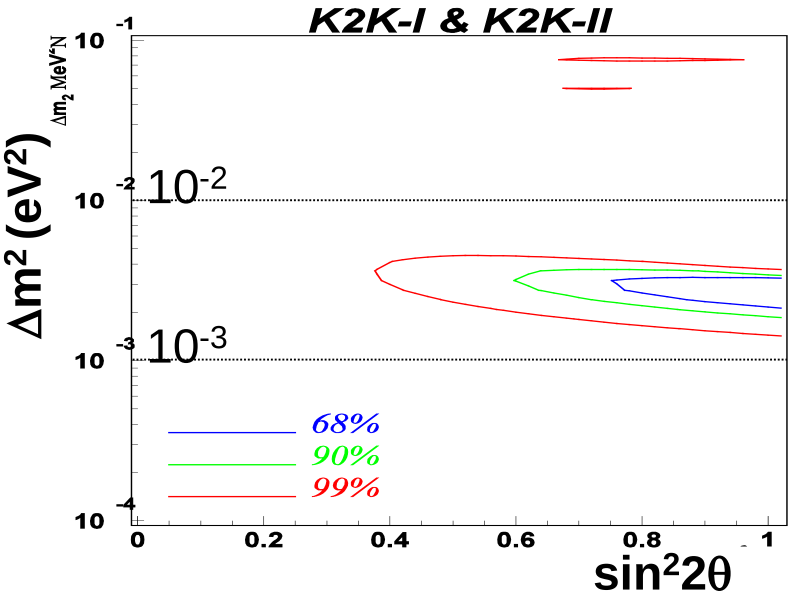


The first artificial neutrino beam experiment in the world.

Results from K2K experiment

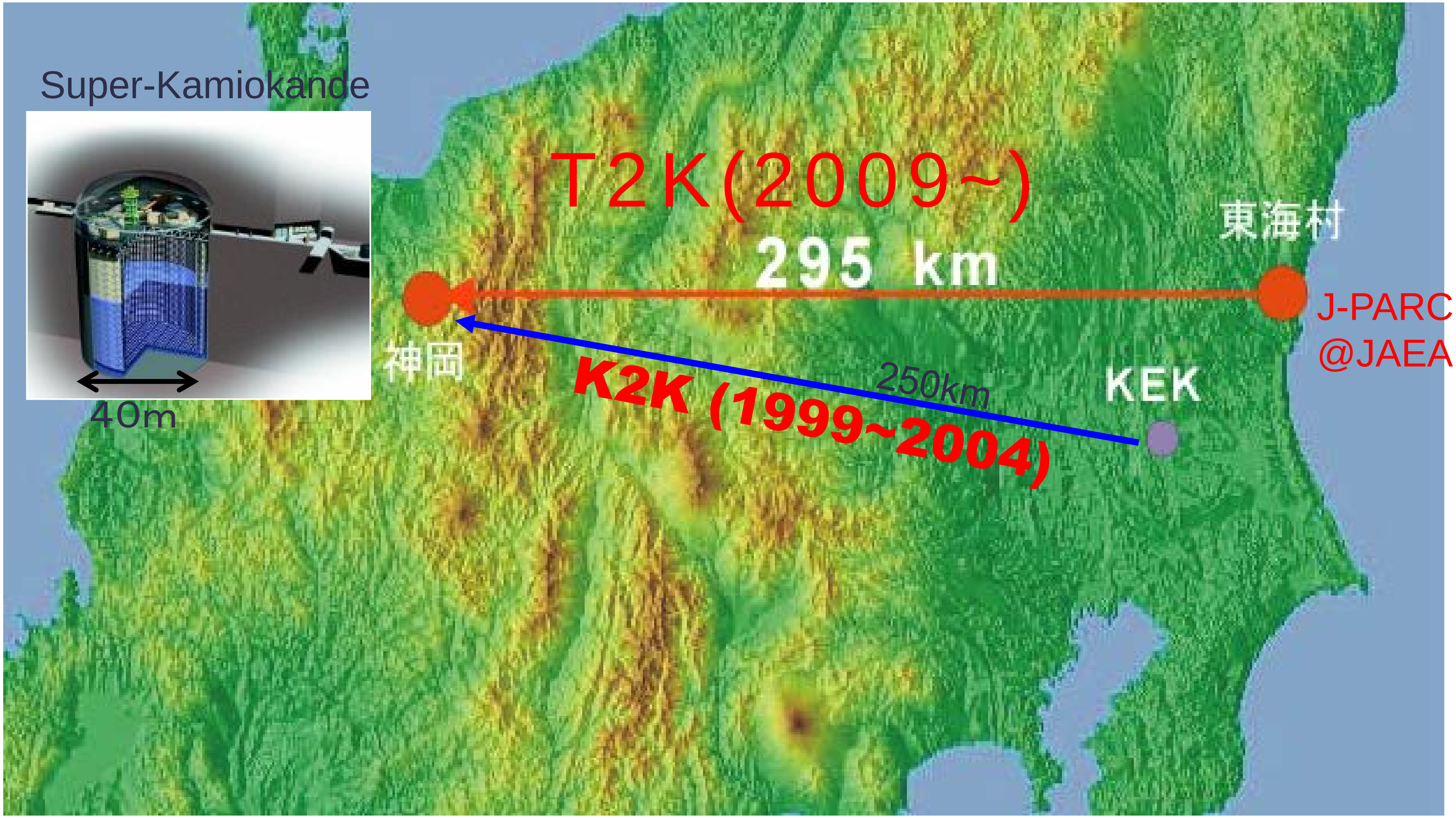
	N_{sk}^{obs}	N_{sk}^{pred}
All	**112**	**155.9**
1 ring	**67**	99.0
μ-like	58	90.8
e-like	9	8.2
multi-ring	**45**	56.8





Confirmed atmospheric oscillation (ν_μ disappearance due to $\Delta m^2_{23}/\theta_{23}$) using an artificial beam.

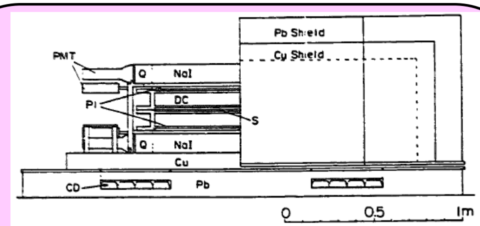
From 2009: T2K (Tokai to Kamioka)



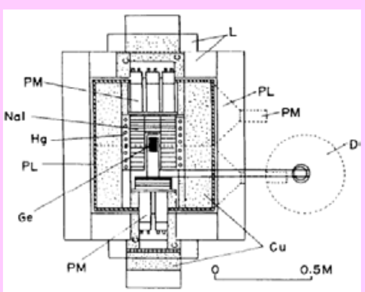
- J-PARC produces high intensity neutrino beam.
- SK detects neutrinos at 295km.
- Off-axis beam technique was adopted to make narrow band neutrino beam.

