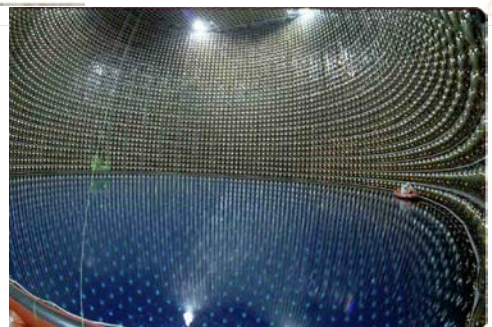
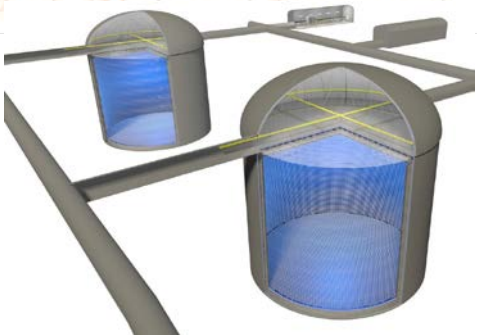
Neutrino Experiments at Kamioka

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

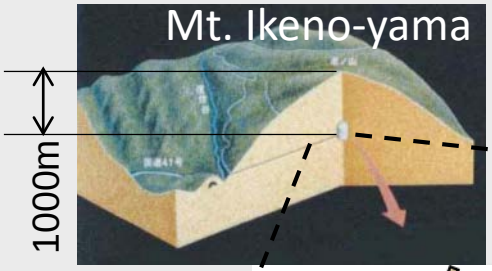




Contents

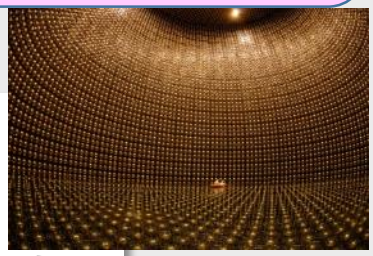
- What experiments are at Kamioka now
- History of neutrino experiments at Kamioka
- Recent highlights from Kamioka
- Future

Kamioka underground (NOW)



KamLAND (Tohoku Univ.)
1000ton liquid scintillator detector
Reactor, 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

KamLAND
(old Kamiokande site)

Lab.A

Super-K dome

clean room

Lab.E/IMPU
Lab.2

water system

IMPU
Lab.1

100m

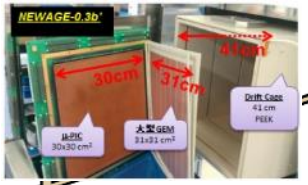
Atotsu entrance

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

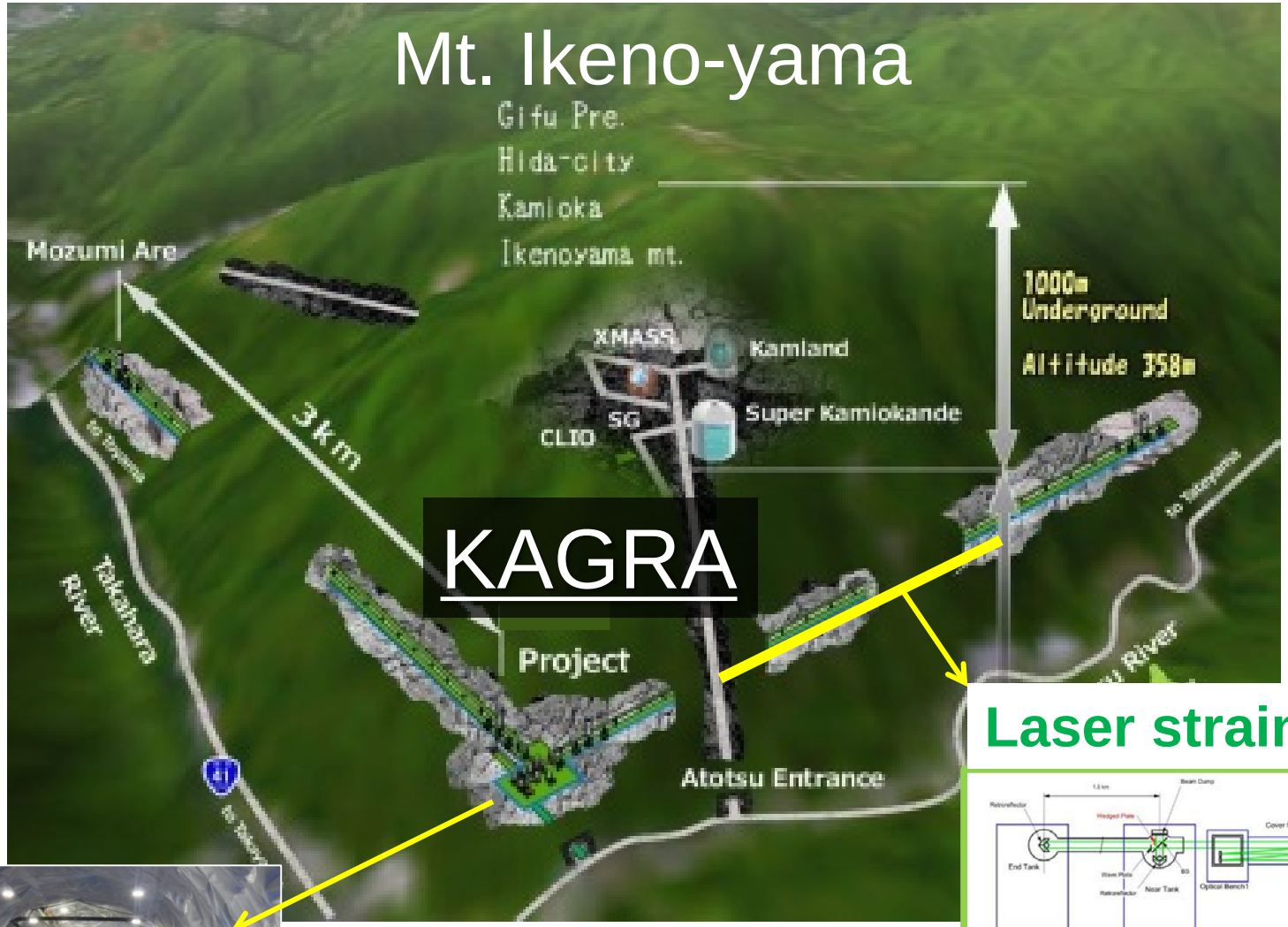
XMASS
Direct dark matter search experiment

EGADS
200t Gd test tank

NEWAGE
Direction dark matter experiment

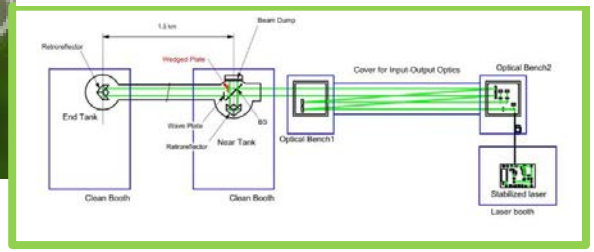


Kamioka underground experiments (NOW)



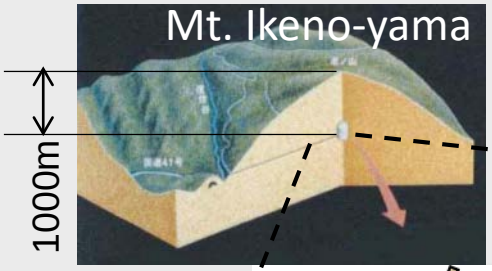
KAGRA
Gravitational-wave
Telescope

Laser strainmeter



1.5km Geophysics interferometer

Kamioka underground (NOW)



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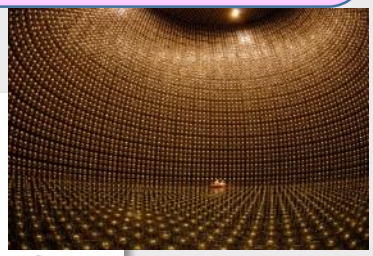

Kamiokande was here

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

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CLIO 100m x 100m prototype
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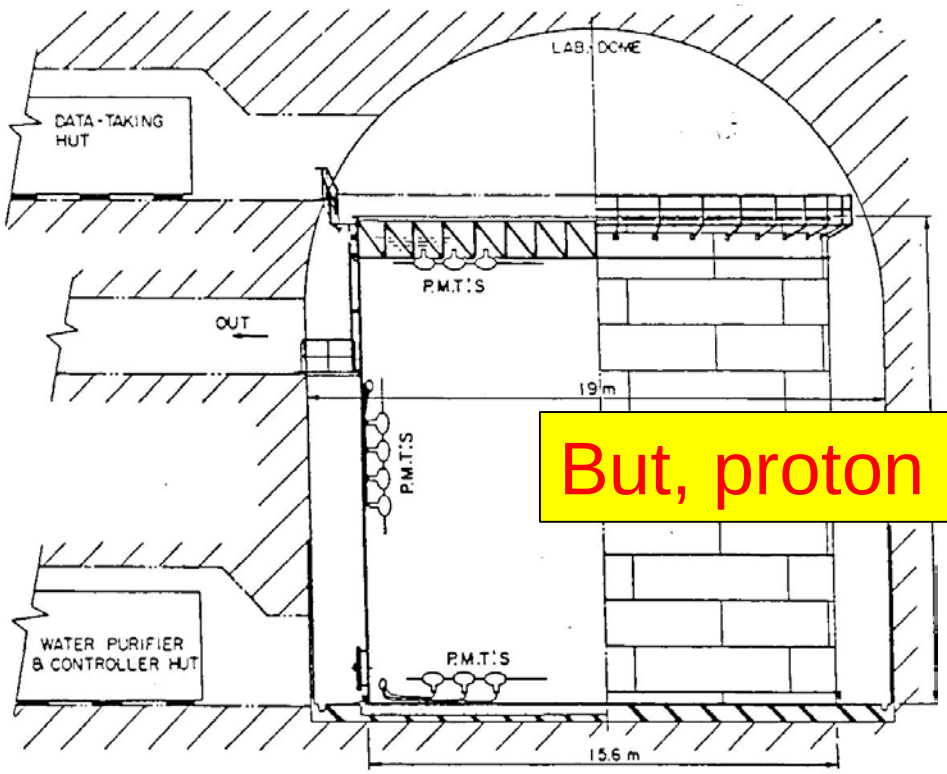
Laser strainmeter

XMASS
Direct dark matter
search experiment

EGADS
200t Gd test tank

NEWAGE
Direction dark
matter experiment

Kamiokande-I detector（1983－1984）



Original purpose:
Search for proton decay

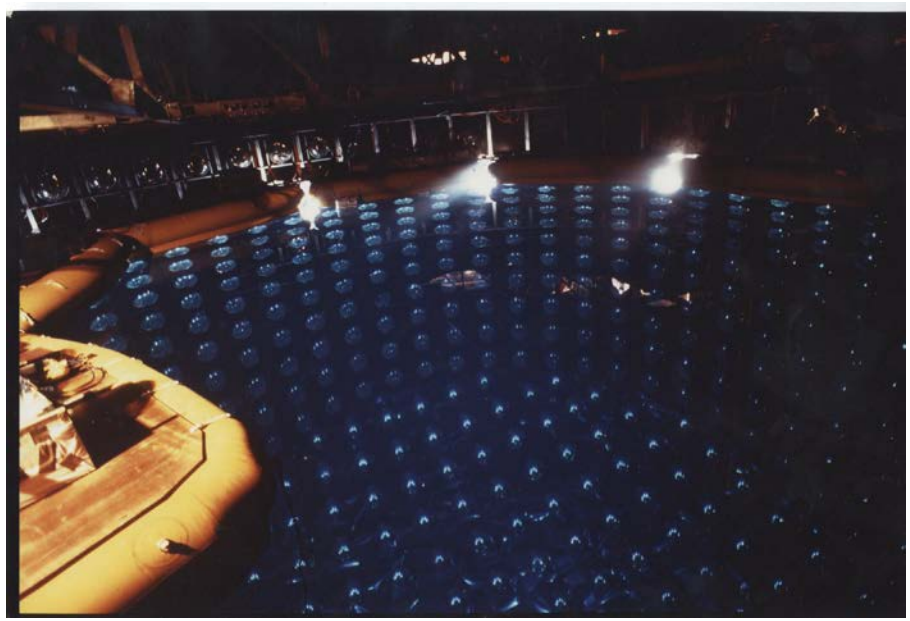
Inner detector only.
Readout of charge information only (i.e. no timing information).

But, proton decay was not observed….

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

1000 20-inch PMTs were used

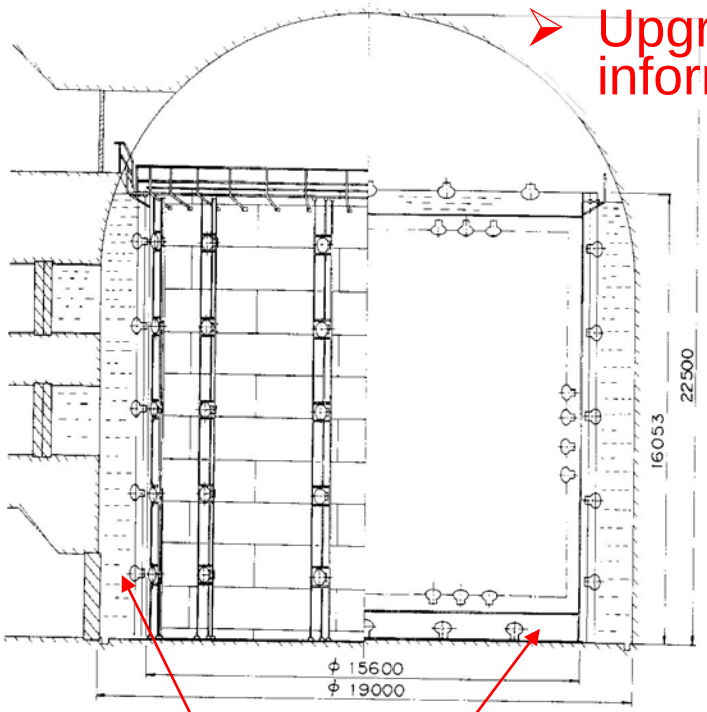
Photo-coverage: 20%



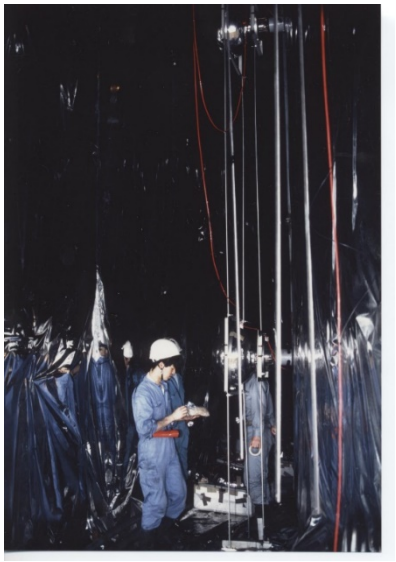
Upgrade to Kamiokande-II (1984-1985)

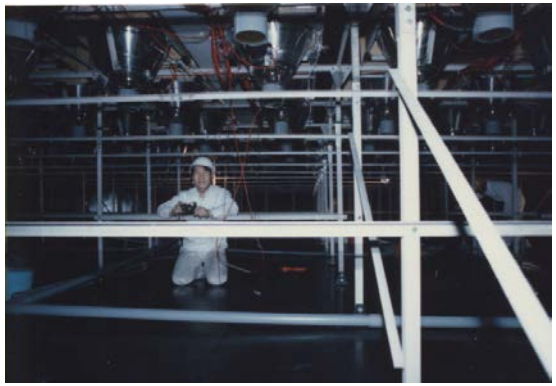
Thanks to large photo-coverage, it was found that the detector is sensitive to low energy events.
So, the detector was upgraded for solar neutrinos in 1984-1985.