History of double beta decay at Kamioka

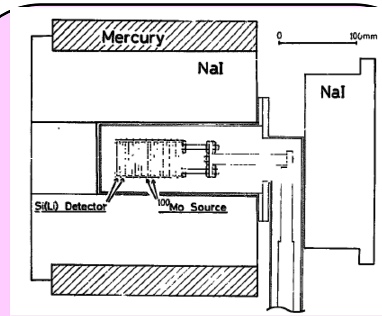
1980	1985	1990	1995	2000	2005	2010	2015



ELEGANT V(^{100}Mo,^{116}Cd)
1989-1995, hosted by
Osaka Univ.(Ejiri et al.)
@Kamiokande site

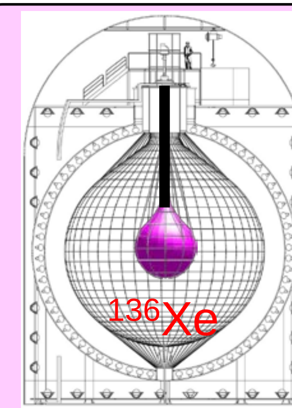


ELEGANT III (^{76}Ge)
1983-1986, hosted by
Osaka Univ.(Ejiri et al.)
@Kamiokande site



ELEGANT IV(^{100}Mo)
1986-1989, hosted by
Osaka Univ.(Ejiri et al.)
@Kamiokande site

CANDLES III (^{48}Ca)
2008-- , hosted by
Osaka Univ.
(Kishimoto et al.)
@ Lab.C

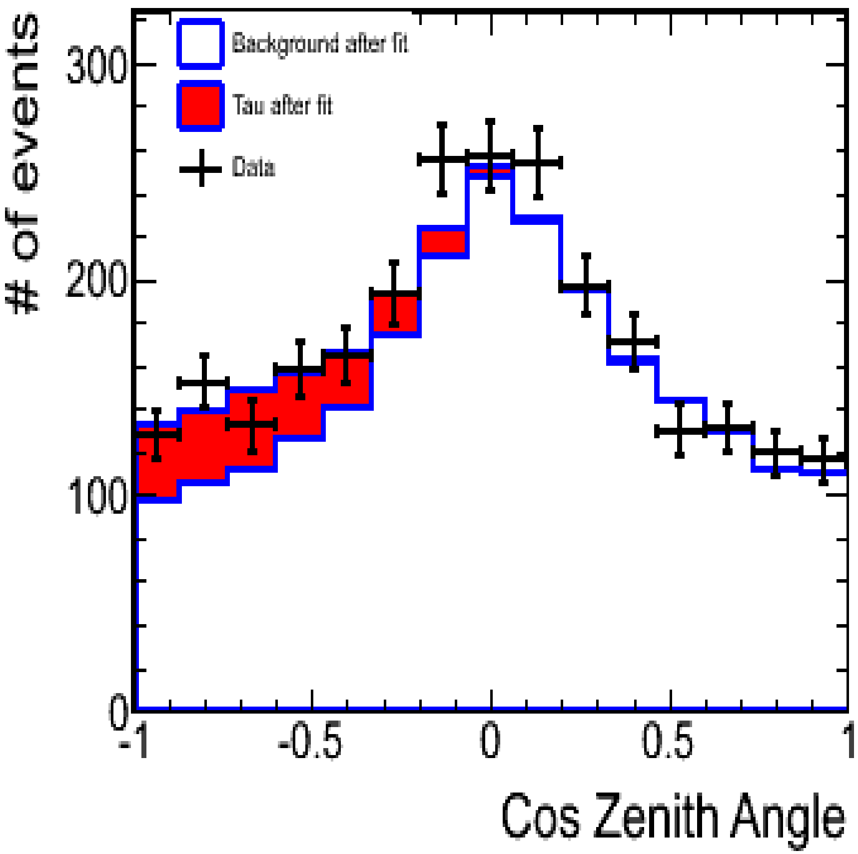


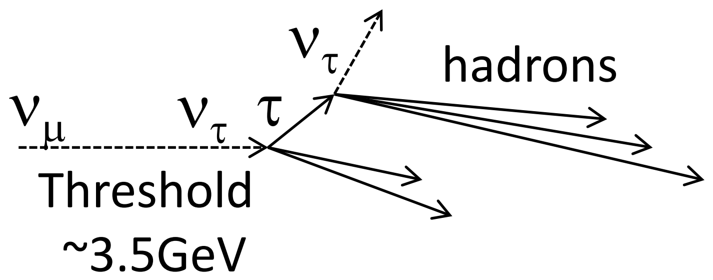
KamLAND-zen
2011-- , hosted by
Tohoku Univ.
(Inoue et al.)
@KamLAND site

Recent Highlights from SK
(including T2K results)

SK atmospheric ν: ν_τ appearance

Published at PRL 110,181802 (2013)



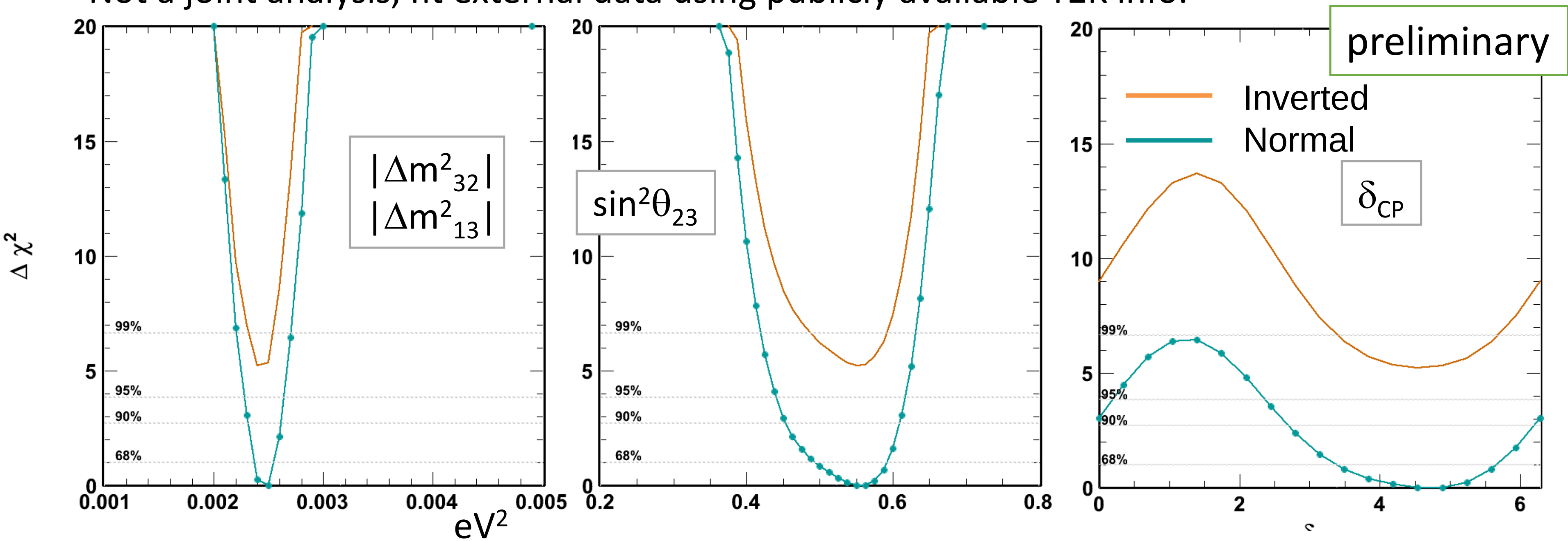


- Search for events consistent with hadronic decay of τ lepton
  - Multi-ring e-like events with visible energy above 1.3GeV.
- Negligible primary ν_τ flux so ν_τ must be oscillation-induced: **upward-going**

Observed # / Expected #
=1.47+/-0.32
(4.6σ from 0)
assuming NH

SK atmospheric ν analysis (with T2K constraint)

Not a joint analysis, fit external data using publicly available T2K info.