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



- Made outer detector to shield external gamma rays

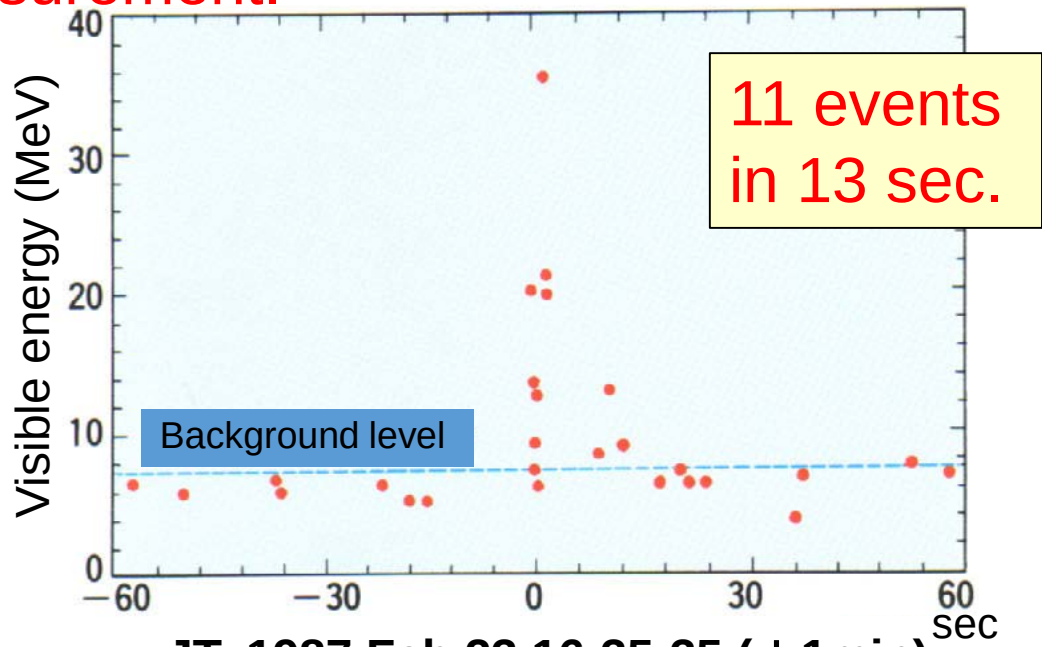




SN1987A: a supernova at LMC (Feb.23rd, 1987)

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

After Before



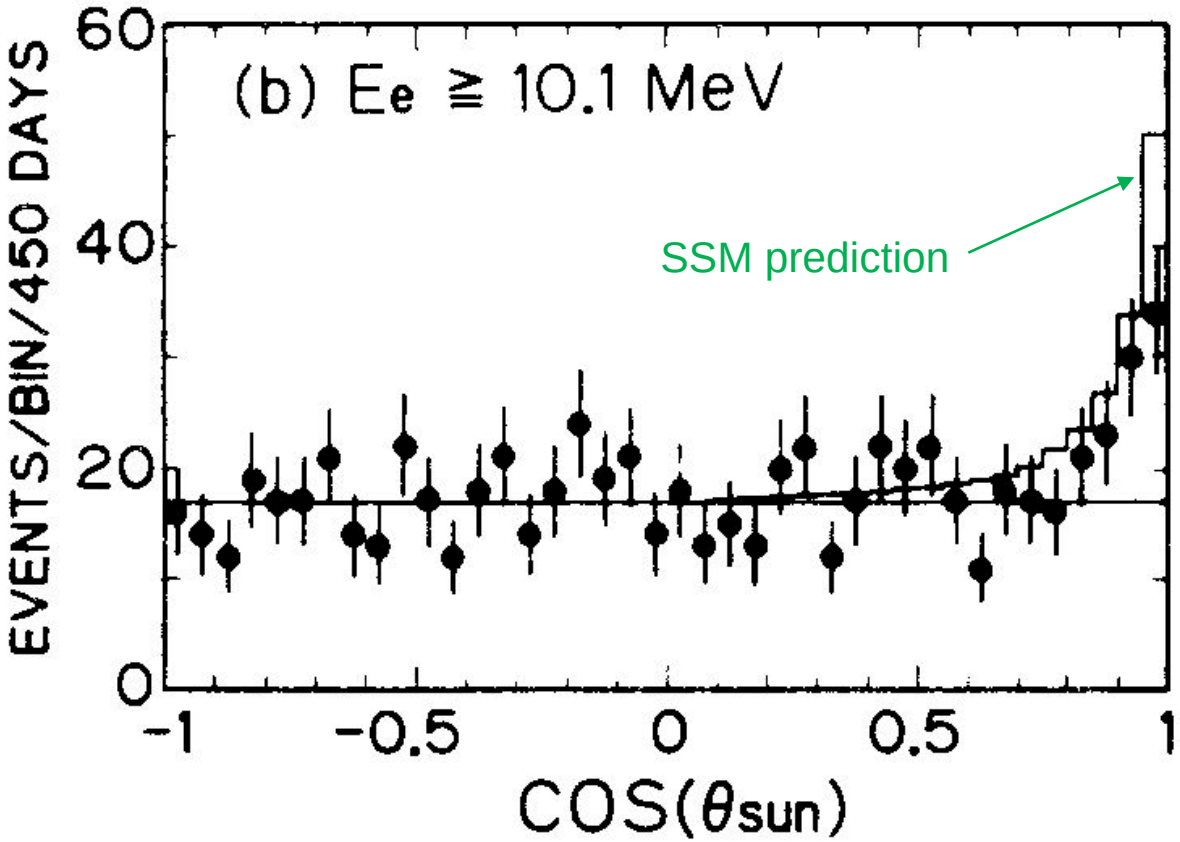
JT: 1987 Feb 23 16:35:35 (±1min)
UT: 7:35:35

Total energy released by $\bar{\nu}_e$ was measured to be ~5×10^{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



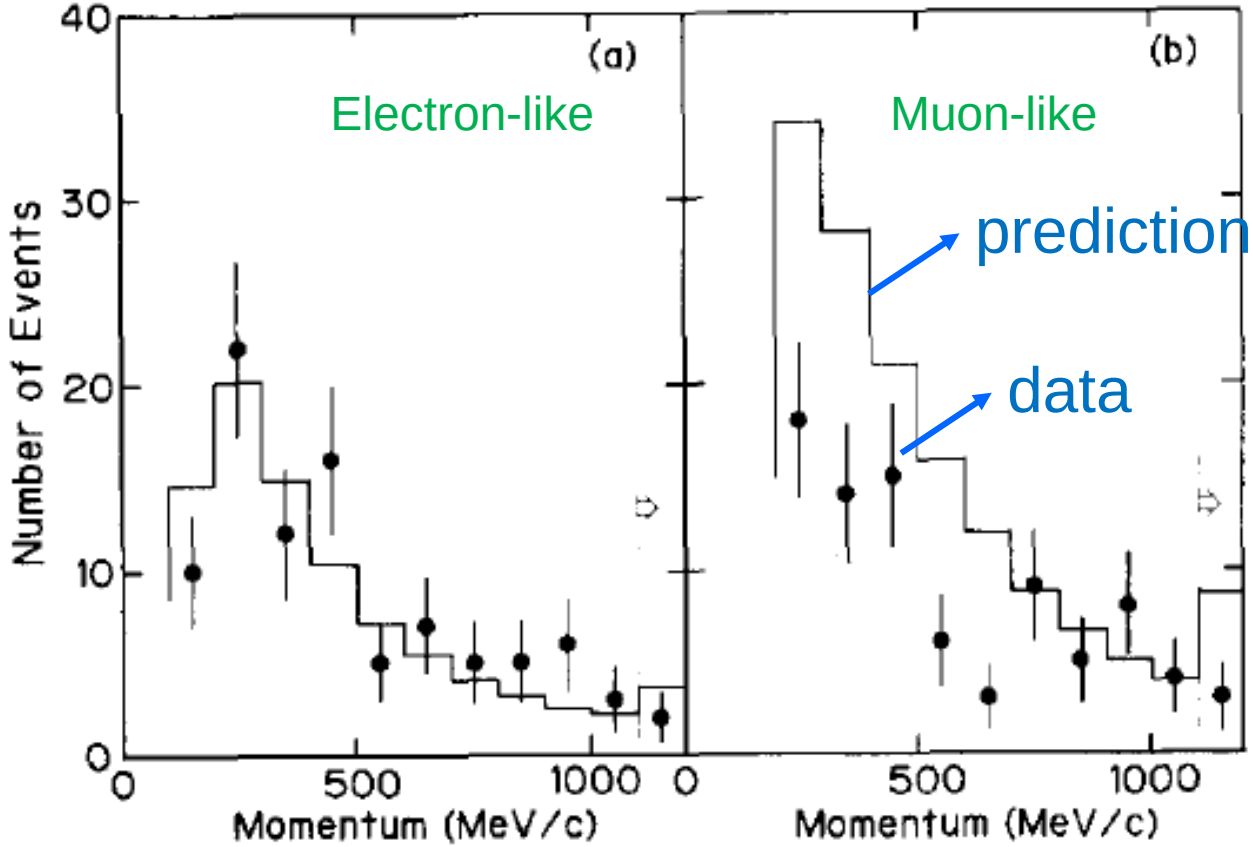
Observed number of solar neutrinos was about 50.

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.)

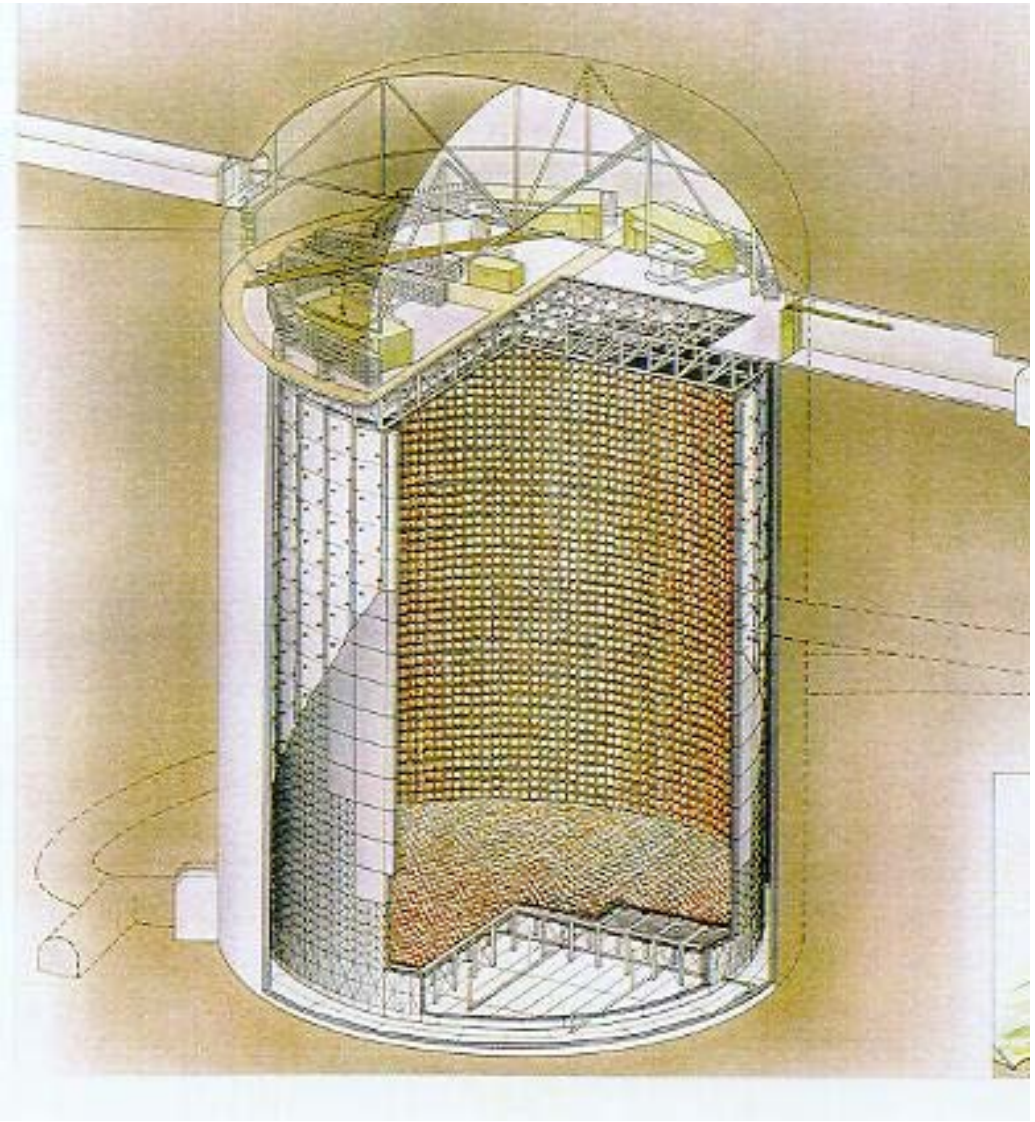


Electron-like data is consistent with prediction.
But, muon-like data is 59±7% of prediction.

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.

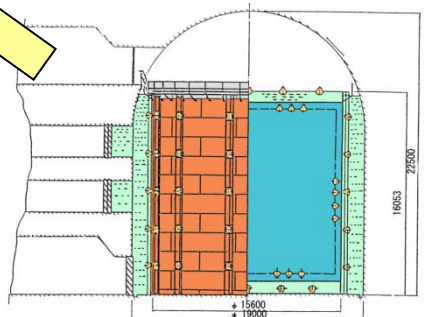


- 50,000 t water tank (42m high, 40m diameter)

  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



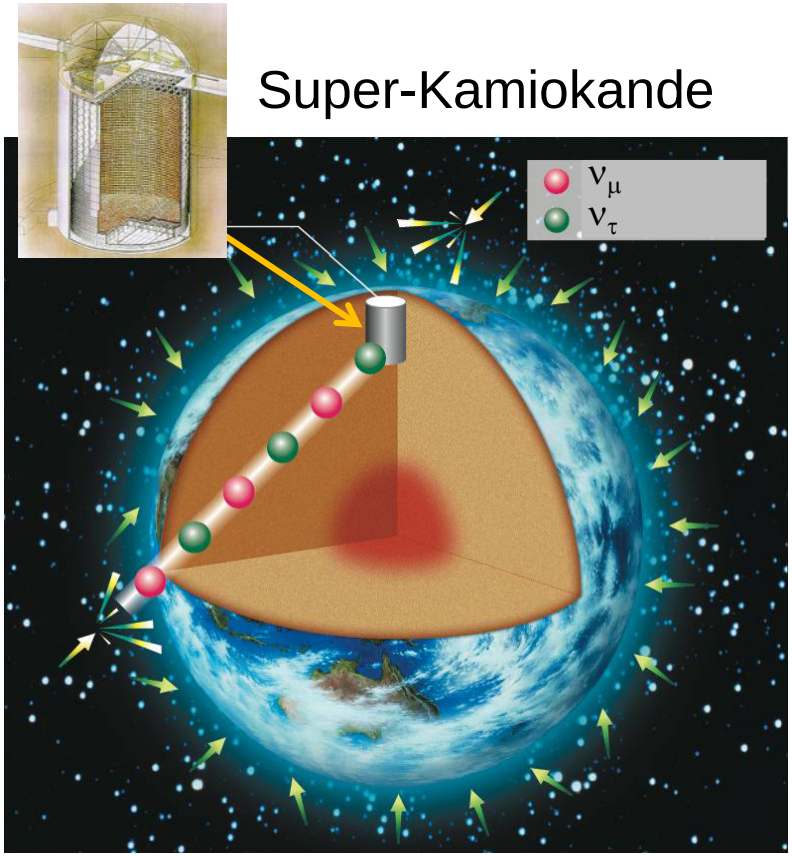
1998: Evidence for atmospheric neutrino oscillation

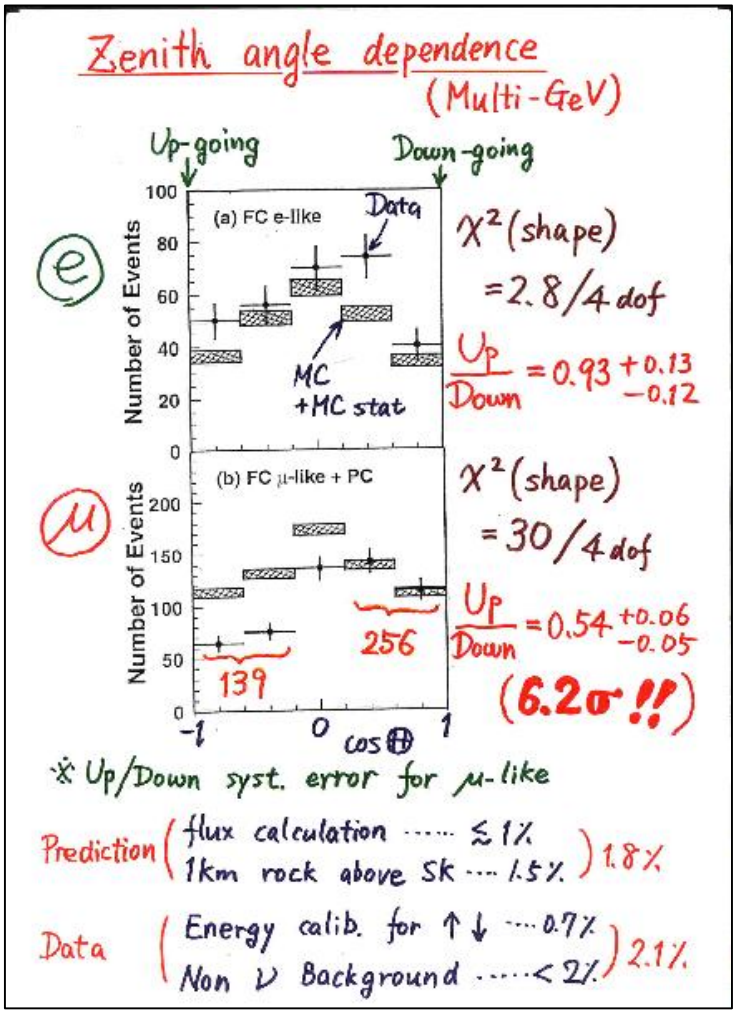
Cosmic rays produce neutrinos.