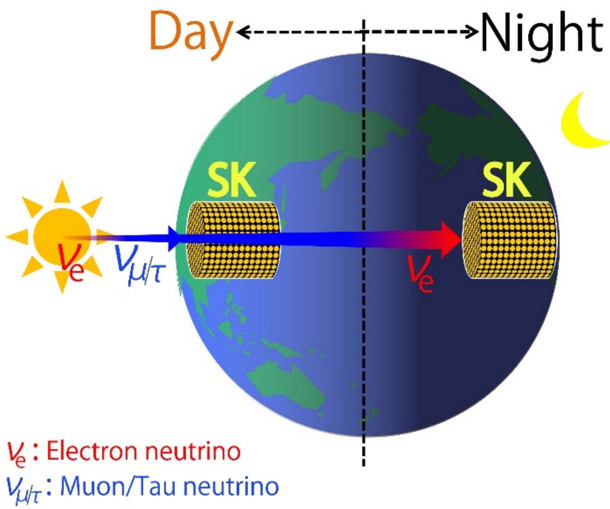


Fit (585 dof)	χ^2	$\sin^2\theta_{13}$	δ_{CP}	$\sin^2\theta_{23}$	$\lvert\Delta m^2_{32}\rvert$ eV^2
SK+T2K (IH)	644.82	0.0219 (fix)	4.538	0.55	2.5×10^{-3}
SK+T2K (NH)	639.61	0.0219 (fix)	4.887	0.55	2.4×10^{-3}

- SK+T2K (θ_{13} fixed): $\Delta\chi^2 = \chi^2_{NH}-\chi^2_{IH} = -5.2$
  (-3.8 exp. for SK best, -3.1 for combined best)
- Under IH hypothesis, the probability to obtain $\Delta\chi^2$ of -5.2 or less is 0.024 ($\sin^2\theta_{23}$=0.6) and 0.001 ($\sin^2\theta_{23}$=0.4).

SK solar ν: day/night effect

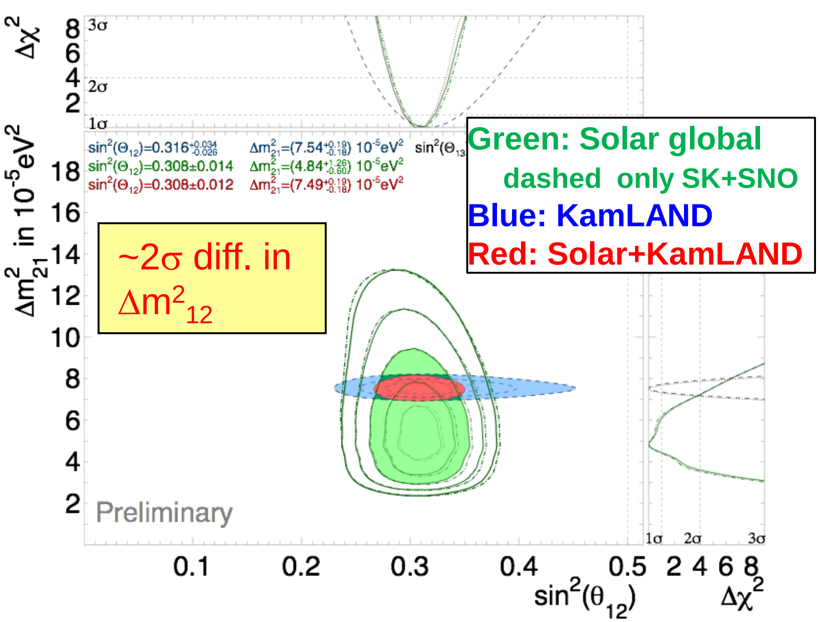
$$A_{DN} = \frac{(Day - Night)}{(Day + Night)/2}$$



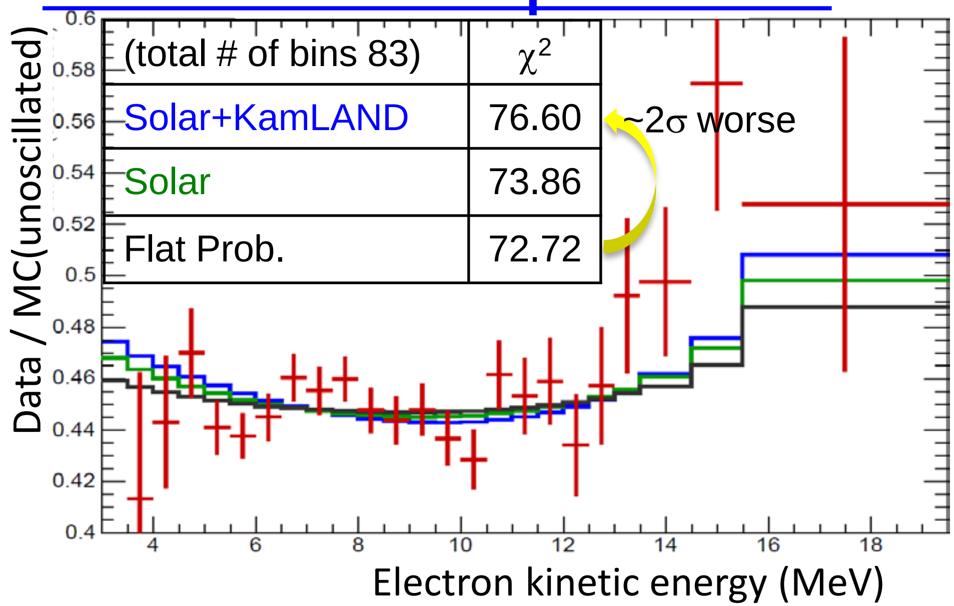
	D/N asymmetry (A_{DN})
	Δm^2_{21}=4.84x10^{-5} eV^2
SK-I	-2.0±1.8±1.0%
SK-II	-4.4±3.8±1.0%
SK-III	-4.2±2.7±0.7%
SK-IV	-3.6±1.6±0.6%
combined	-3.3±1.0±0.5%
non-zero significance	3.0σ

Direct indication of matter effect.