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

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

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

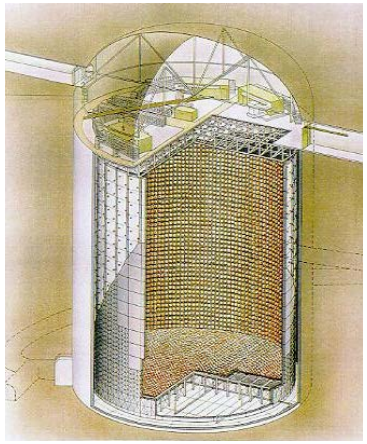


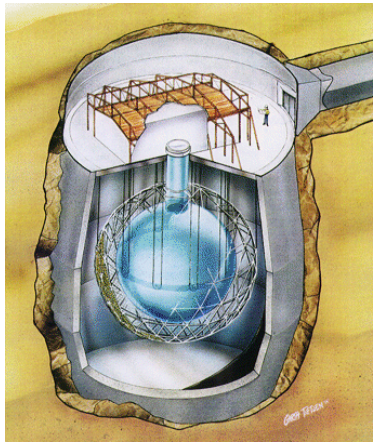


Kajita's presentation in Neutrino 1998 conference.

ν_μ disappearance

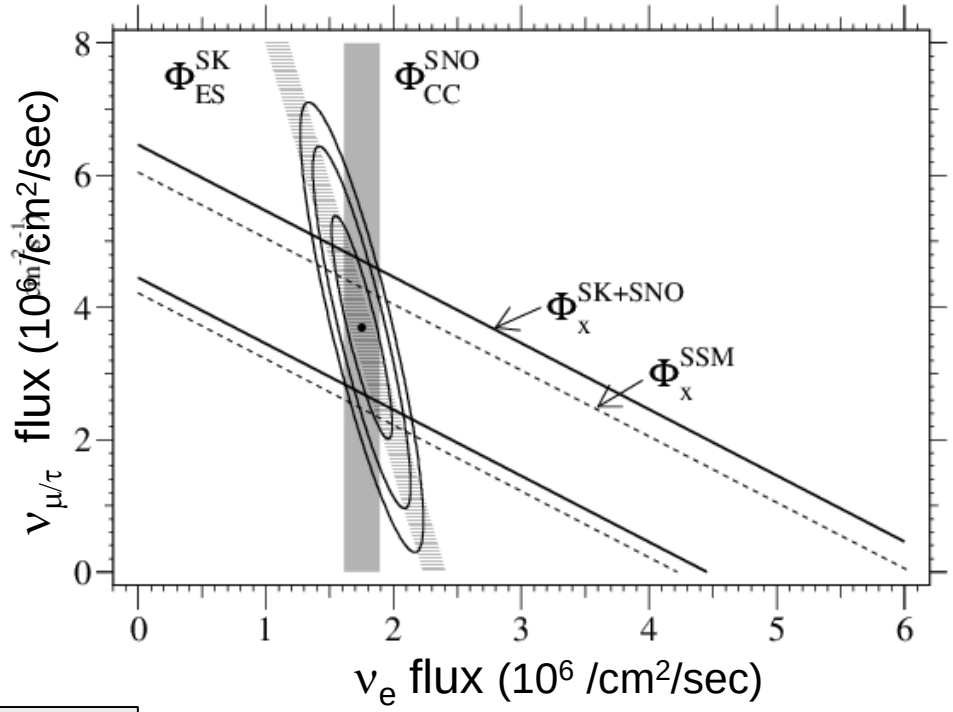
2001: Evidence for solar neutrino oscillation





SK ES vs. SNO CC

2001 SNO paper



Interactions

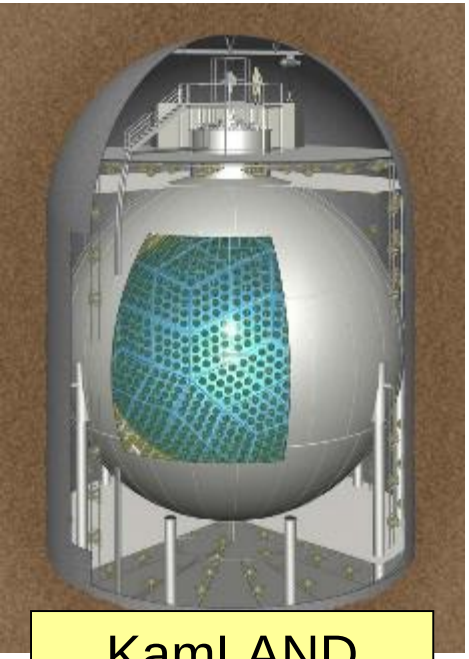
(ES) $\nu + e^- \rightarrow \nu + e^-$ (σ of $\nu_{\mu/\tau}$ is 1/7 of ν_e)

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

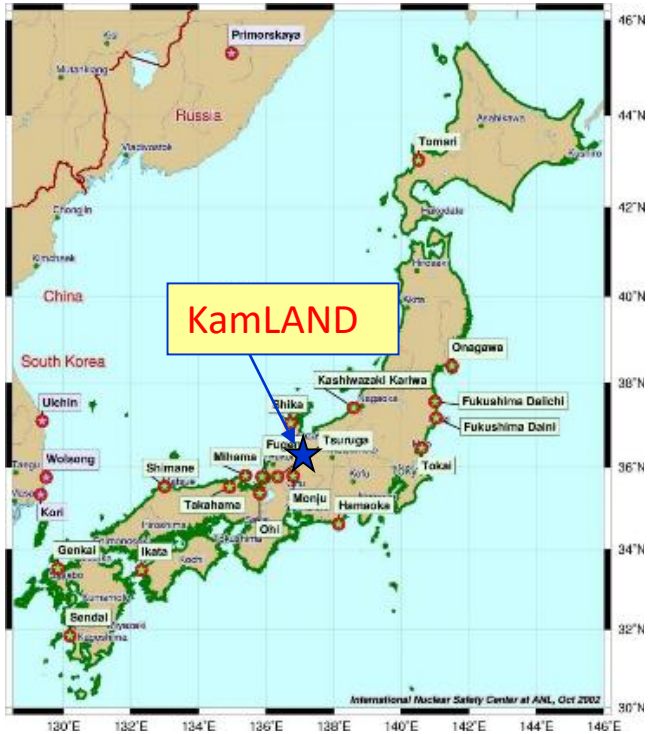
(NC) $\nu_x + d \rightarrow \nu_x + p + n$ ($X=e,\mu,\tau$)

ν_e to $\nu_{\mu/\tau}$ conversion

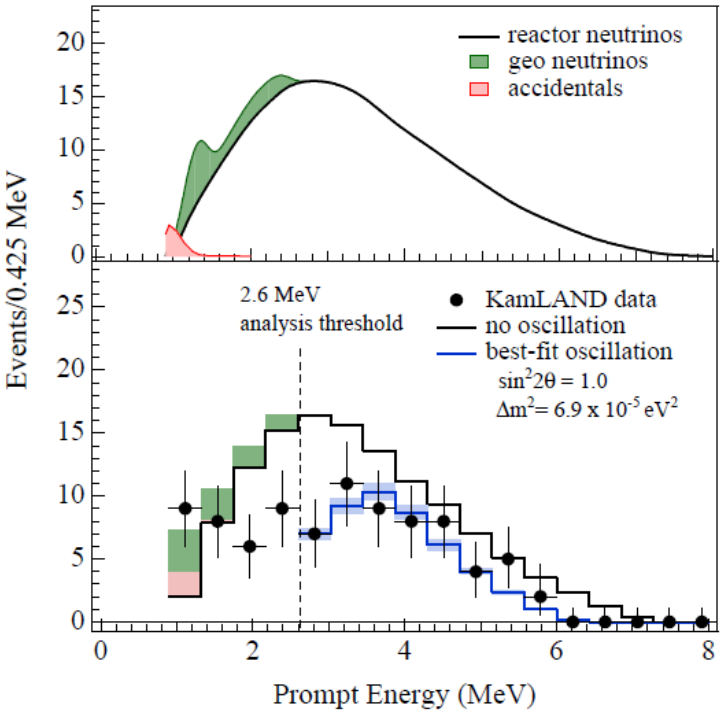
2002: Reactor neutrino oscillation by KamLAND



KamLAND



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



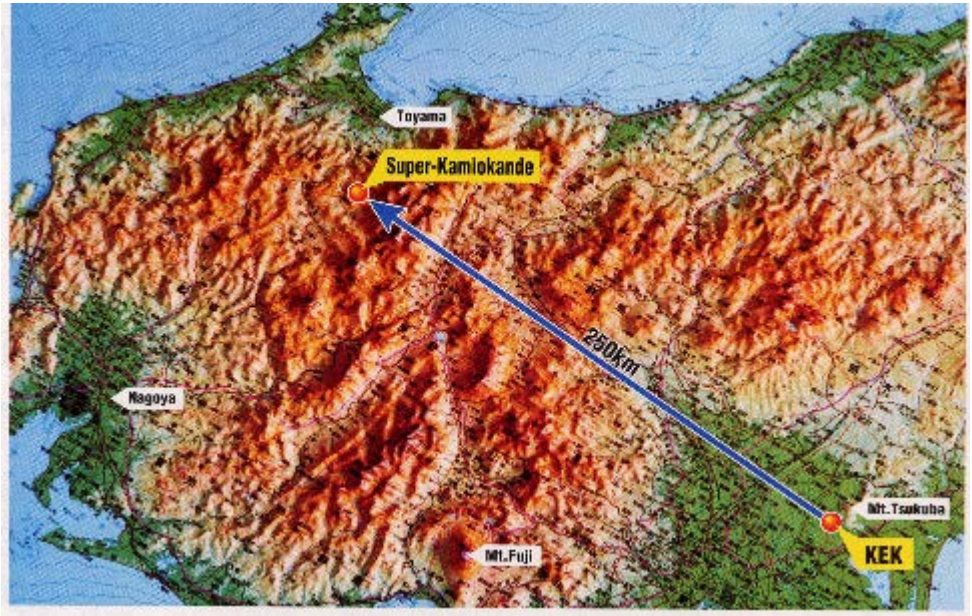
Built at old Kamiokande site

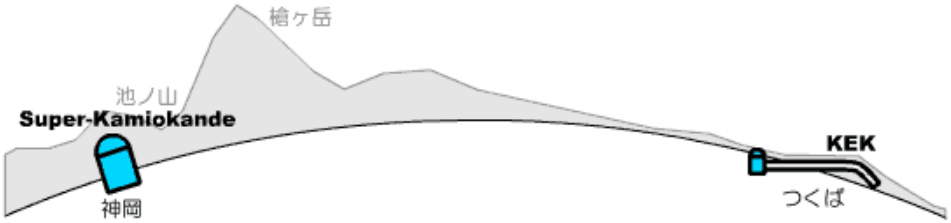
1000 ton liquid scintillator.

Run by Tohoku University.

$\bar{\nu}_e$ disappearance

1999-2004：K2K (KEK to Kamioka)

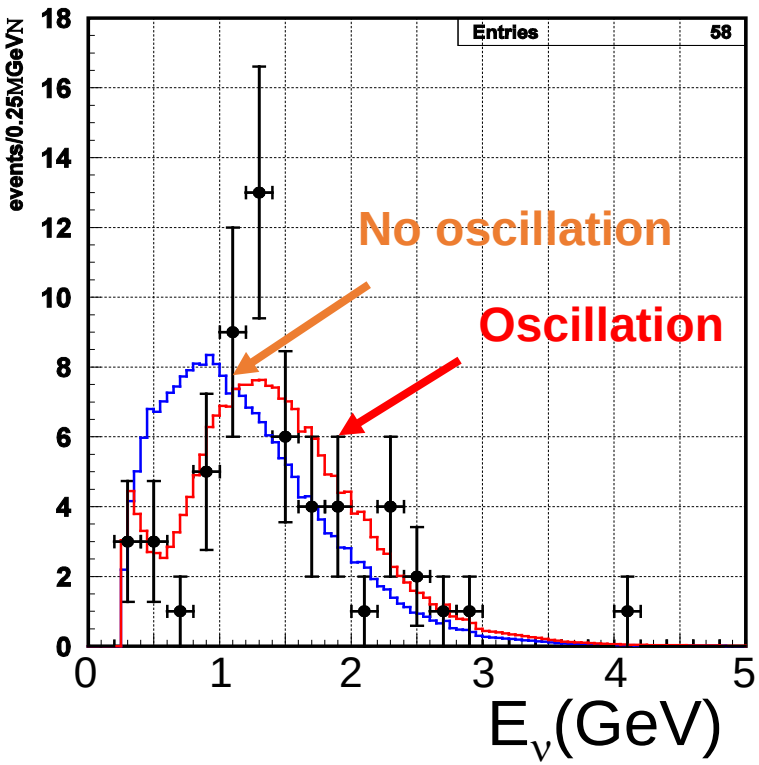


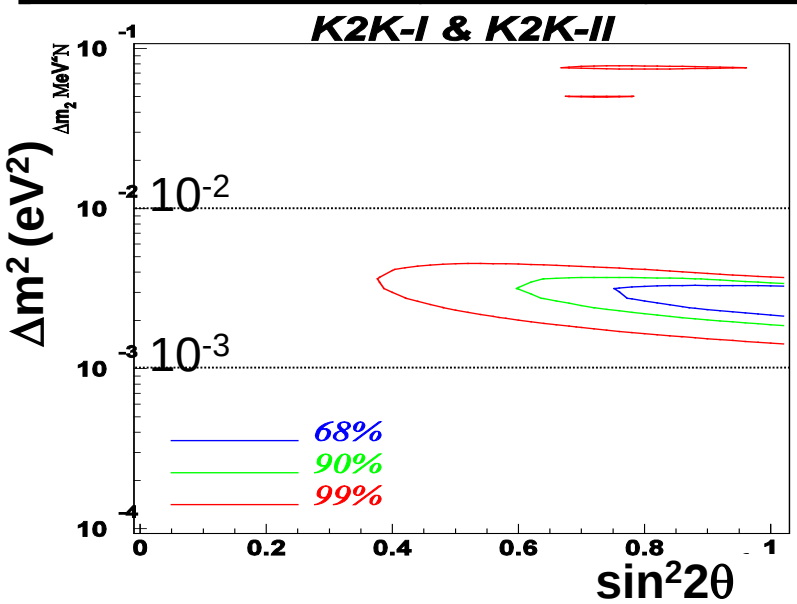


The first artificial neutrino beam experiment in the world.

Results from K2K experiment

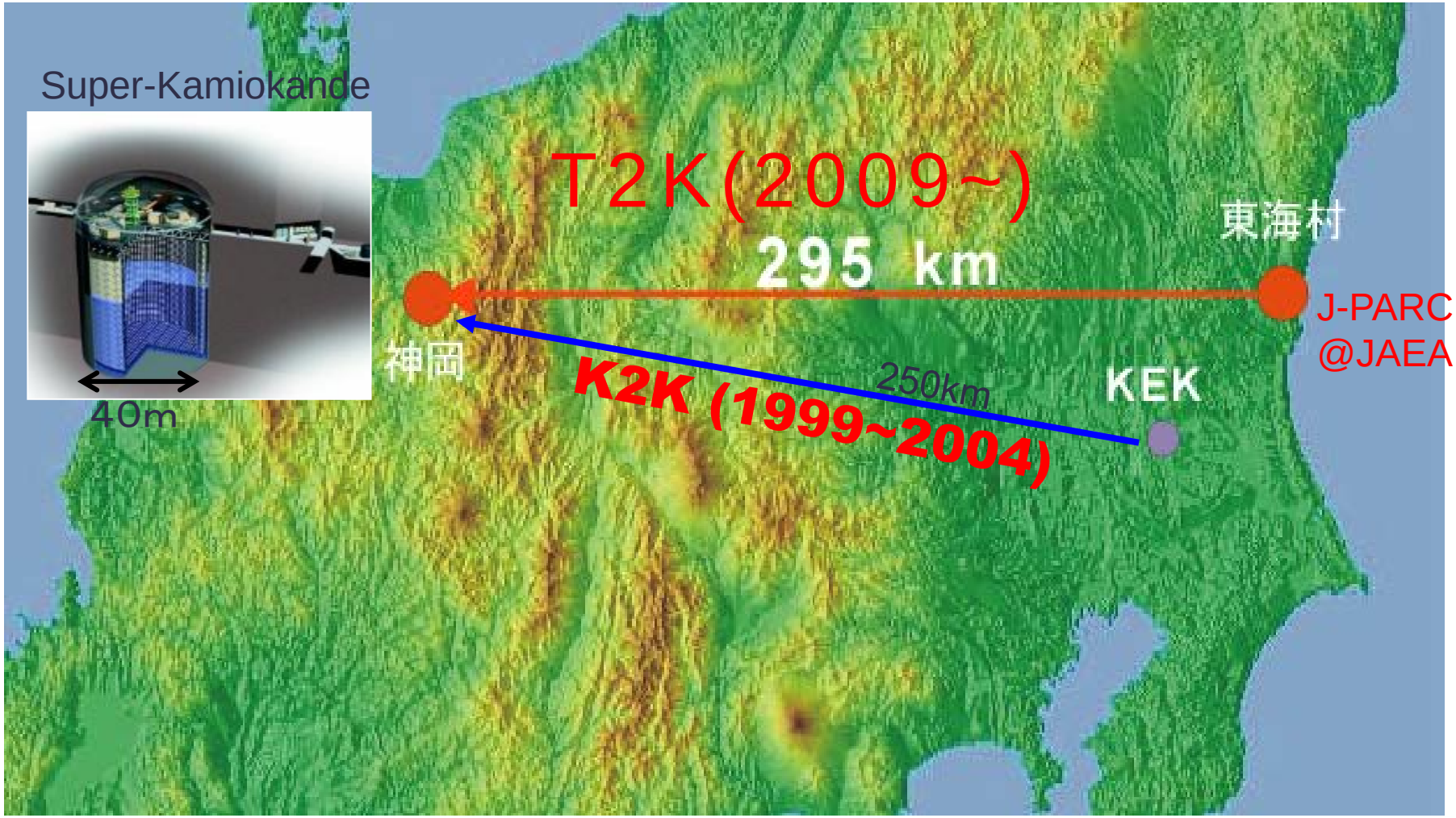
	N_{sk}^{obs}	N_{sk}^{pred}
All	**112**	**155.9**
1 ring	**67**	99.0
μ-like	58	90.8
e-like	9	8.2
multi-ring	**45**	56.8





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.

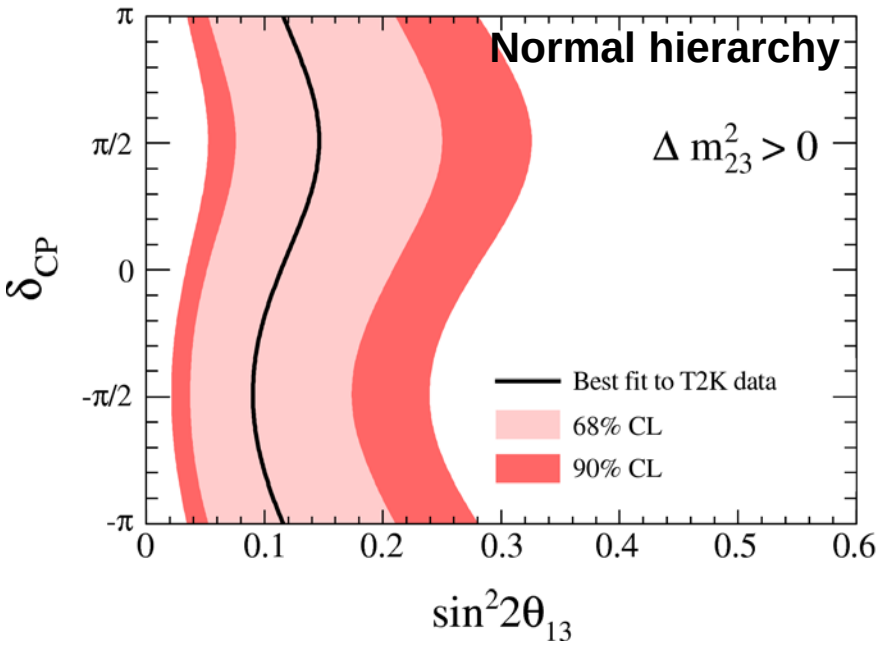
2011: Discovery of θ13 by T2K

Search for ν_e appearance from ν_μ beam

6 events were observed.

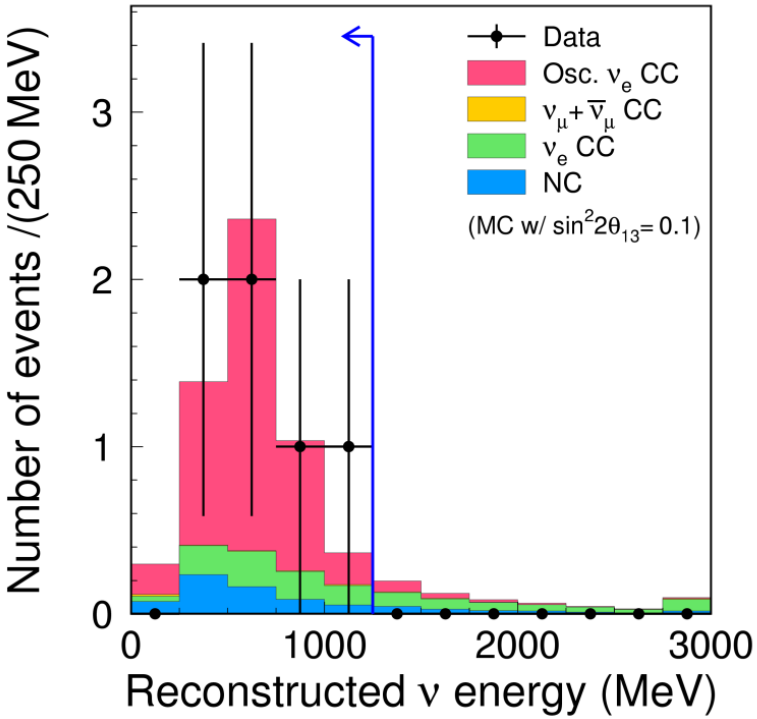
Number of background was 1.5 ±0.3 (syst.) for $\sin^2(2\theta_{13})=0$

Allowed region of $\sin^2 2\theta_{13}$ and δ_{CP}



$\theta_{13}=0$ was excluded with 2.5σ

Reconstructed ν energy



90% C.L. interval and best fit (for $\Delta m^2_{23}=2.4 \times 10^{-3}$ eV^2, $\delta_{CP}=0$)

$0.03 < \sin^2 2\theta_{13} < 0.28$

$\sin^2 2\theta_{13} = 0.11$

Maki-Nakagawa-Sakata-Pontecorvo(MNSP) Matrix

Weak interaction eigenstate $\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$ Mass eigenstate

$$\begin{pmatrix} 1 & 0 & 0 \\ 0 & +c_{23} & +s_{23} \\ 0 & -s_{23} & +c_{23} \end{pmatrix} \begin{pmatrix} +c_{13} & 0 & +s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta} & 0 & +c_{13} \end{pmatrix} \begin{pmatrix} +c_{12} & +s_{12} & 0 \\ -s_{12} & +c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$$= \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23}-c_{12}s_{13}s_{23}e^{-i\delta} & c_{12}c_{23}-s_{12}s_{13}s_{23}e^{-i\delta} & c_{13}s_{23} \\ s_{12}s_{23}-c_{12}s_{13}c_{23}e^{-i\delta} & -c_{12}s_{23}-s_{12}s_{13}c_{23}e^{-i\delta} & c_{13}c_{23} \end{pmatrix}$$

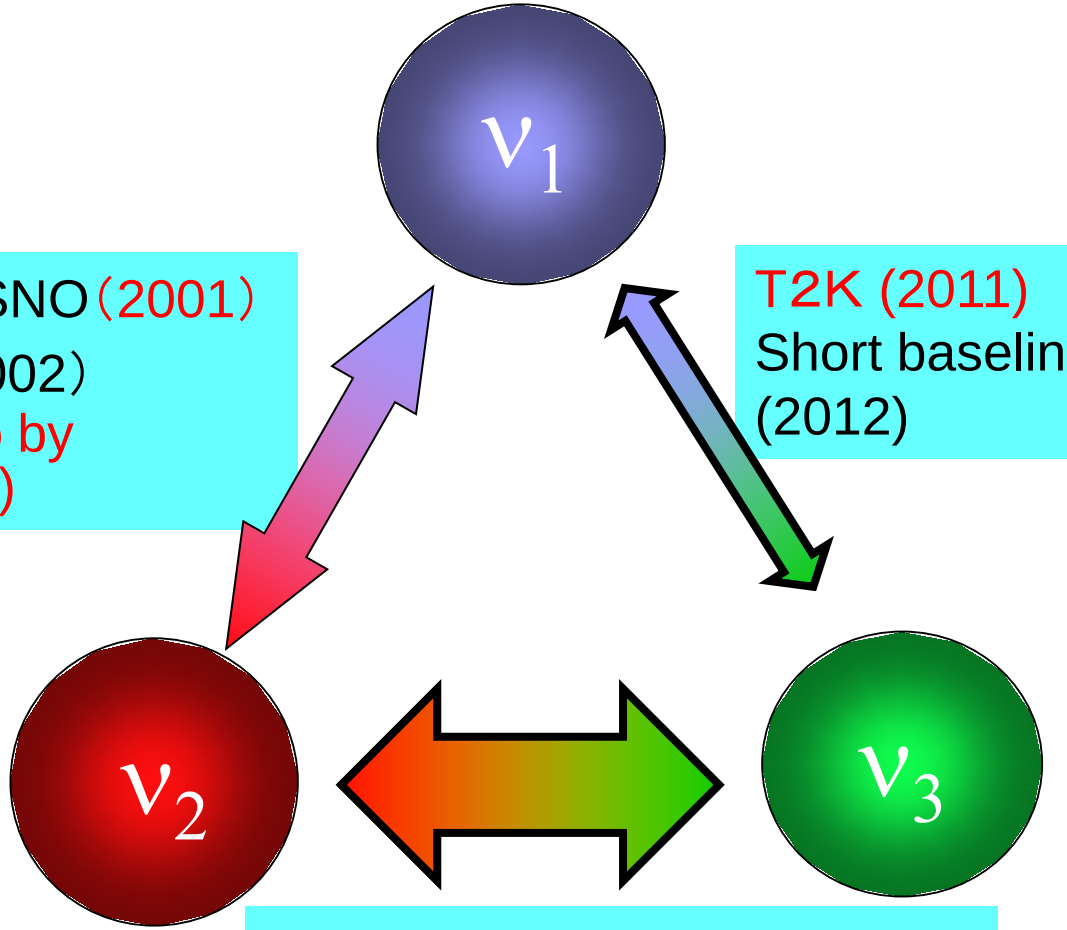
$s_{ij}=\sin\theta_{ij}$、$c_{ij}=\cos\theta_{ij}$

$\Delta m_{ij}^2= m_i^2-m_j^2$;Δm_{12}^2, Δm_{23}^2, Δm_{31}^2

δ : Dirac CP phase

Majorana CP phase is not shown here because it does not affect neutrino oscillations.

Summary of discoveries of neutrino oscillations



Solar ν: SK vs. SNO（2001）

Solar ν: SNO（2002）

Reactor neutrino by KamLAND(2002)

T2K (2011)

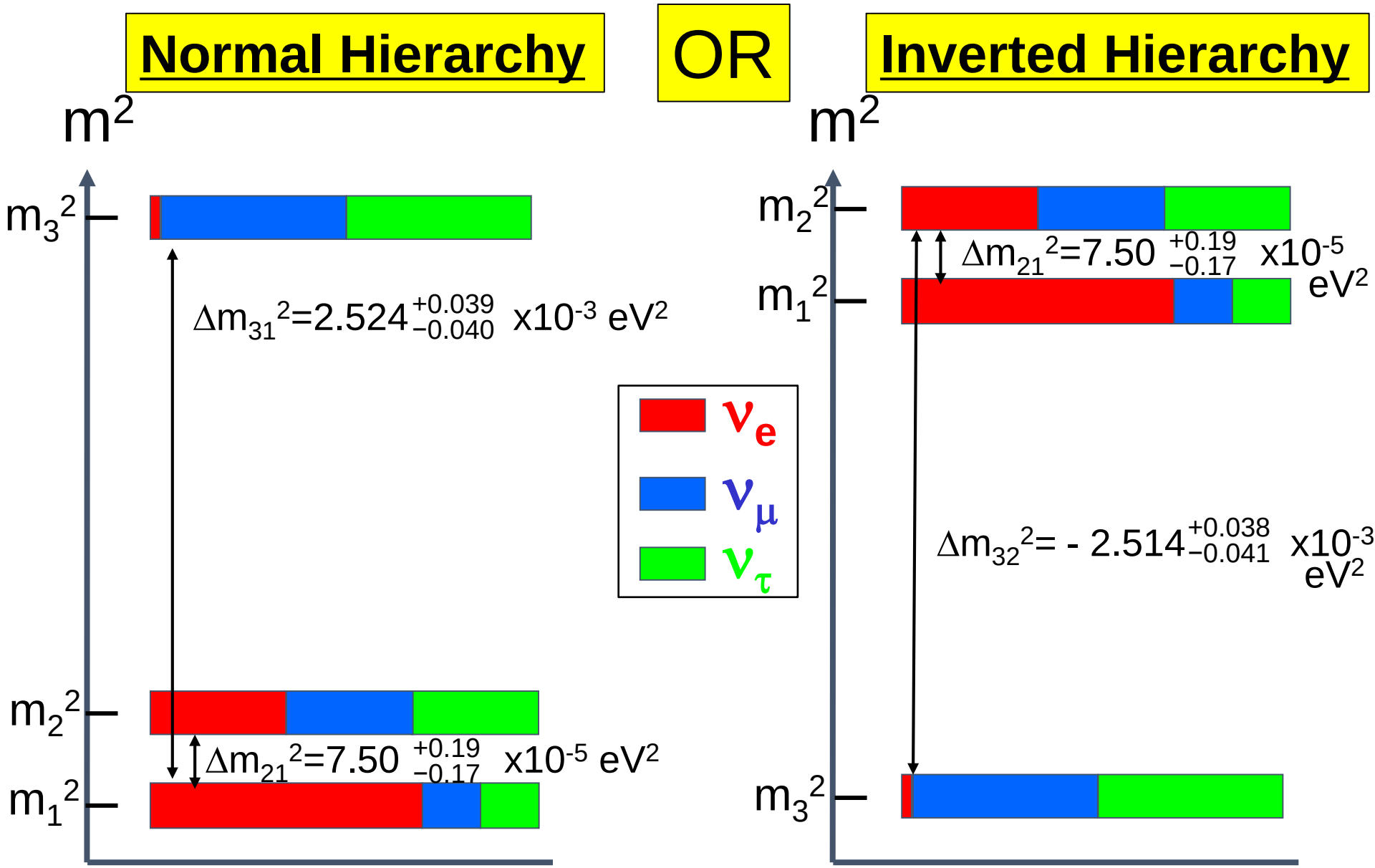
Short baseline reactor ν (2012)

Atmospheric neutrino（1998）

K2K (2004), MINOS(2006)

Experiments at Kamioka revealed all oscillation modes for the first time and further.

Neutrino mass and mixing (what we know now)



Numbers from I. Esteban et al., JHEP 01 (2017) 087

Neutrino mixing vs. quark mixing

Neutrino mixing

(3σ C.L. range)

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

$$\begin{pmatrix} 0.800\text{-}0.844 & 0.515\text{-}0.581 & 0.139\text{-}0.155 \\ 0.229\text{-}0.516 & 0.438\text{-}0.699 & 0.614\text{-}0.790 \\ 0.249\text{-}0.528 & 0.462\text{-}0.715 & 0.595\text{-}0.776 \end{pmatrix}$$

I. Esteban et al., JHEP 01 (2017) 087

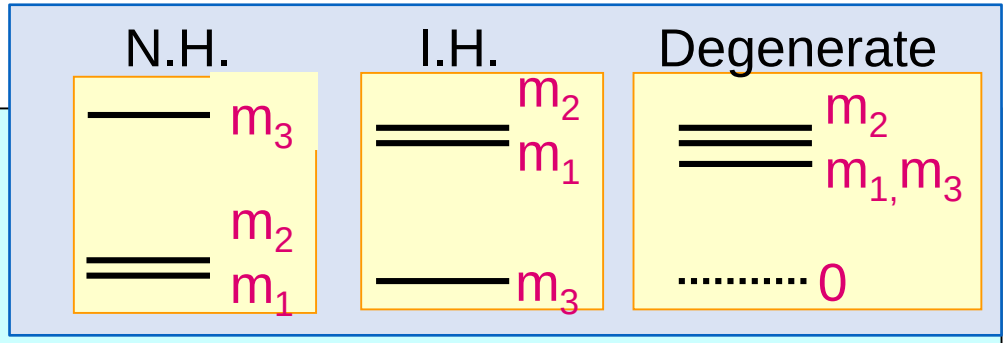
Quark mixing (CKM matrix)

$$\begin{pmatrix} 0.97434 & 0.22506 & 0.00357 \\ 0.22492 & 0.97351 & 0.0414 \\ 0.00875 & 0.0403 & 0.99915 \end{pmatrix}$$

Particle Data Group (2016)

They are so much different!

What are unknowns?