Solar global analysis



SK solar ν: spectrum

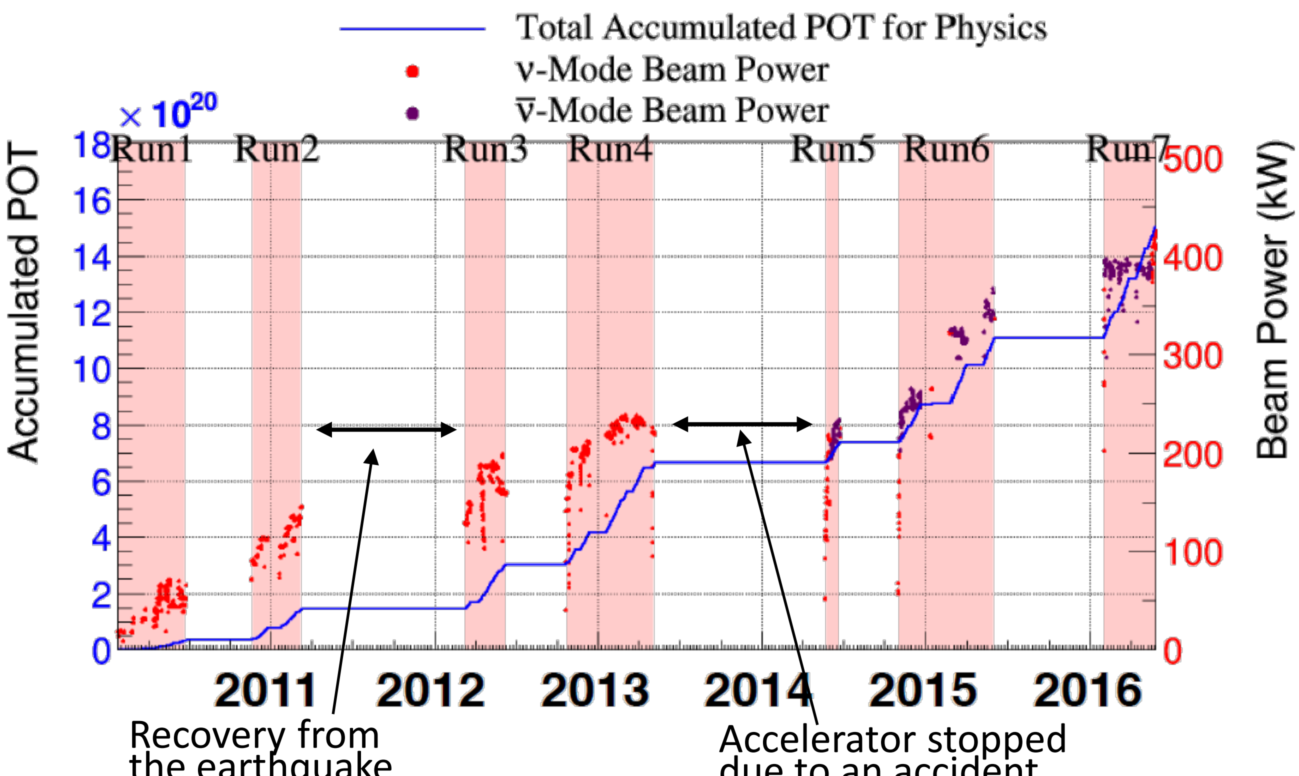


(total # of bins 83)	χ^2
Solar+KamLAND	76.60
Solar	73.86
Flat Prob.	72.72

Latest results from T2K

J.Imber in Session VII

- ν_e appearance for the study of θ_{13} and δCP
- ν_μ disappearance for the study of θ_{23} & Δm^2_{23}



Until May 2016

15 x 10^{20} POT

(~20% of the planned total)

Neutrino mode

7.57×10^{20} POT

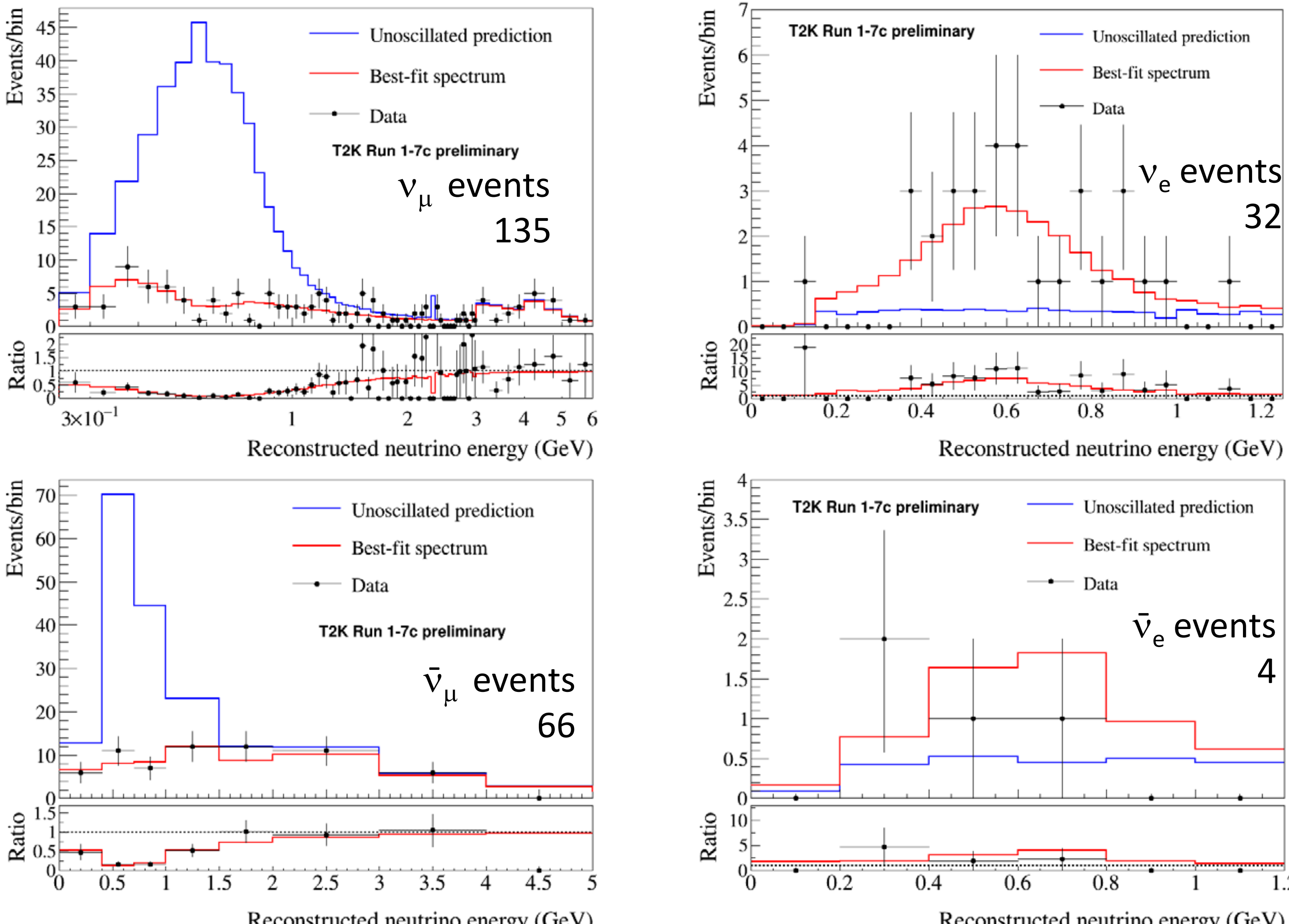
Anti-Neutrino mode

7.53×10^{20} POT

(POT: Proton On Target)