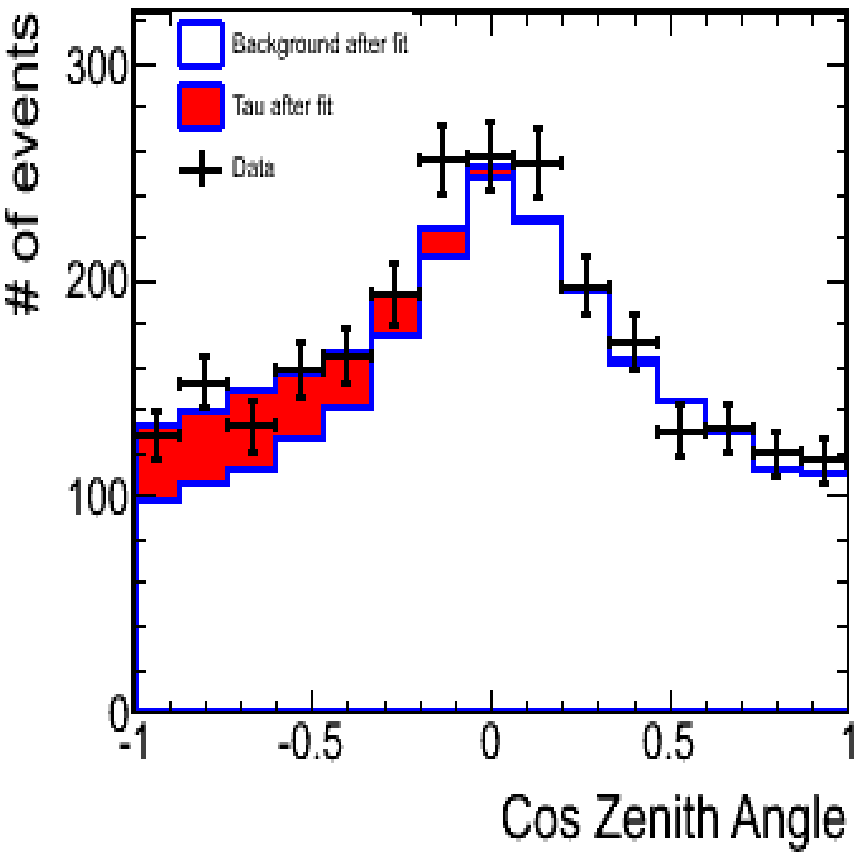
- Which mass hierarchy?
- Is CP phase δ finite?
- Is θ_{23} =45° >45° or <45° ?
- Absolute mass of neutrinos? (→ direct mass experiments)
- Majorana or Dirac mass? (→ double beta decay experiments)
- Sterile neutrino (LSND anomaly)? (→ short baseline accelerator/source experiments)

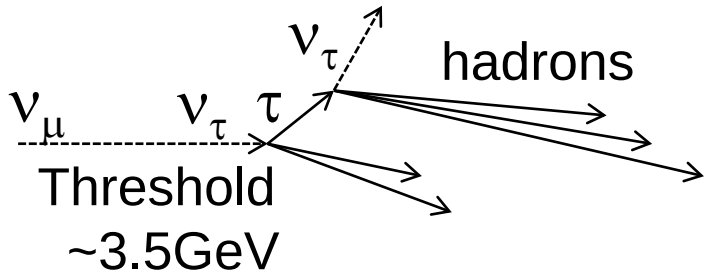
Those are interesting future subjects.

Recent Highlights from Kamioka
(SK, T2K, KamLAND)

SK atmospheric ν: ν_τ appearance

Published at PRL 110,181802 (2013)



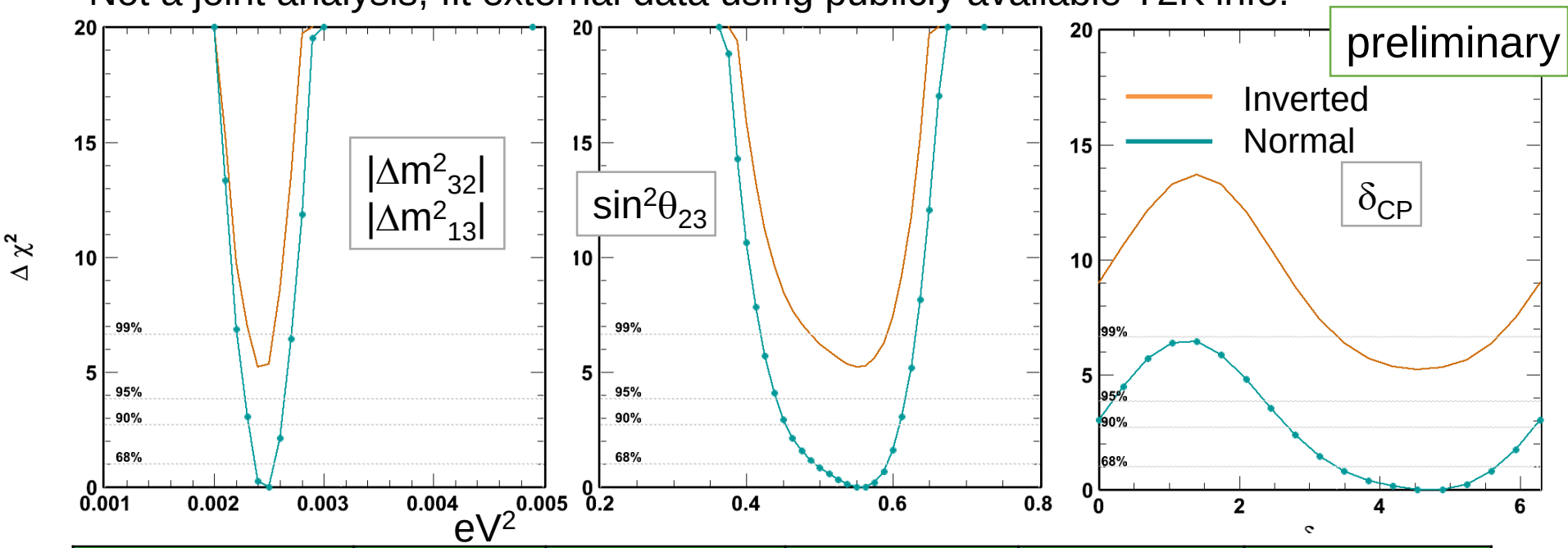


- Search for events consistent with hadronic decay of τ lepton
  - Multi-ring e-like events with visible energy above 1.3GeV.
- Negligible primary ν_τ flux so ν_τ must be oscillation-induced: **upward-going**

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}

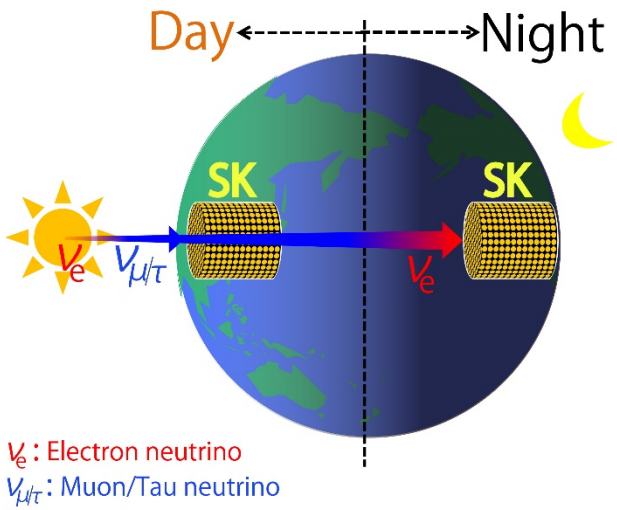
- SK+T2K (θ_{13} fixed): $\Delta\chi^2 = \chi^2_{NH} - \chi^2_{IH} = -5.2$

  (-3.8 (-3.1) expected for SK best(combined) oscillation parameters)

- Under IH hypothesis, the confidence level of this $\Delta\chi^2$ is 5.4%, i.e. “IH disfavored at 94.6%”.

SK solar ν: day/night effect

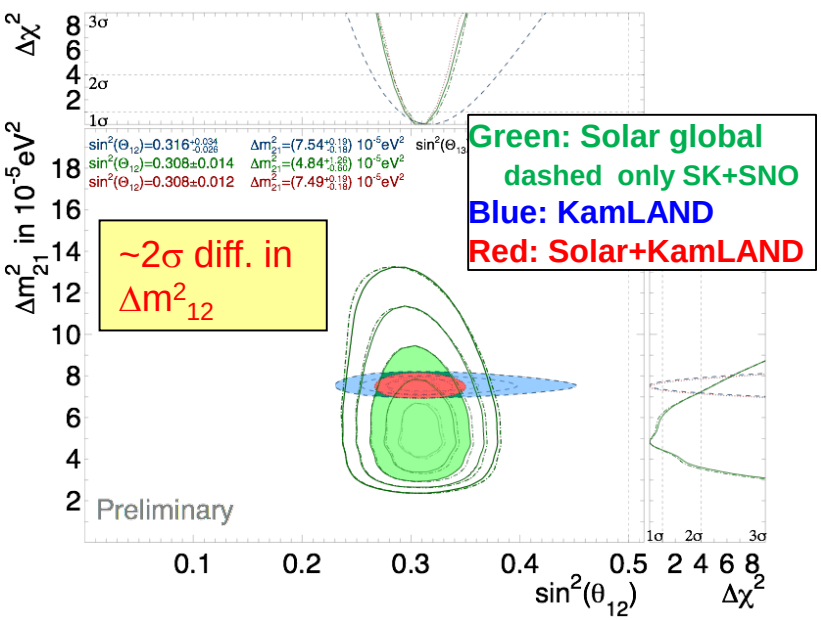
$$A_{DN} = \frac{(Day - Night)}{(Day + Night)/2}$$



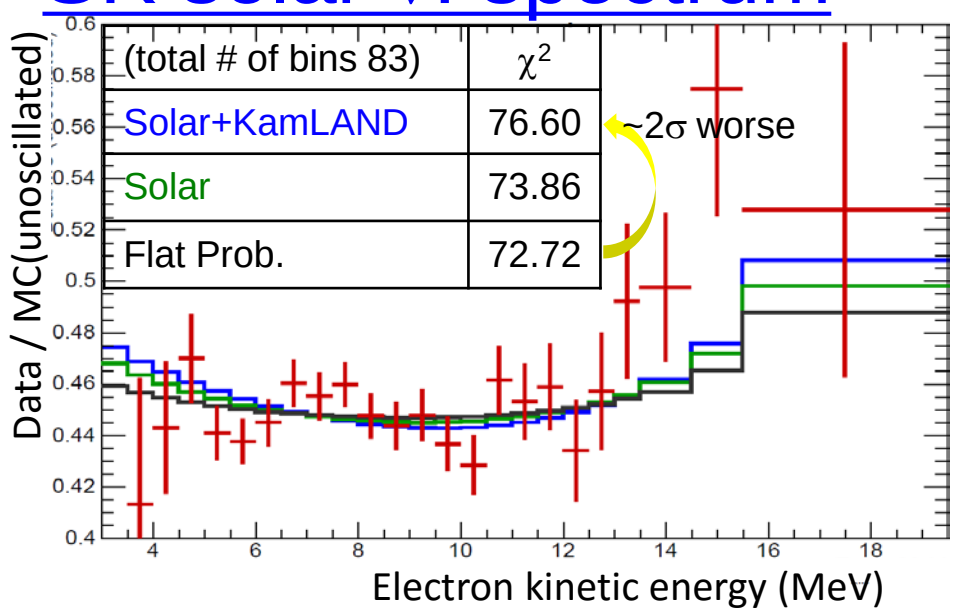
	D/N asymmetry (A_{DN})
	$\Delta m^2_{21}=4.84\times10^{-5}$ eV^2
SK-I	-2.0±1.8±1.0%
SK-II	-4.4±3.8±1.0%
SK-III	-4.2±2.7±0.7%
SK-IV	-3.6±1.6±0.6%
combined	-3.3±1.0±0.5%
non-zero significance	3.0σ

Direct indication of matter effect.

Solar global analysis

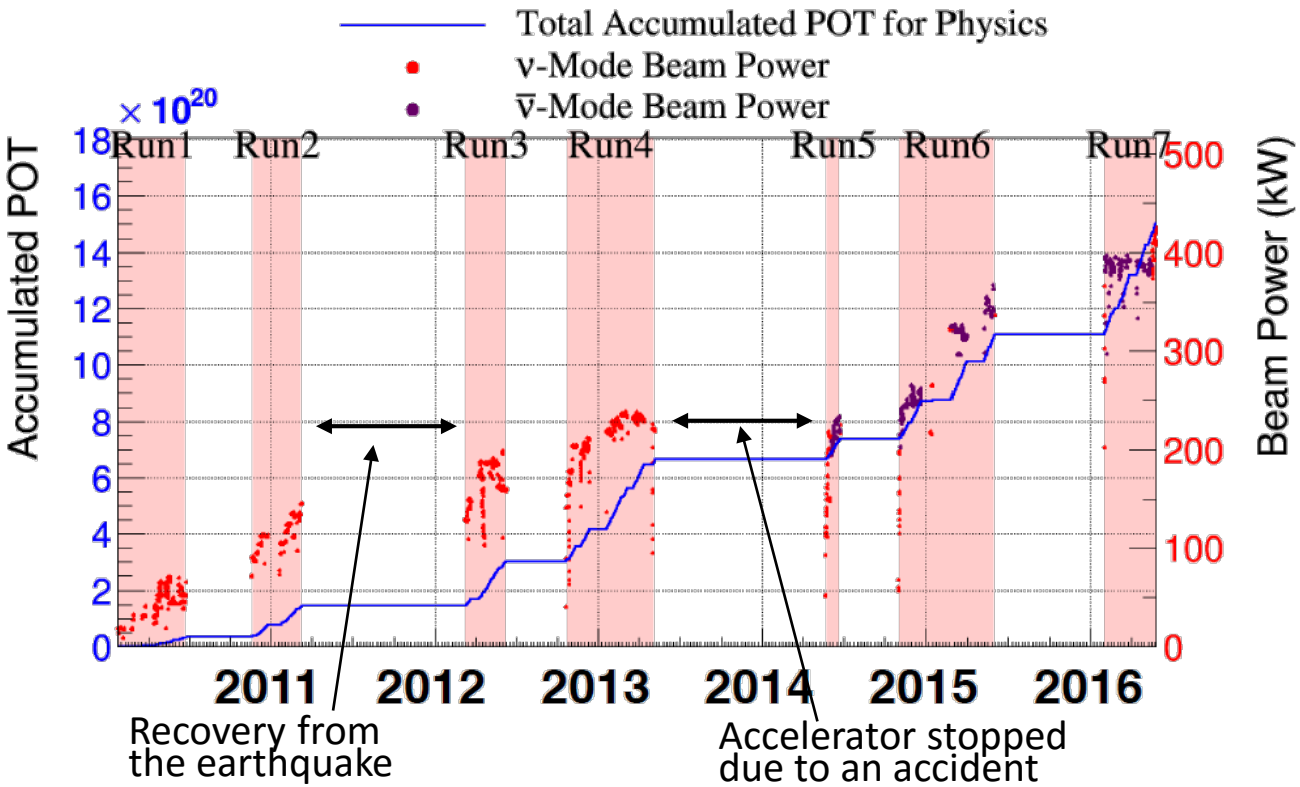


SK solar ν: spectrum



Results from T2K

- 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

7.57x10^{20} POT

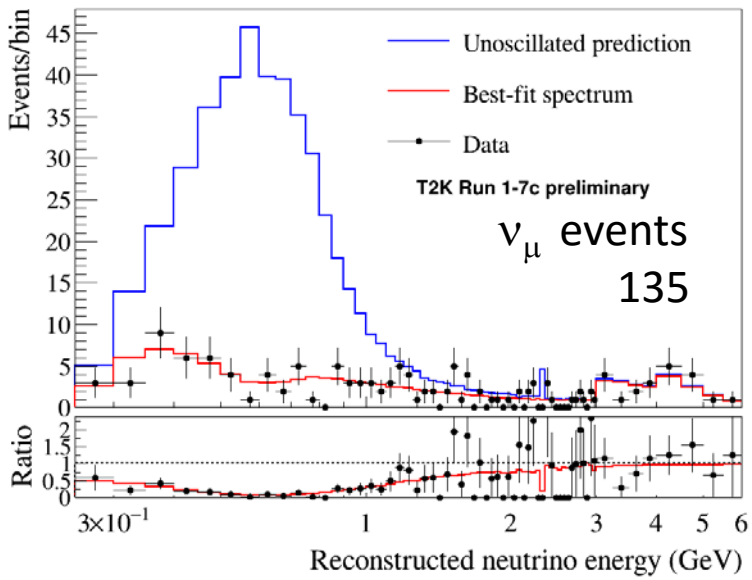
Anti-Neutrino mode

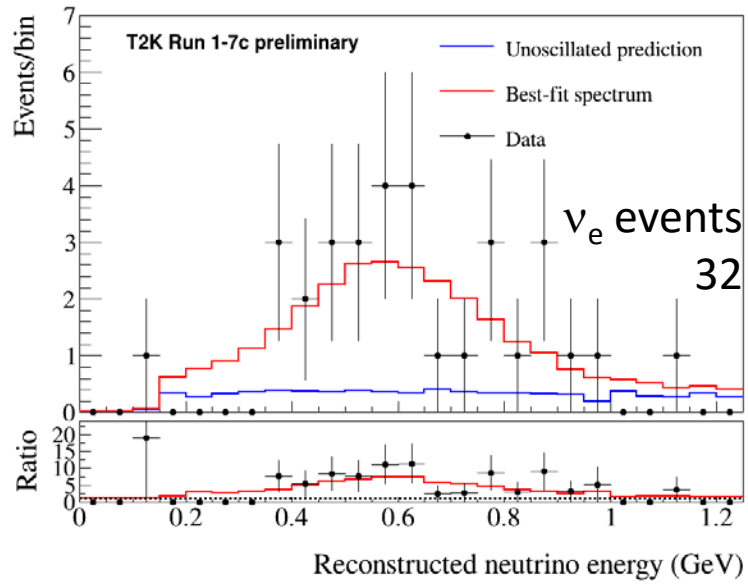
7.53x10^{20} POT

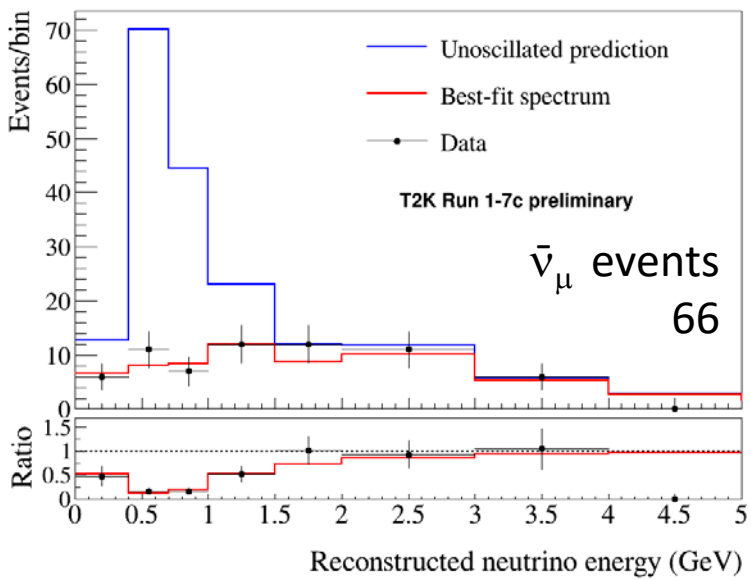
(POT: Proton On Target)