T2K: ν_μ disappearance and ν_e appearance data

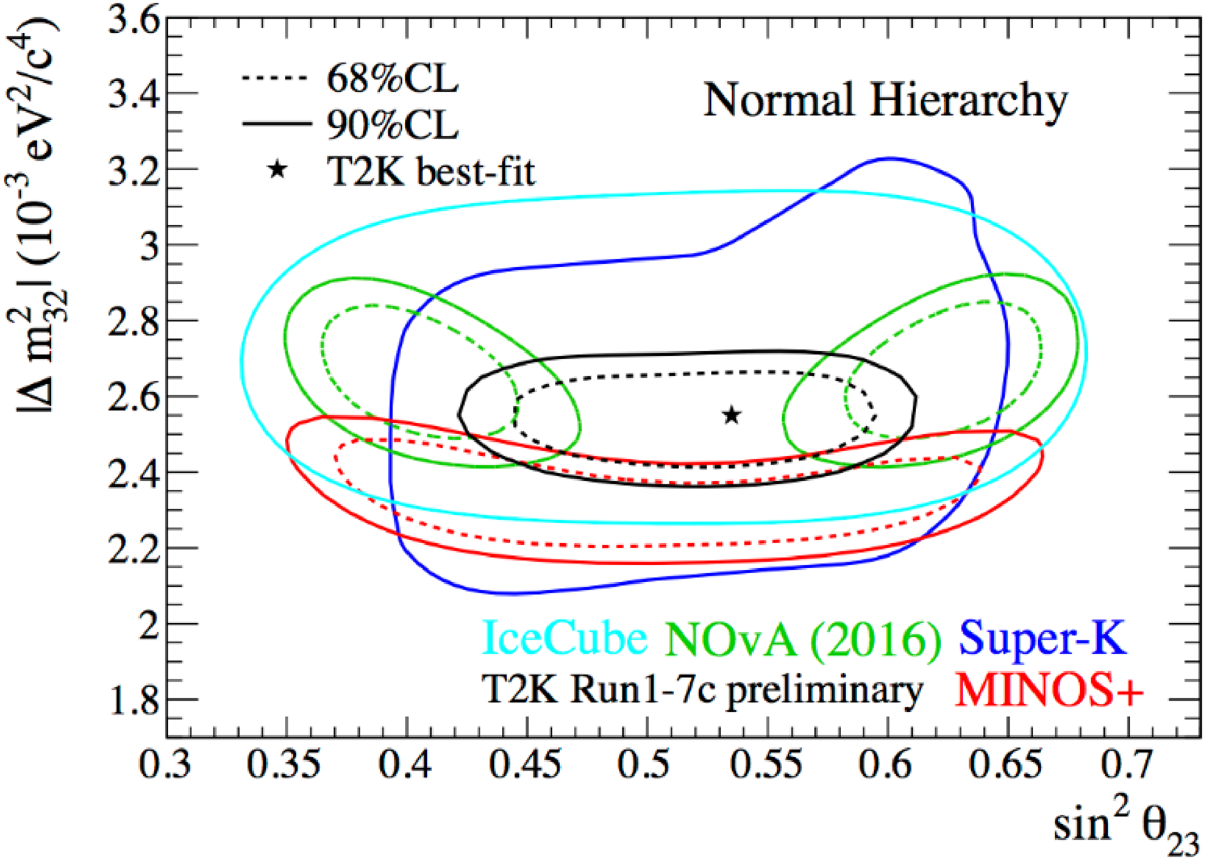
ν_μ 7.57x10^{20} POT, $\bar{\nu}_\mu$ 7.53x10^{20} POT data



T2K: results from ν_μ+$\bar{\nu}_\mu$ disappearance

ν_μ 7.57x10^{20} POT, $\bar{\nu}_\mu$ 7.53x10^{20} POT data

Oscillation parameters of $\sin^2\theta_{23}$ and Δm^2_{32} compared with others

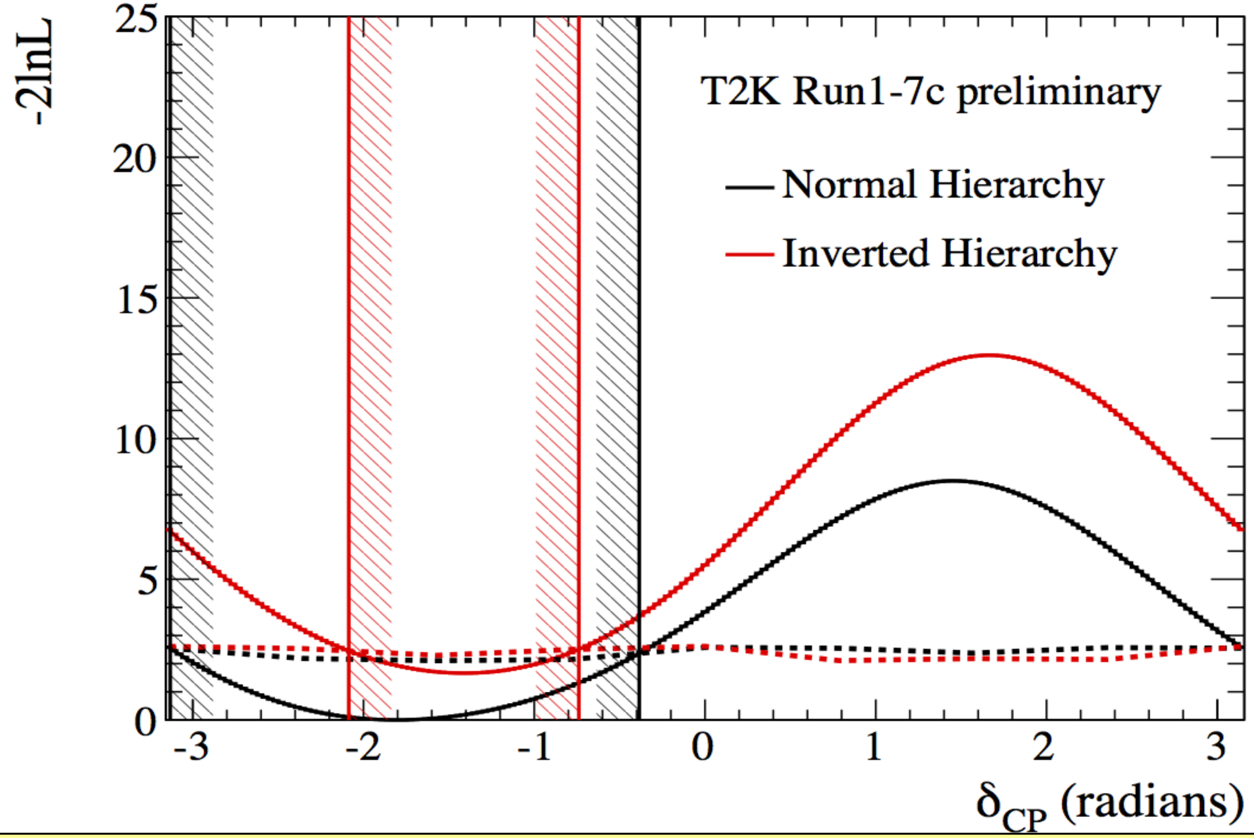


Best fit values:
$(\sin^2(\theta_{23}), |\Delta m^2_{32}|)$=
(0.532, 2.545 × 10^{-3}(eV^2))

T2K has given the most previse measurement. T2K favors maximal mixing ($\sin^2\theta_{23}$=0.5) but NOvA disfavors. Need more data to conclude.