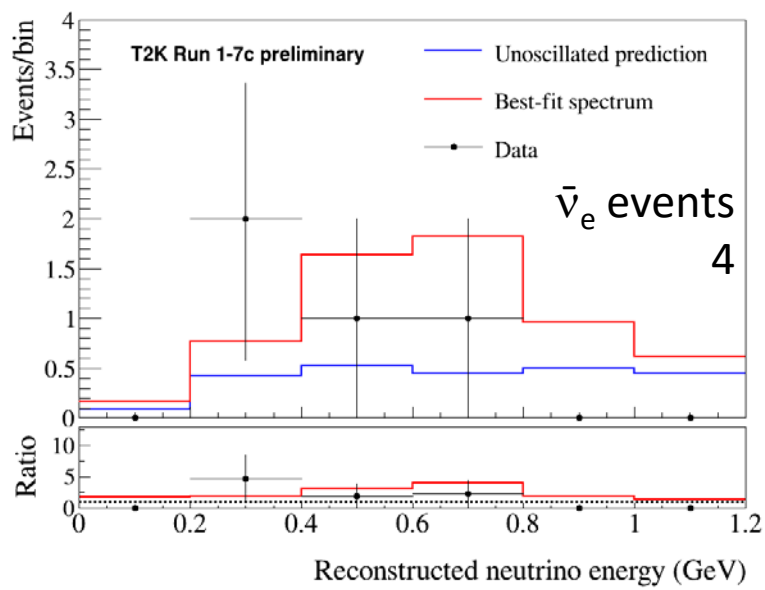
T2K: ν_μ disappearance and ν_e appearance data

ν_μ 7.57×10^{20} POT, $\bar{\nu}_\mu$ 7.53×10^{20} POT data







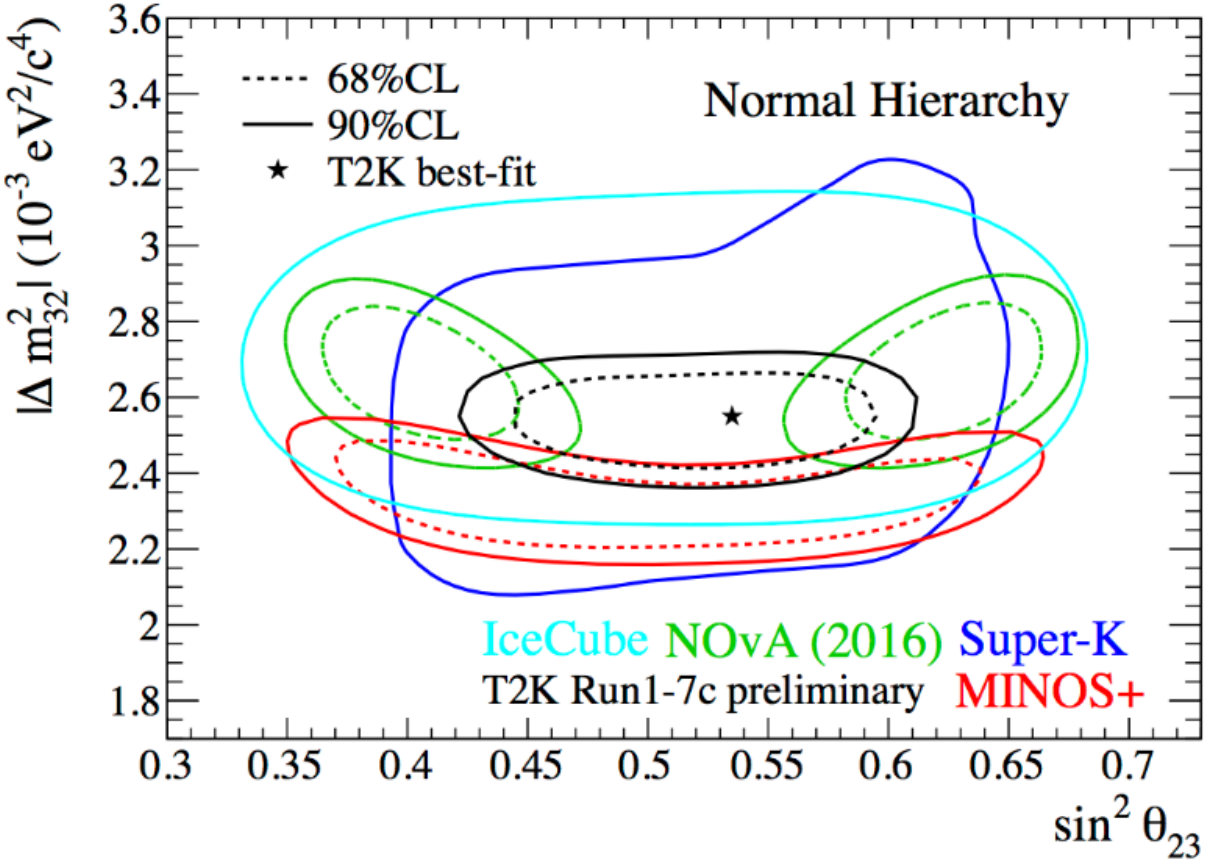


T2K: results from $\nu_\mu+\bar{\nu}_\mu$ disappearance

ν_μ 7.57×10^{20} POT, $\bar{\nu}_\mu$ 7.53×10^{20} POT data

arXiv:1701.00432 [hep-ex]

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



Best fit values:

$(\sin^2(\theta_{23}), |\Delta m^2_{32}|)=$

$(0.532, 2.545\times10^{-3}(\mathrm{eV}^2))$

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.

θ_{13} and δCP measurements

- Short baseline reactor: $\bar{\nu}_e$ disappearance

$$P(\bar{\nu}_e \to \bar{\nu}_e) \approx 1 - \underline{\sin^2(2\theta_{13})}\sin^2\left(\frac{1.27\Delta m^2{}_{31}L(m)}{E_\nu(MeV)}\right)$$

θ_{13} only

- Long baseline accelerator: ν_e appearance

$$P(\nu_\mu \to \nu_e) \approx \underline{\sin^2(2\theta_{13})}\sin^2\theta_{23}\sin^2\left(\frac{1.27\Delta m^2{}_{31}L(km)}{E_\nu(GeV)}\right)$$

Leading term

Sub-leading

$\delta \to -\delta$
$a \to -a$
for $P(\bar{\nu}_\mu \to \bar{\nu}_e)$

$$\begin{aligned}
&+8C_{13}^2S_{12}S_{13}S_{23}(C_{12}C_{23}\cos\delta - S_{12}S_{13}S_{23})\cos\Delta_{32}\sin\Delta_{31}\sin\Delta_{21} \\
&-8C_{13}^2C_{12}C_{23}S_{12}S_{13}S_{23}\sin\delta\sin\Delta_{32}\sin\Delta_{31}\sin\Delta_{21} \\
&+4S_{12}^2C_{13}^2(C_{12}^2C_{23}^2 + S_{12}^2S_{23}^2S_{13}^2 - 2C_{12}C_{23}S_{12}S_{23}S_{13}\cos\delta)\sin^2\Delta_{21} \\
&-8C_{13}^2S_{13}^2S_{23}^2\frac{aL}{4E_\nu}(1-2S_{13}^2)\cos\Delta_{32}\sin\Delta_{31} \\
&+8C_{13}^2S_{13}^2S_{23}^2\frac{a}{\Delta m_{31}^2}(1-2S_{13}^2)\sin^2\Delta_{31}
\end{aligned}$$

CPC
CPV
"solar"
matter

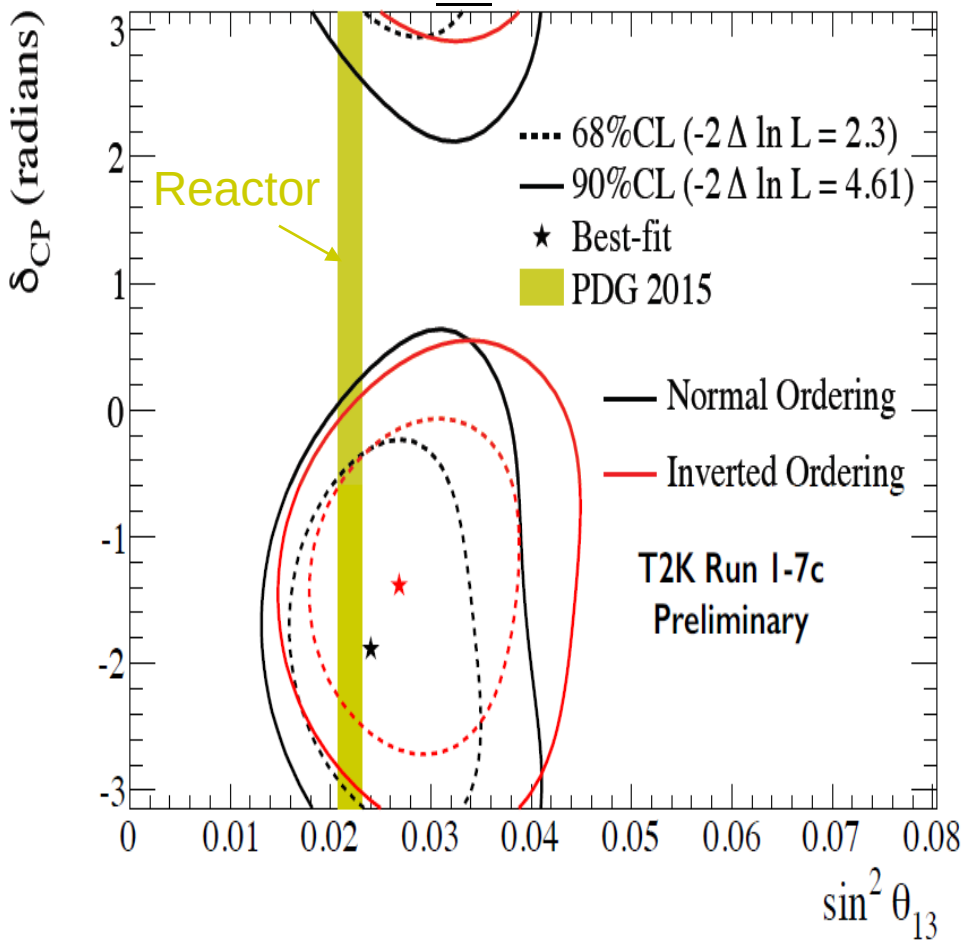
$$S_{ij} \equiv \sin\theta_{ij}, C_{ij} \equiv \cos\theta_{ij}$$
$$\Delta_{ij} \equiv \Delta m_{ij}^2 L / E_\nu$$
$$a = 2\sqrt{2}G_F.n_eE_\nu$$

ν_e appearance: depends on δ and mass hierarchy

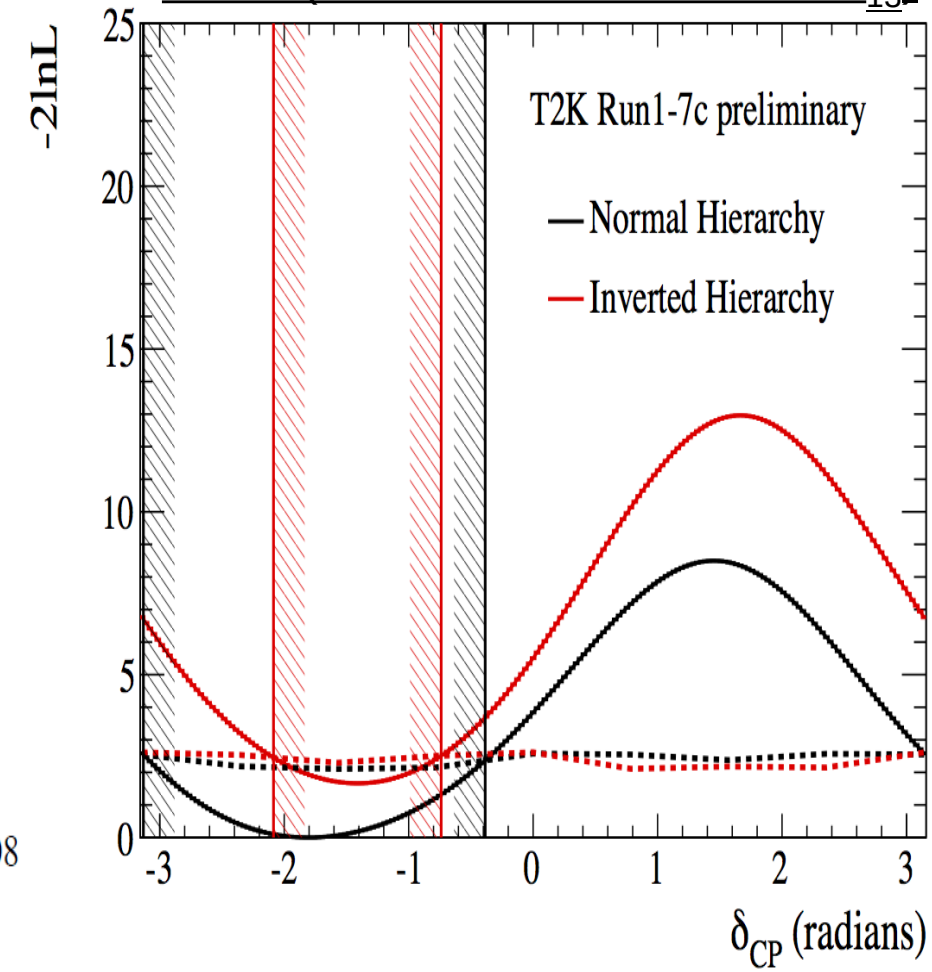
T2K: Results on $\sin^2\theta_{13}$ and δCP

arXiv:1701.00432 [hep-ex]

$\sin^2\theta_{13}$ vs. δCP



δCP (constrained with reactor θ_{13})