T2K: Results on δCP from $\nu_e + \bar{\nu}_e$ appearance

ν_e events(data)	32	$\bar{\nu}_e$ events(data)	4
Expectation (δCP=0)	24	Expectation (δCP=0)	7



δ_{CP} = [-3.13, -0.39] (NH),
[-2.09, -0.74] (IH)
@90% CL

The best fit points lie near the maximally CP violating value δCP=-0.5π.
The CP conserving values (δCP=0 and δCP= π) lying outside of the T2K 90% confidence level interval.

Interesting to proceed. Towards T2K-II

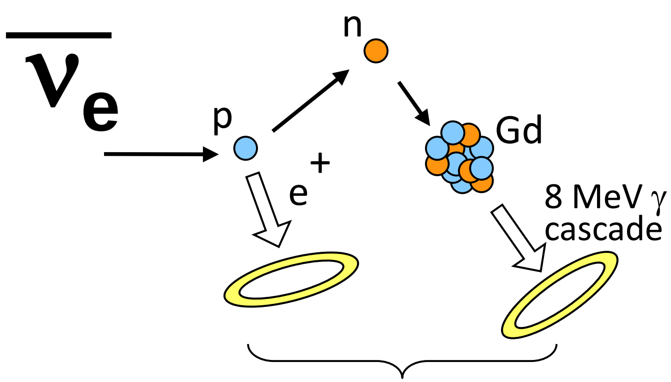
J.Imber in Session VII

Future of Super-K, and Hyper-K project

SK-Gd project

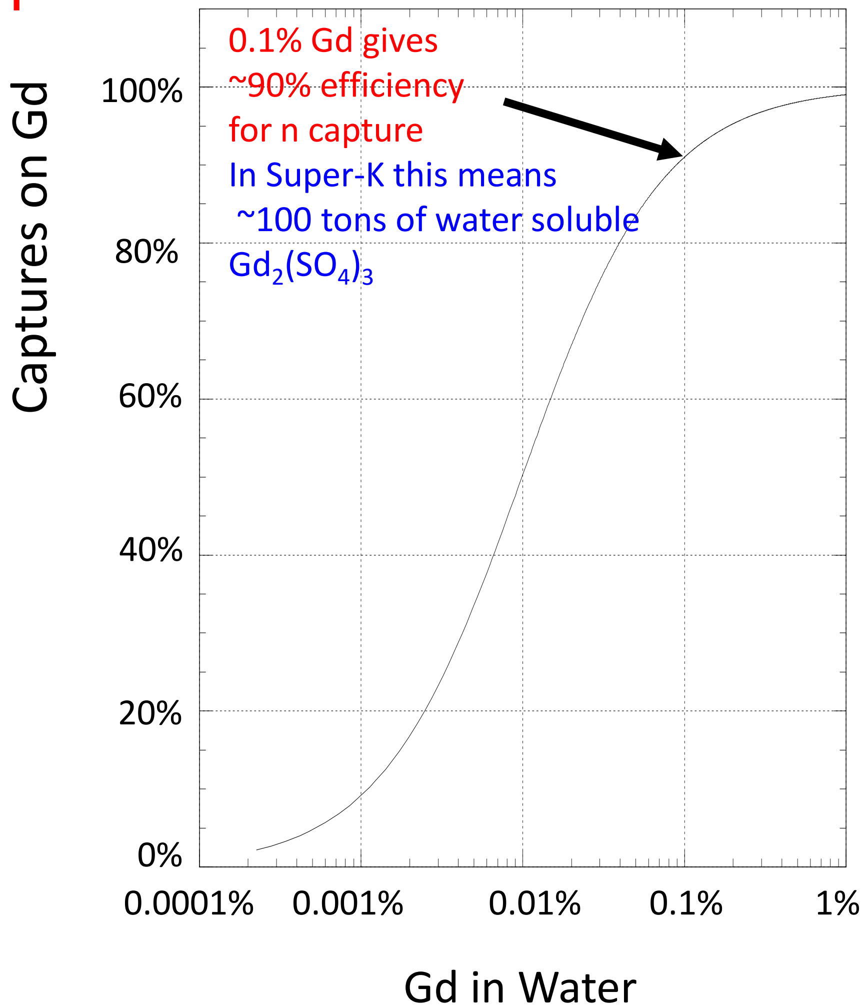
Identify $\bar{\nu}_e p$ events by neutron tagging with Gadolinium.

Gadolinium has large neutron capture cross section and emit 8MeV gamma cascade.