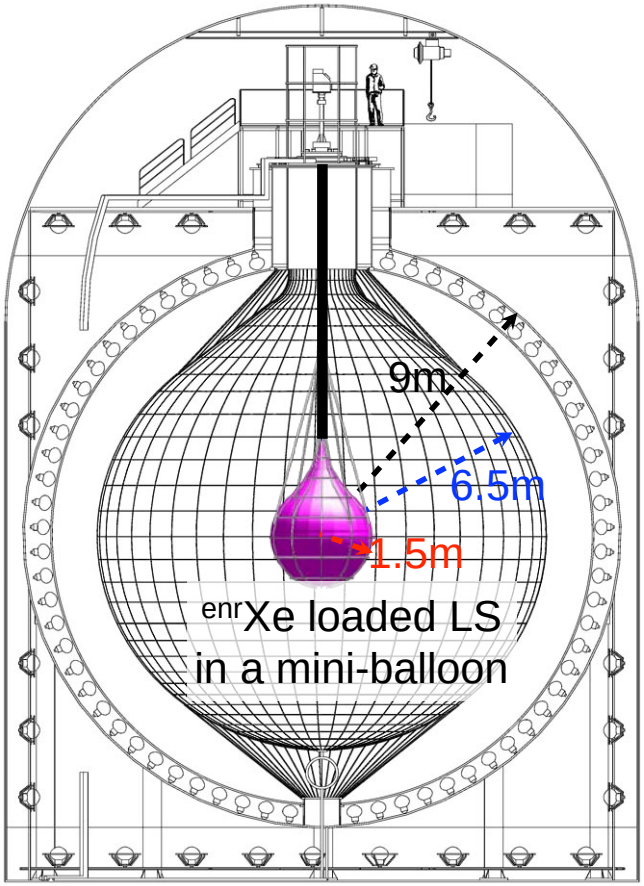


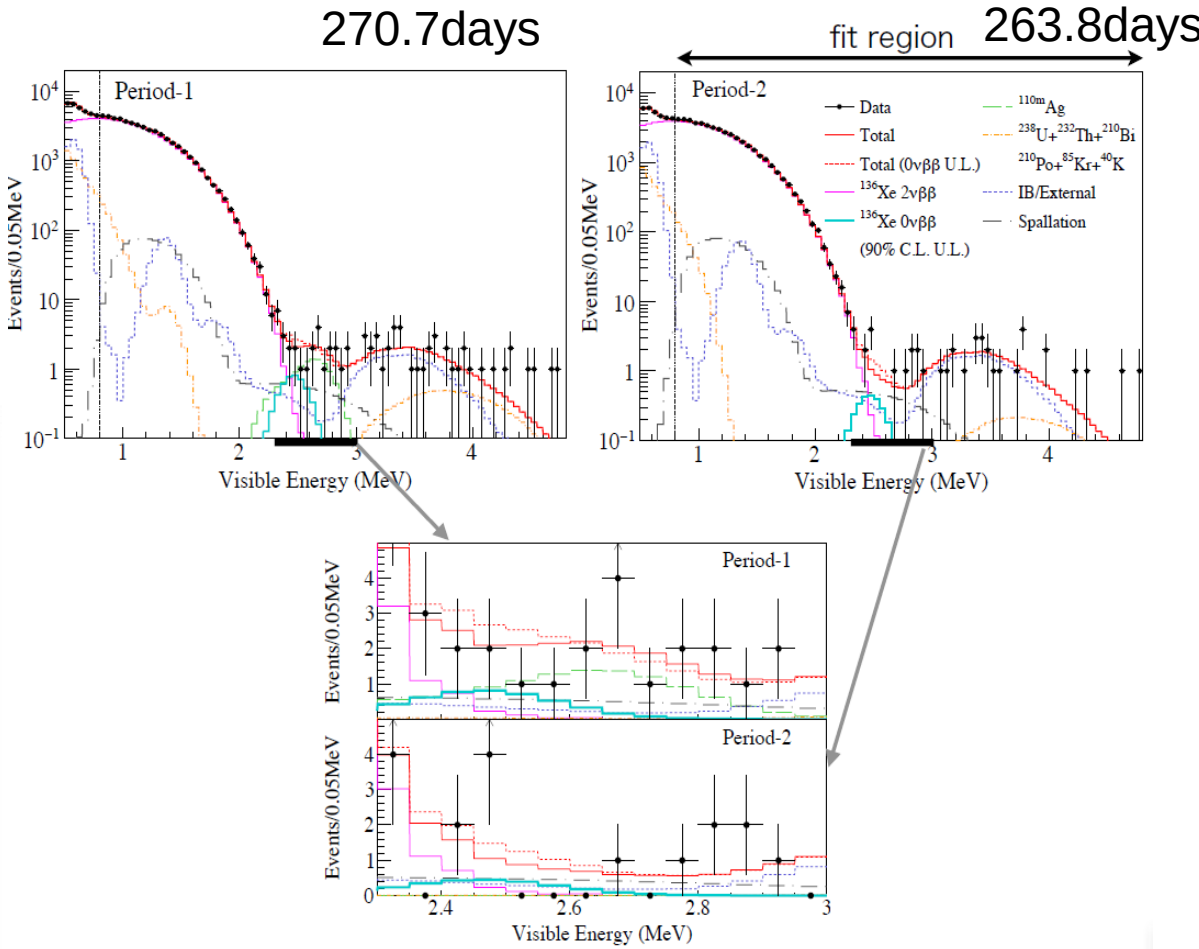
The best fit points lie near the maximally CP violating value $\delta CP=-0.5\pi$. The CP conserving values ($\delta CP=0$ and $\delta CP=\pi$) lying outside of the T2K 90% confidence level interval.

KamLAND-Zen

World best 0νββ experiment at present

Zero Neutrino
double beta decay search



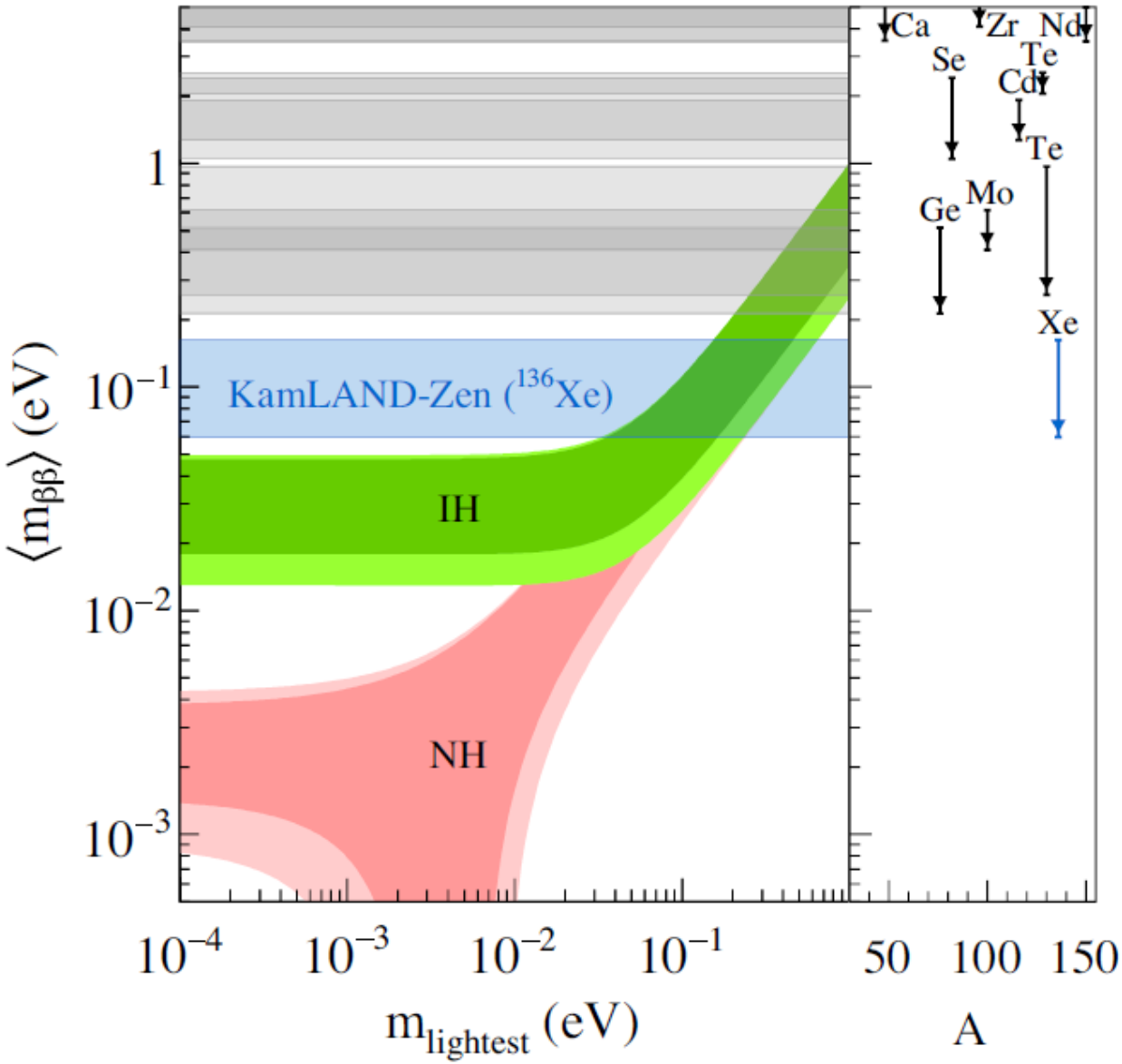


380kg 90% enriched ^{136}Xe
for phase-II

No significant excess of 0νββ

$$T^{0\nu}_{1/2} > 1.07 \times 10^{26}\ \mathrm{yr}$$

KamLAND-Zen result on $<m_{\beta\beta}>$



$$\langle m_{\beta\beta} \rangle < (61 - 165)\,\mathrm{meV}$$

It also provides upper limit of $m_{lightest}$ at 180-480 meV.

A. Gando et al., PRL 117,082503(2016)

Future

How to measure CP phase δ

Long baseline accelerator: ν_e appearance

$$P(\nu_\mu \to \nu_e) \approx \sin^2(2\theta_{13})\sin^2\theta_{23}\sin^2\left(\frac{1.27\Delta m^2{}_{31}L(km)}{E_\nu(GeV)}\right)$$ Leading term

Sub-leading

$$+8C_{13}^2S_{12}S_{13}S_{23}(C_{12}C_{23}\cos\delta - S_{12}S_{13}S_{23})\cos\Delta_{32}\sin\Delta_{31}\sin\Delta_{21}$$ CPC

$$-8C_{13}^2C_{12}C_{23}S_{12}S_{13}S_{23}\sin\delta\sin\Delta_{32}\sin\Delta_{31}\sin\Delta_{21}$$ CPV

$$+4S_{12}^2C_{13}^2(C_{12}^2C_{23}^2 + S_{12}^2S_{23}^2S_{13}^2 - 2C_{12}C_{23}S_{12}S_{23}S_{13}\cos\delta)\sin^2\Delta_{21}$$ "solar"

$$-8C_{13}^2S_{13}^2S_{23}^2\frac{aL}{4E_\nu}(1-2S_{13}^2)\cos\Delta_{32}\sin\Delta_{31}$$

$$+8C_{13}^2S_{13}^2S_{23}^2\frac{a}{\Delta m_{31}^2}(1-2S_{13}^2)\sin^2\Delta_{31}$$ matter

$$S_{ij} \equiv \sin\theta_{ij}, C_{ij} \equiv \cos\theta_{ij}$$
$$\Delta_{ij} \equiv \Delta m_{ij}^2 L/E_\nu$$
$$a = 2\sqrt{2}G_F.n_eE_\nu$$

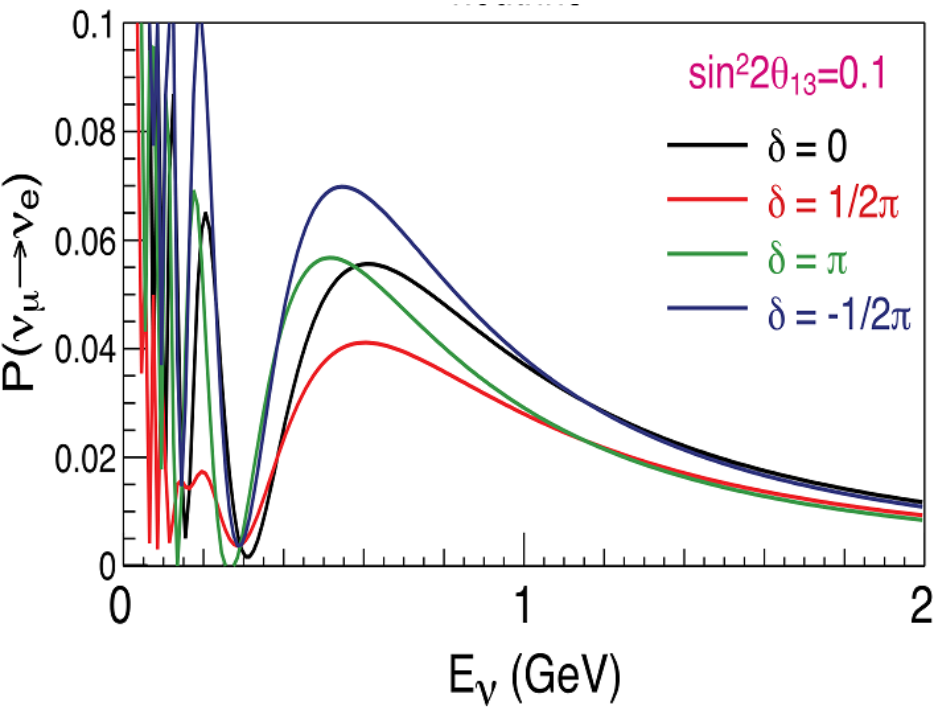
for $P(\bar{\nu}_\mu \to \bar{\nu}_e)$ $\delta \to -\delta$ and $a \to -a$

Compare $P(\nu_\mu \to \nu_e)$ and $P(\bar{\nu}_\mu \to \bar{\nu}_e)$ for CP phase measurement

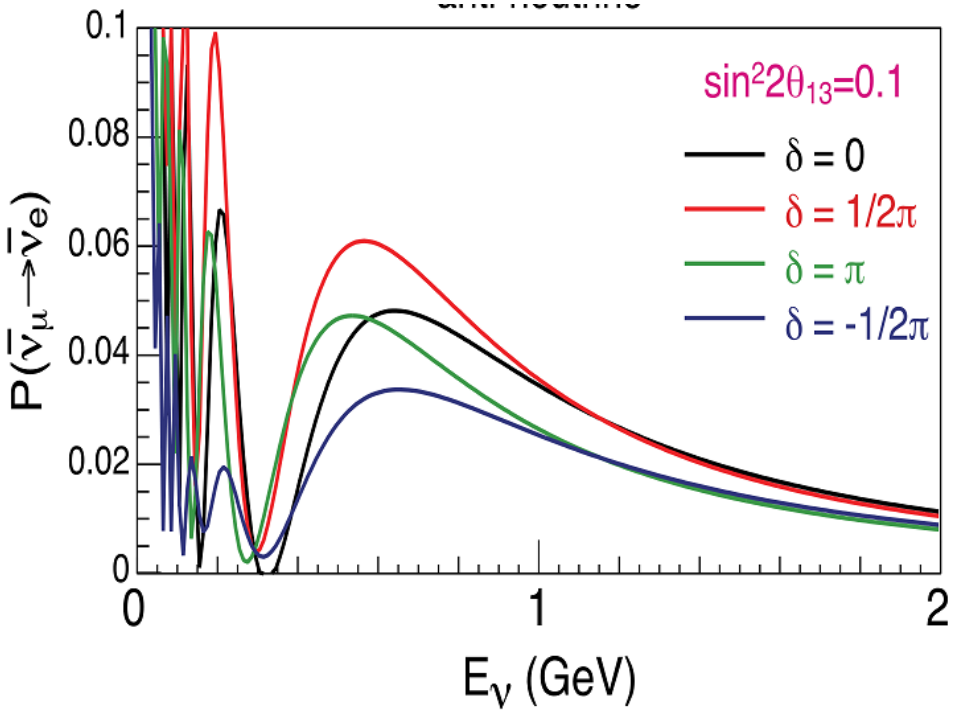
$\nu_\mu \rightarrow \nu_e$ probability (L=295km)

Normal hierarchy

Neutrino case



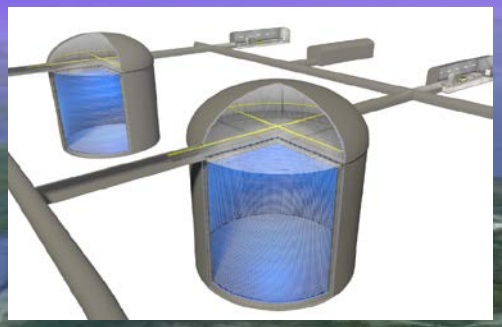
Anti-neutrino case



- Comparison between $P(\nu_\mu \rightarrow \nu_e)$ and $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$
  - As large as ~25% from nominal
- It is sensitive also to exotic (non-PMNS) CP violation cases.

Neutrino oscillation vs. anti-neutrino oscillation

Evidence and precise measurement by Hyper-Kamiokande



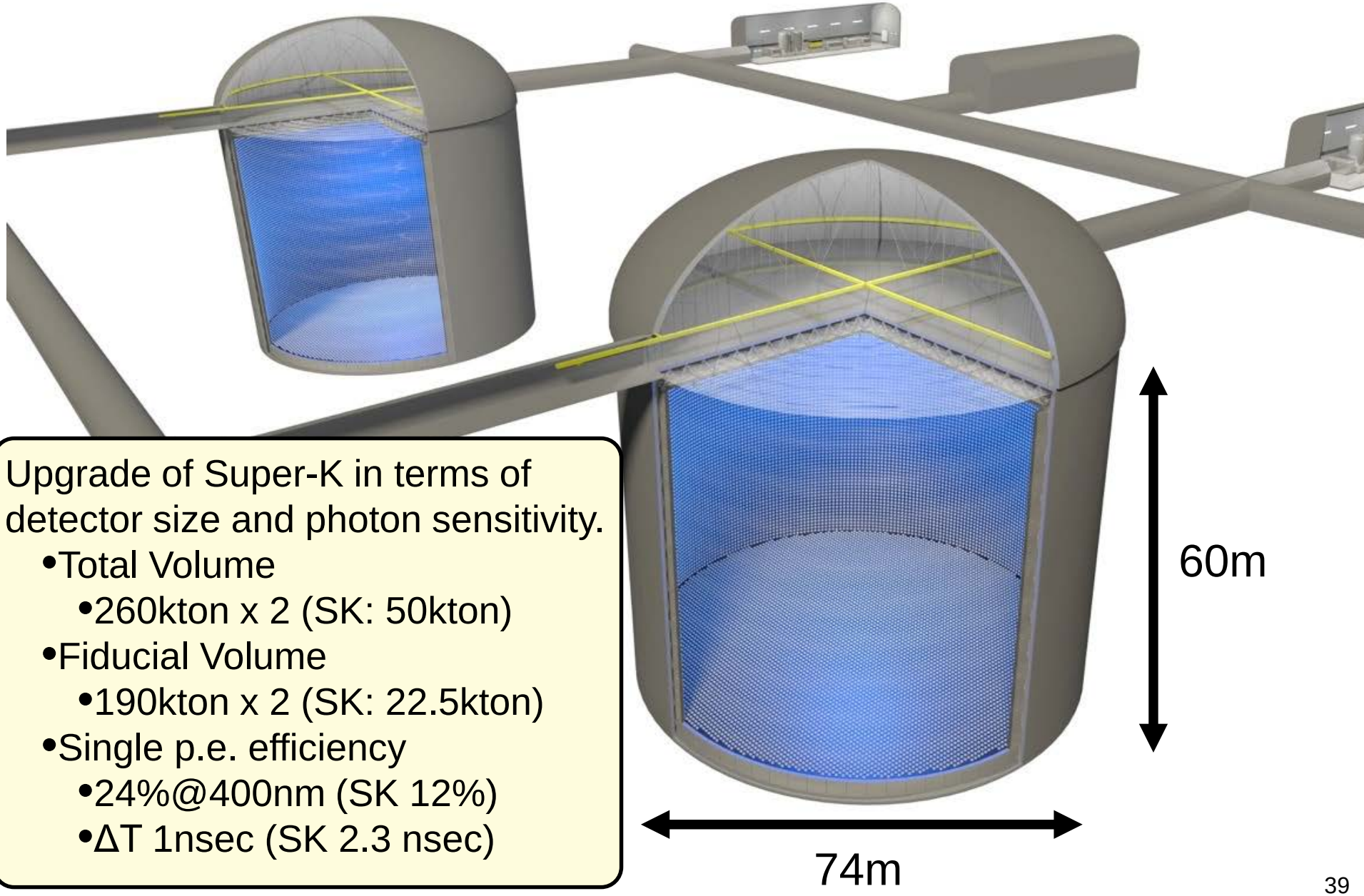
Hint of CP violation by T2K

Super-K

~0.6GeV νμ
295km long baseline

High intensity
neutrino beam
produced at J-PARC

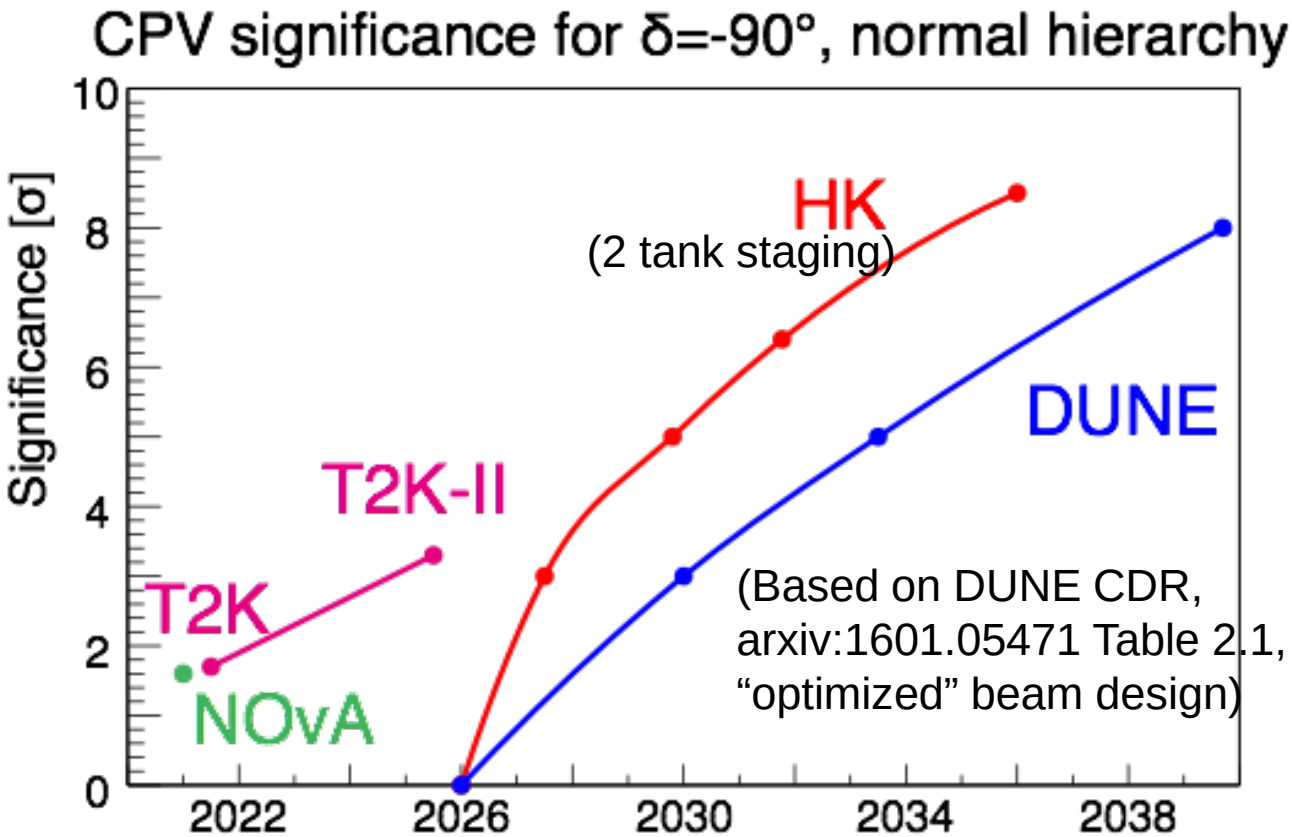
Hyper-Kamiokande



Upgrade of Super-K in terms of detector size and photon sensitivity.

- Total Volume
  - 260kton x 2 (SK: 50kton)
- Fiducial Volume
  - 190kton x 2 (SK: 22.5kton)
- Single p.e. efficiency
  - 24%@400nm (SK 12%)
  - ΔT 1nsec (SK 2.3 nsec)

Towards leptonic CP asymmetry



Strategy of Japan-based program

~3σ indication with T2K→T2K-II,

>5σ discovery and measurement with HK

A Multi-purpose Experiment

Comprehensive study of ν oscillation

- CPV
- Mass hierarchy with beam+atmosph. ν
- θ_{23} octant
- Test of exotic scenarios

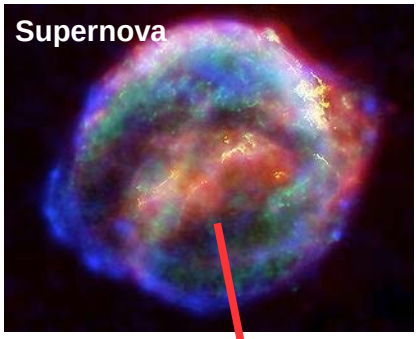
Nucleon decay discovery potential

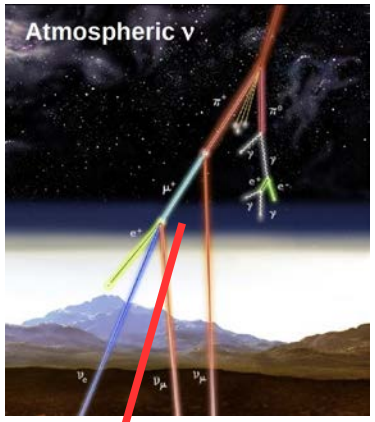
- All visible modes including p → $e^+ \pi^0$ and p→$\bar{\nu}K^+$ can be advanced beyond SK.
- Reaching 10^{35}yrs sensitivity

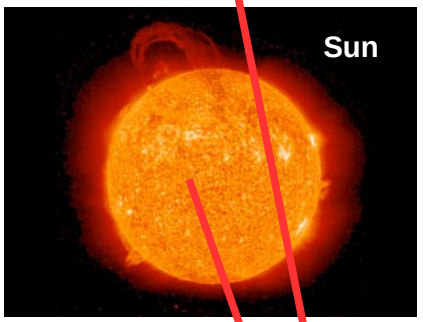
Unique Astrophysics

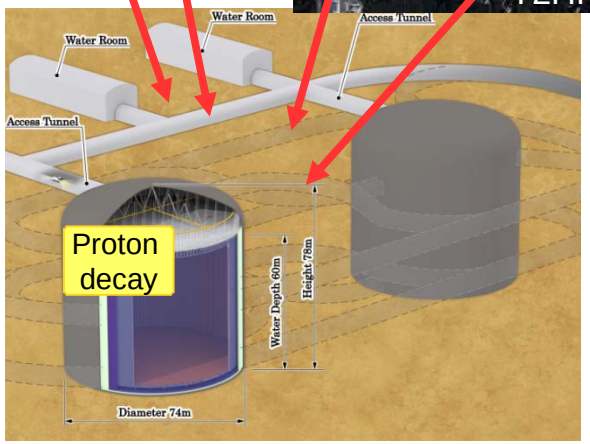
- Precision measurement of solar ν
- High statistics Supernova ν with pointing capability and energy info.
- Supernova relic ν (non-burst $\bar{\nu}$) observation is also possible

Earth core's chemical composition Etc.





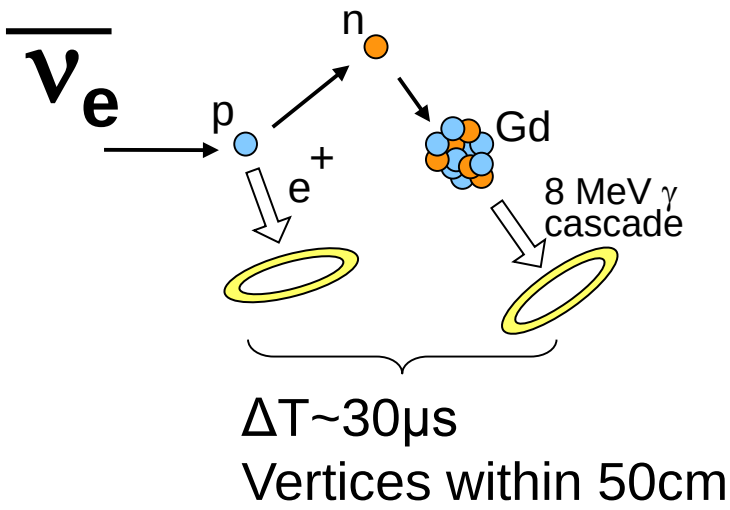


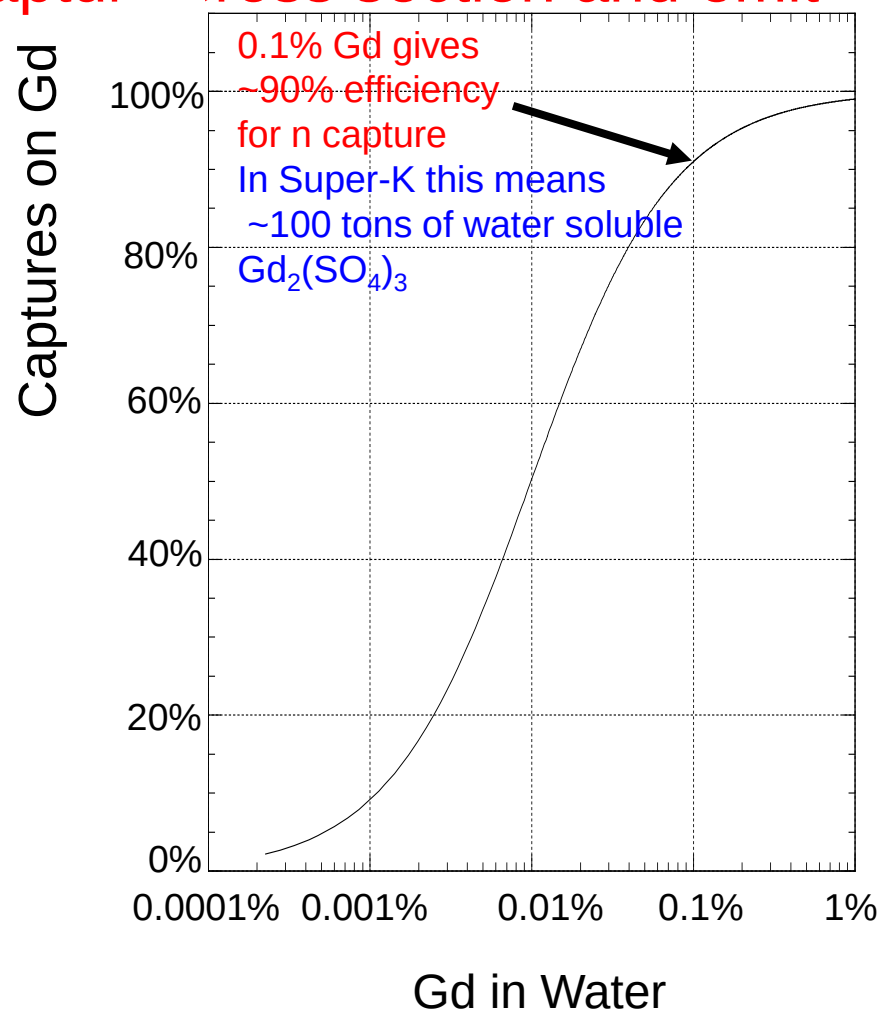


SK-Gd project

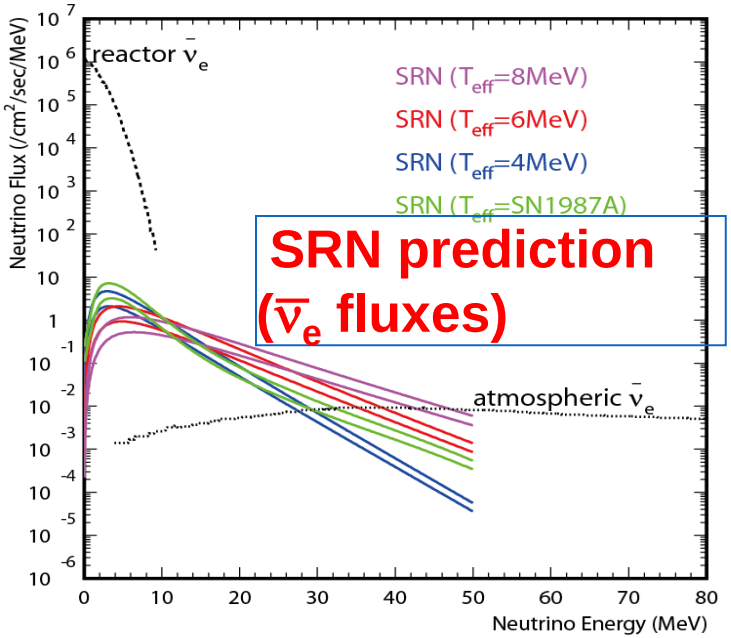
Identify $\bar{\nu}_e p$ events by neutron tagging with Gadolinium.

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





Physics with SK-Gd



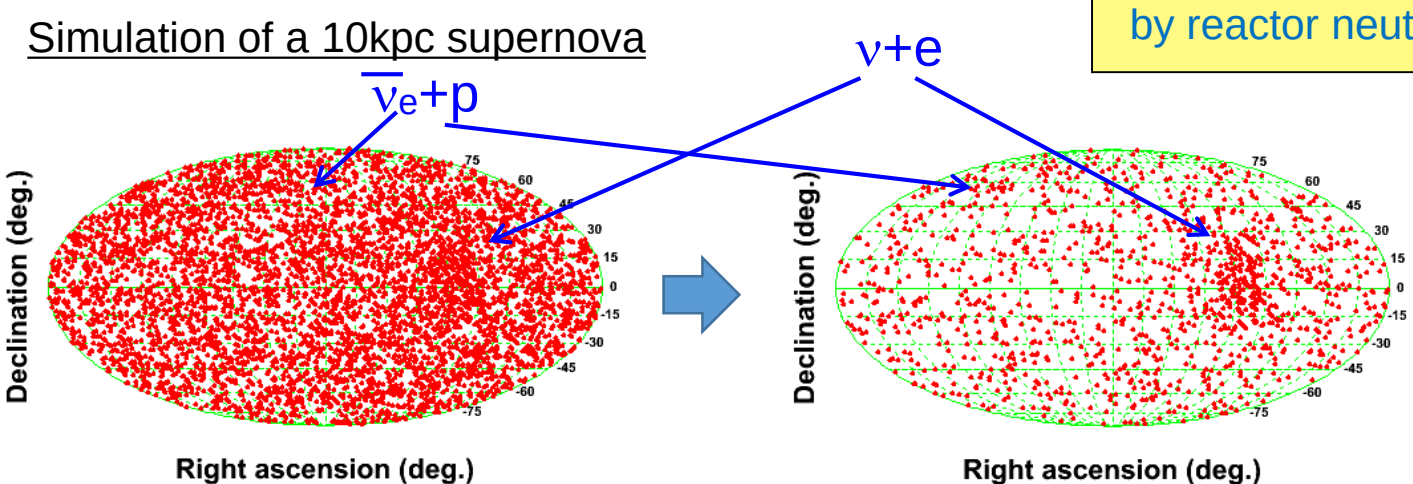
Supernova Relic Neutrinos (SRN)

- 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



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!