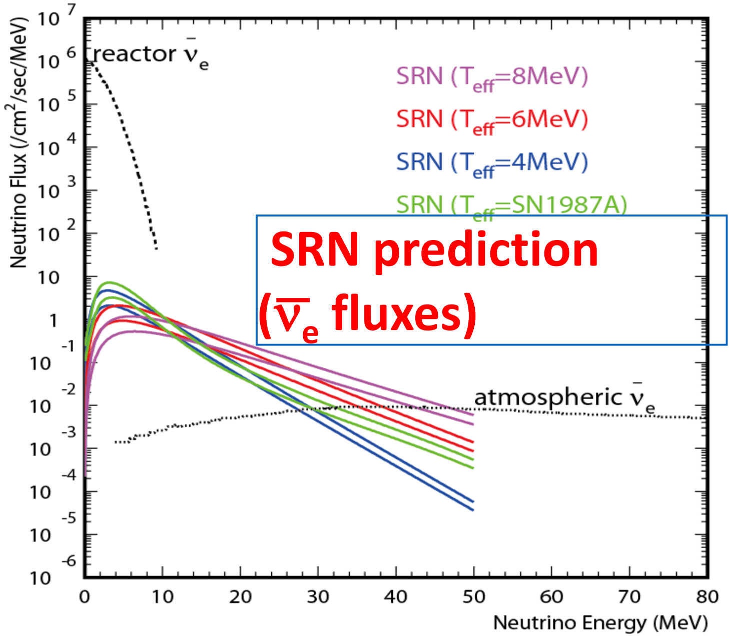


ΔT~30μs

Vertices within 50cm



Physics with SK-Gd



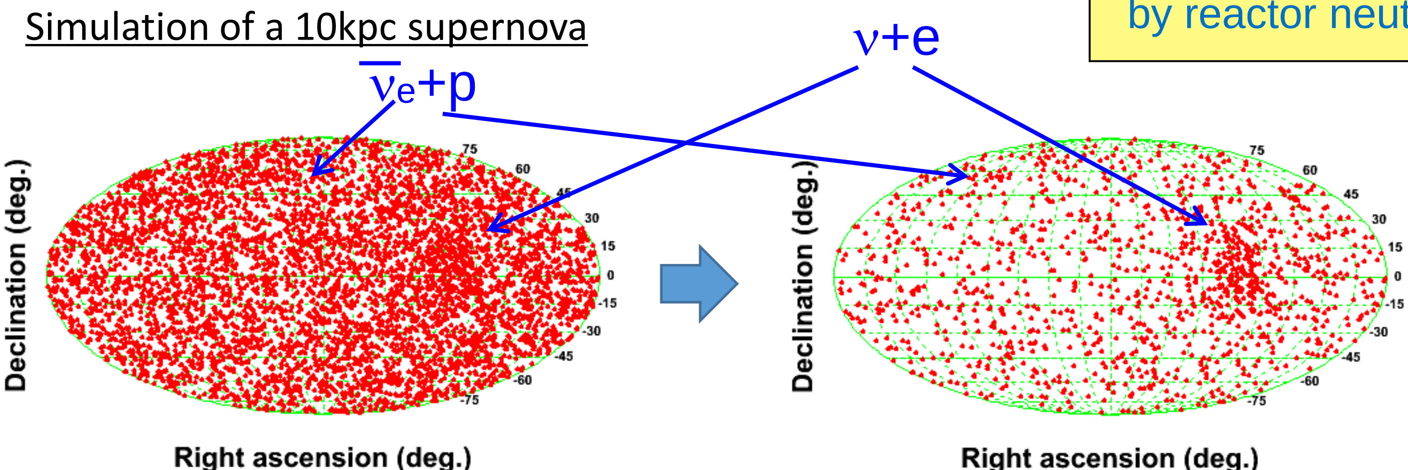
Supernova Relic Neutrinos (SRN)

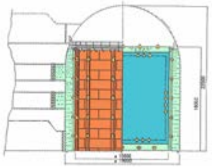
- Open widow for SRN at 10-30MeV
- Expected event rate 1.3 -6.7 events/year/22.5kt(10-30MeV)
- Study supernova rate from the beginning of universe.
- Averaged energy spectrum.

- Discriminate proton decay (essentially no neutron) and atmospheric neutrino background(with neutrons).
- Neutrino/anti-neutrino identification.
- Precise measurement of θ_{12} and Δm^2_{21} by reactor neutrinos.

Improve pointing accuracy for supernova bursts, e.g. 4~5°→ 3°(90%C.L.) for 10kpc

Simulation of a 10kpc supernova





Kamiokande 880 ton fiducial / 3000 ton total water Cherenkov detector

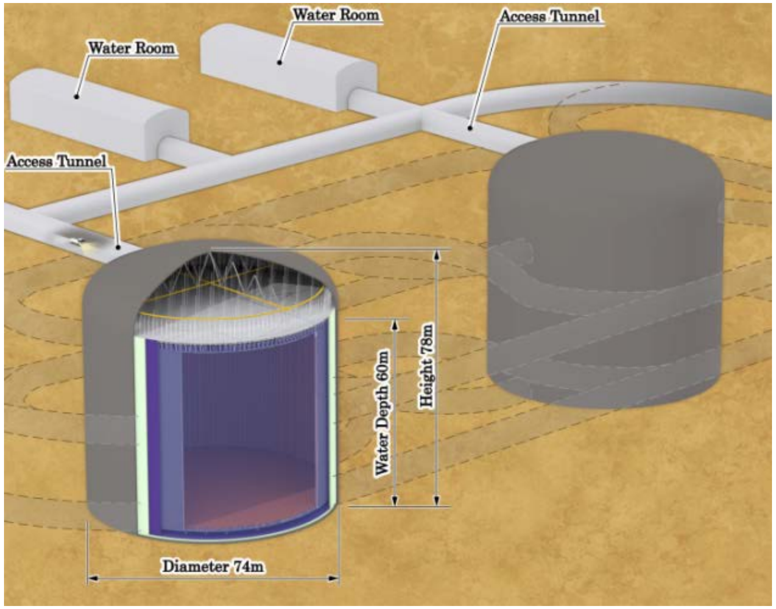
X ~25 times

Super-Kamiokande 22,500 ton fiducial / 50,000 total water Cherenkov detector

X ~20 times

Hyper-Kamiokande 190,000x2 ton fiducial / 260,000x2 total water Cherenkov detector

Physics at Hyper-K:
J. Kameda in Session VIII



Japanese saying: 3度目の正直.

The third time's the charm.

<u>My translation</u>

Proton decay will be observed in the third generation experiment.

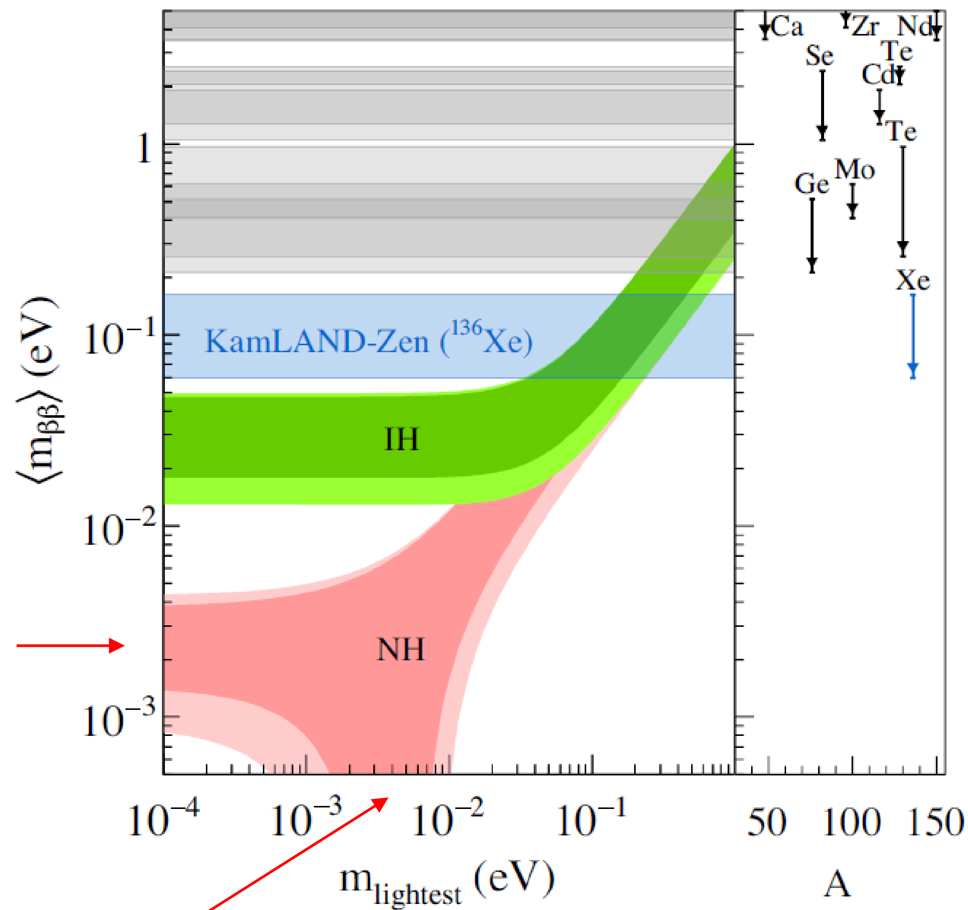
Future++

(my personal view)

Future++

- A larger volume detector(Hyper-K) would start ~10years from now.
- (Hope to) Observe SRN at SK within ~10 years from now.
- What physics SK-site (50,000m^3) can do after that?
- Are neutrinos Majorana particles?
- Double Beta Decay (DBD) is the unique method to verify that.
- So, DBD is very important.
  - Yanagida-san said DBD is more important than proton decay.
- As I presented, SK atmospheric ν indicates normal hierarchy.
- Initial indications have been always true so far at Kamioka (unfortunately).
- So, let's think about very big DBD detector to reach normal hierarchy.

Future++



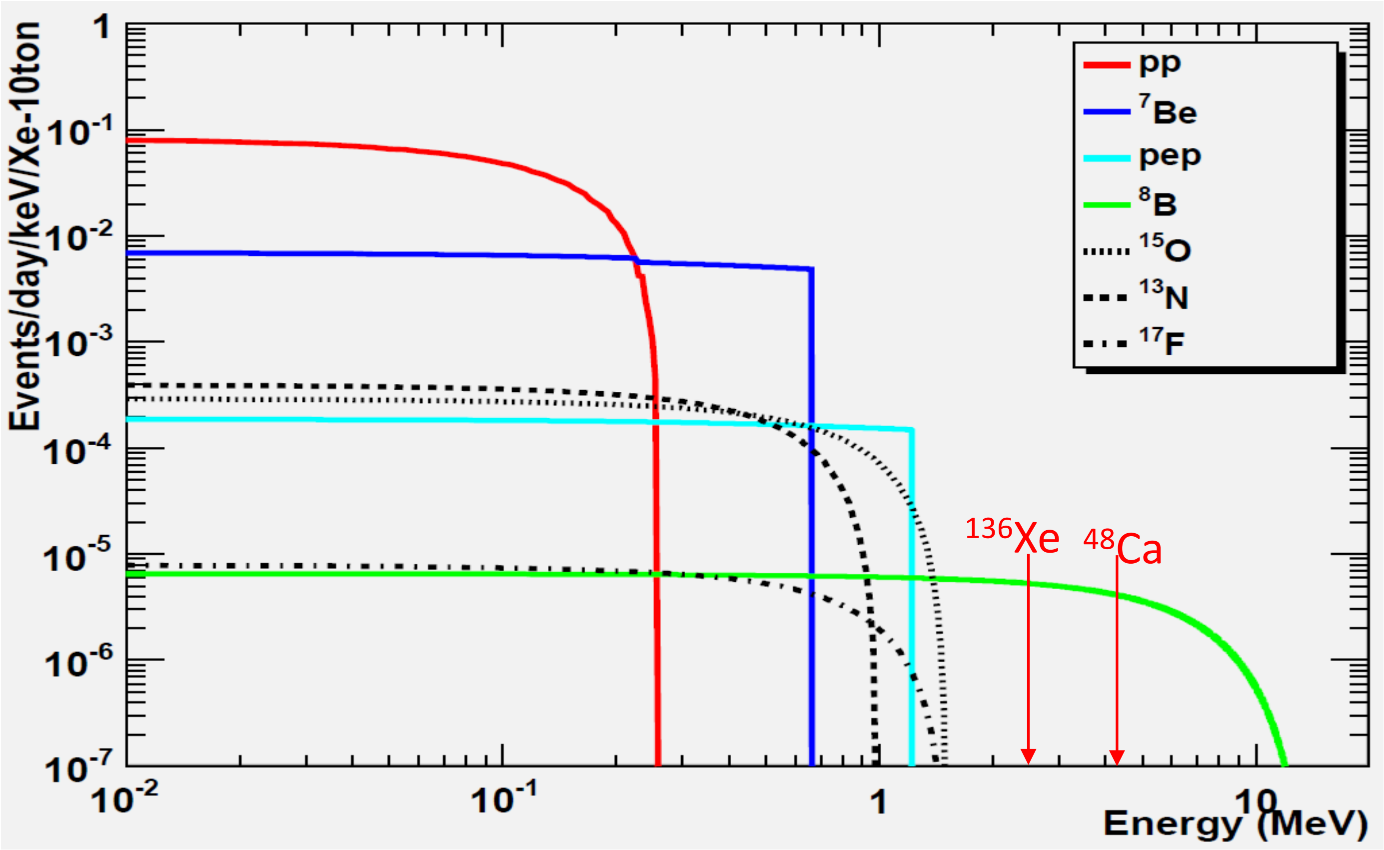
Towards 2-3 meV →

What about this?
Forget about it.
Neutrino parameters are always lucky.

Future++

- What is $\tau_{1/2}$ of $0\nu\beta\beta$ for 2.5 meV?
  - $\tau_{1/2}$ = 1.8 x 10^{29} years for ^{136}Xe (QRPA-B, g_A=1.269)
  - $\tau_{1/2}$ = 2.1 x 10^{29} years for ^{48}Ca (IBM-2, g_A=1.269)
- (Many thanks to T.Iida-san and I.Shimizu-san for various information)
- How much weight is necessary to detect one $0\nu\beta\beta$ event/year?
  - 59 tons of ^{136}Xe (~20m^3 liquid Xe, ~10,000m^3 1atm. gas Xe)
  - 24 tons of ^{48}Ca
- Remark: solar neutrino background (next page)

Solar Neutrino background



~0.1 ^{8}B solar neutrino events/year for 10keV window for 59 tons' Xe

Today's signal is tomorrow's background.

Future++

- What is $\tau_{1/2}$ of $0\nu\beta\beta$ for 2.5 meV?
  - $\tau_{1/2}$ = 1.8 x 10^{29} years for ^{136}Xe (QRPA-B, g_A=1.269)
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- How much weight is necessary to detect one $0\nu\beta\beta$ event/year?
  - 59 tons of ^{136}Xe (~20m^3 liquid Xe, ~10,000m^3 1atm. gas Xe)
  - 24 tons of ^{48}Ca
- Remark: solar neutrino background (next page)
- So, good energy resolution is necessary.
  Also, for separating from $2\nu\beta\beta$.
- Let's think about possible techniques (high resolution, tracking, tagging $\beta\beta$ decay products....)

Conclusions

- More than 30 years have passed since we started experiments at Kamioka.
- Neutrino oscillations have been established in the last 30 years.
- There are still many important unknowns in neutrino physics.
- Future developments are expected.

Let's enjoy neutrino physics!